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WASTE MANAGEMENT AND CONVERSION

<p>Title/Author</p>	<p>A critical review of the effects of pretreatment methods on the exergetic aspects of lignocellulosic biofuels / Soltanian, S., Aghbashlo, M., Almasi, F., Hosseinzadeh-Bandbafha, H., Nizami, A. S., Ok, Y. S., Lam, S. S., & Tabatabaei, M.</p>
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<p>Title/Author</p>	<p>Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates / Gold, M., Cassar, C. M., Zurbrügg, C., Kreuzer, M., Boulos, S., Diener, S., & Mathys, A.</p>
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<p>Title/Author</p>	<p>Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: Recent progress and future directions elsewhere worldwide / Uzoejinwa, B. B., He, X., Wang, S., El-Fatah Abomohra, A., Hu, Y., & Wang, Q.</p>
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Title/Author	Fatty acid composition of black soldier fly larvae (<i>Hermetia illucens</i>) - Possibilities and limitations for modification through diet / Ewald, N., Vidakovic, A., Langeland, M., Kiessling, A., Sampels, S., & Lalander, C.
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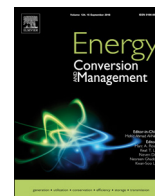
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Title/Author	Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management / Nižetić, S., Djilali, N., Papadopoulos, A., & Rodrigues, J. J. P. C.
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A critical review of the effects of pretreatment methods on the exergetic aspects of lignocellulosic biofuels



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ABSTRACT

Pretreatment process is the key technological step in lignocellulose bioconversion into biofuel owing to its robust molecular structure. This pivotal process can markedly affect the overall sustainability of lignocellulosic biofuel systems because of its energy-intensive, chemical-dependent, and time-consuming nature. More advanced methods should then be developed to evaluate the effects of pretreatment methods on the thermodynamic, economic, and environmental features of lignocellulosic biofuel systems. Among the various tools developed so far, exergetic approaches have attracted a great deal of interest for decision-making purposes because of their interdisciplinary character. Exergy-based methods could provide invaluable information regarding the technical characteristics, economic costs, and environmental impacts of lignocellulosic biofuel systems. Hence, this review is aimed at briefly summarizing the lignocellulose pretreatment methods as well as comprehensively reviewing and critically discussing their key effects on the exergetic aspects of the resulting biofuels. Overall, the hotspots of thermodynamic inefficiency, cost loss, and environmental burden of lignocellulosic biofuel systems could be reliably identified using exergetic methods. Much of the current literature on exergetic analysis of the lignocellulose pretreatment process has been particularly limited to dilute sulfuric acid, organosolv, and steam explosion pretreatment methods, while exergetic aspects of alkaline, liquid hot water, biological, and combined approaches have not been evaluated well enough. In addition, the majority of the published works have only focused on quantifying thermodynamic imperfections and determining exergetic efficiencies of the simulation-based lignocellulosic biofuel systems, while a limited number of studies have investigated exergy-based economic and environmental aspects of such biofuel systems. As a suggestion, future studies need to be concentrated on investigating exergetic aspects of the unexplored pretreatment strategies as well as applying exergoeconomic and exergoenvironmental methods for providing information regarding the formation processes of cost and environmental burden.

1. Introduction

The world's population, urbanization, and modernization are

progressively growing and, therefore, skyrocketing the global energy demand [1,2]. According to the annual outlook report issued by the U.S. Energy Information Administration (EIA), the global energy

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Nomenclature

b	Unitary exergy environmental impact (mPts/GJ)
\dot{B}	Exergy environmental impact rate (mPts/s)
c	Unitary exergy cost (USD/kJ)
C	Specific heat capacity (kJ/kg K)
\dot{C}	Exergy cost rate (USD/s)
DP	Depletion number (-)
e	Specific exergy (kJ/kg)
\dot{E}	Exergy rate (kW)
f	Exergoeconomic/Exergoenvironmental factor (-)
g	Gravitational constant (m ² /s)
G	Gibbs free energy (kJ)
h	Specific enthalpy (kJ/kg)
H	Annual working hour (h)
I	Interest rate (%)
$\dot{I}P$	Exergetic improvement potential rate (kW)
m	Economic modification requirement index (-)
\dot{m}	Mass flow rate (kg/s)
M	Molar mass (kg/mol)
n	Mole number (mol)
N	Plant lifetime (year)
P	Pressure (kPa)
\dot{Q}	Heat transfer rate (kW)
r	Relative cost difference (-)
\bar{R}	Gas constant (kJ/kg K)
\bar{R}	Universal gas constant (8.314 kJ/mol K)
s	Specific entropy (kJ/kg)
SI	Sustainability index (-)
T	Absolute temperature (K)
\dot{W}	Work rate (kW)
x	Mass fraction (-)
y	Molar fraction (-)
Y	Component-related environmental impact (mPts)
V	Velocity (m/s)
\dot{Y}	Component-related environmental impact rate (mPts/h)
Z	Capital cost (USD)
\dot{Z}	Investment cost rate (USD/s)
z	Height (m)

Greeks

β	Weighting factor (-)
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γ	Exergy destruction ratio (%)
ε	Standard chemical exergy (kJ/mol)
ϕ	Maintenance factor (-)
ψ	Exergy efficiency (%)
ω	Humidity ratio (-)

Subscripts

0	Reference state
a	Air
b	Environment-related parameter
c	Cost-related parameter
d	Destruction
e	Exit
f	Fuel
F	Functional
i	Inlet
i, j, k, l	Numerator
k	k th component
p	Product
q	Heat transfer
tot	Total
U	Universal
v	Water vapor
w	Work

Superscripts

ch	Chemical
ke	Kinetics
pe	Potential
ph	Physical

Abbreviations

CHP	Combined heat and power
CRF	Capital recovery factor
SHF	Separate hydrolysis and fermentation
SPECO	Specific exergy costing
SSCF	Simultaneous saccharification and co-fermentation
SSF	Simultaneous saccharification and fermentation

consumption is envisaged to reach more than 106 quadrillions Btu by 2050 (Fig. 1). Furthermore, the future limited availability of fossil fuels and uncertain energy policies not only can destabilize energy markets but also jeopardize energy security [3].

On the other hand, combustion of fossil-based fuels emits massive amounts of carbon dioxide as a principal greenhouse gas and polyaromatic hydrocarbon aerosols as persistent organic pollutants [6]. The high levels of these anthropogenic greenhouse gas emissions have led to tremendous climate change and environmental issues (Fig. 2). Given the multitude of the reasons mentioned above, a swift switch should be taken from fossil-originated fuels to renewable and clean alternatives like wind, solar, biofuel, geothermal, etc. [7].

Among the different substitutes developed to date for petro-fuels, biofuels can efficiently resolve the challenges associated with energy security, environmental degradation, foreign exchange deficits, socio-economic development, and rural backwardness [9]. Production and consumption of these renewable fuels have increasingly drawn attraction in the twenty-first century (Fig. 3). Biofuel generally refers to a wide range of solid, gaseous, and liquid fuels like alcohols (ethanol, methanol, butanol), biodiesel, Fischer-Tropsch gasoline/diesel, bio-oil, bio-crude, hydrogen, methane, and biochar derived from bio-originated

feedstocks [10,11]. It is important to note that the carbon dioxide emitted from biofuel combustion is inherently biogenic and consequently posing no additional negative effect on the environment. This is due to the fact that the carbon contained in biofuels is captured from the atmosphere through “present-day” photosynthetic conversion, unlike ancient photosynthesis for fossil fuels [12].

During the past few decades, biofuel production through bio-conversion of lignocellulose has attracted increasing attention due to its mild operating condition [13]. However, due to the robust structure of lignocellulosic biomass, a pretreatment process is found to be necessary to disintegrate cross-linked fractions of lignocellulosic biomass for enhancing the accessibility and biodegradability of cellulose microfibrils and hemicellulose matrices before their exposure to downstream biological processes such as enzymatic hydrolysis, fermentation or anaerobic digestion [14,15]. In fact, the pretreatment step is of crucial importance in bioconversion of lignocellulosic materials into biofuels mainly due to (a) its high investment and operational costs, (b) its huge chemical consumption and energy demand, and (c) its substantial effect on all operational aspects of the whole system including feedstock selection and logistics, production scale, hydrolysis, fermentation, product recovery/upgrading, residue treatment, and co-product efficiency

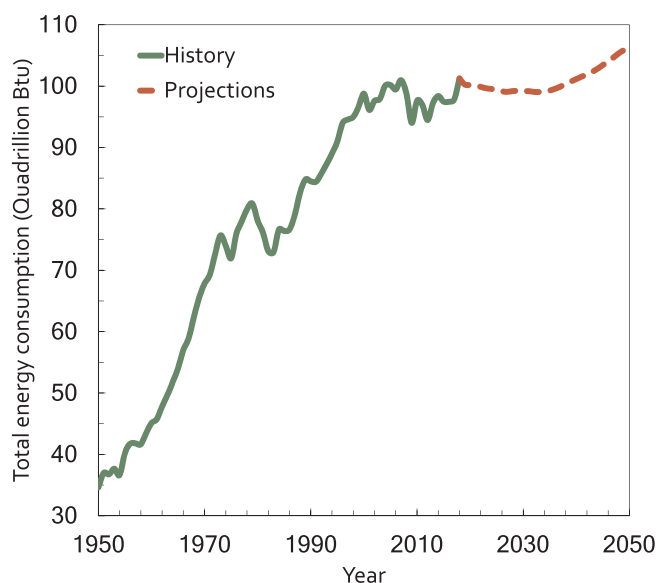


Fig. 1. The history and projections of the global energy consumption issued by the U.S. EIA [4,5].

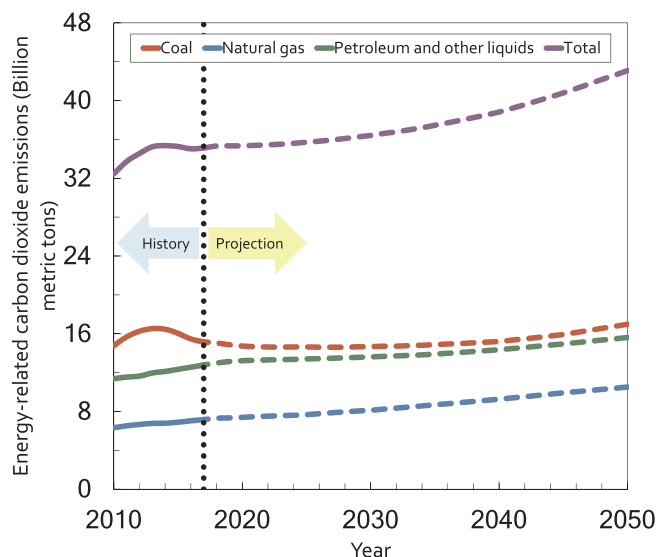


Fig. 2. Global energy-related carbon dioxide emissions of various fossil fuels by the U.S. EIA [8].

[16]. Accordingly, pretreatment process can remarkably affect the overall sustainability of lignocellulose bioconversion into biofuel.

Various tools like techno-economic analysis, energy accounting, emergy synthesis, life cycle assessment, and exergy-based approaches have been used during the past decades in order to make decisions on the sustainability aspects of lignocellulose bioconversion systems. Among the approaches mentioned, exergy-based methods rooted in the laws of thermodynamics have been proven capable of providing invaluable insights into thermodynamic, economic, and environmental aspects of lignocellulose bioconversion into biofuel. Given the importance of the pretreatment step on the overall sustainability of lignocellulosic biofuel systems, this paper is devoted to comprehensively reviewing and critically discussing the key effects of pretreatment methods on their exergetic aspects.

1.1. Biofuel generations

Based on the biomass type and production technology used, biofuels

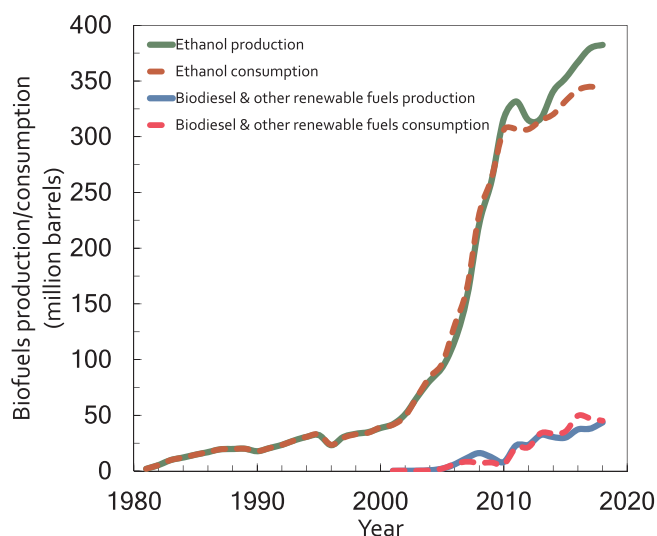


Fig. 3. Global biofuels production and consumption by U.S. EIA [4].

are mainly categorized into first-, second-, third-, and fourth-generation biofuels [17,18]. A comparison among different biofuel generations is presented in Table 1. It is worth mentioning that only the first and second categories have been commercialized so far, while further efforts are currently being undertaken to make third- and fourth-generation marketable.

1.2. Lignocellulosic biomass composition

Typically, lignocellulosic materials consist mainly of cellulose, hemicellulose, and lignin along with trace amounts of extractive fractions (e.g., tannins, resins, fatty acids) and inorganic salts [28]. In general, cellulose, hemicellulose, and lignin contents of lignocelluloses are reported to be in the range of 30–55 wt%, 15–40 wt%, and 10–35 wt%, respectively. Generally, the cell wall of lignocellulosic biomass is composed of crystalline cellulose nanofibrils surrounded by an amorphous matrix of cross-linked lignin and hemicellulose, rigidifying the structure of lignocelluloses [29] (Fig. 4).

In lignocellulosic structure, cellulose refers to a linear homopolymer consisting of many D-glucopyranose units linked by β -1,4-glycosidic bonds [30] (Fig. 4). Depending on the origin of lignocellulosic biomass, the number of glucose units ranges from 2000 up to 20,000 [31]. In addition, cellulose is a semi-crystalline macromolecular comprising both crystalline (i.e., high-ordered) domains and amorphous (i.e., low-ordered) regions. Typically, its degree of crystallinity is determined in the range of 40–60% [32]. Due to the strong intermolecular and intramolecular hydrogen bonding, cellulose is insoluble in the majority of standard solvents like water as well as is highly resistant to enzymatic attack [31]. The chain stiffness and sheet-like configuration of cellulose could relate to the intramolecular and intermolecular hydrogen linkages, respectively [32].

Hemicellulose is a highly branched heteropolymer including pentoses (mainly xylose and arabinose), hexoses (glucose, galactose, mannose) along with some other compounds (glucuronic acid and acetyl groups) (Fig. 4). In hardwoods, the hemicellulose contains 15–30 wt% of xylan that is a polysaccharide consisting of D-xylose units linked together through β -1,4-glycosidic bonds. In softwoods, the hemicellulose is formed of 15–20 wt% galactoglucomannan that is a polysaccharide comprising D-galactose and D-glucose units connected by β -1,4-glycosidic linkages [33]. Generally, hemicellulose has a lower degree of polymerization (i.e., a few hundred) than cellulose [34]. Unlike cellulose, hemicellulose is highly hydrophilic and amenable to hydrolysis.

Lignin is a highly complex phenolic heteropolymer consisting of

Table 1
Comparison among different biofuel generations [10,19–27].

Biofuel class	Feedstocks	Biofuels	Main production and processing technologies	Merits	Drawbacks
First-generation	<ul style="list-style-type: none"> • Cereal crops (e.g., maize, wheat, barley, rye) • Sugar crops (e.g., sugarcane, sweet sorghum, sugar beet) • Edible oil seeds (e.g., soybeans, coconut, sunflower, rapeseed) • Animal fats (e.g., tallow, lard, yellow grease, chicken fat) 	<ul style="list-style-type: none"> • Biodiesel • Bioethanol • Biobutanol • Biogas • Biohydrogen 	<ul style="list-style-type: none"> • Oil extraction • Transesterification • Hydrolysis and fermentation 	<ul style="list-style-type: none"> • Simple conversion technology • Availability of commercial-scale equipment • Fairly less capital cost 	<ul style="list-style-type: none"> • Food vs. energy debate • Increasing global food price • Extensive demand for arable agricultural lands for cultivation • Severe water consumption in the cultivation phase • Massive usage of pesticides and fertilizers • Conflict with biodiversity conservation • Relatively laborious harvesting process • Need for the precise control of environmental conditions such as humidity and temperature • Low potential for the full substitution of petroleum fuels
Second-generation	<ul style="list-style-type: none"> • Non-edible oil seeds • Energy crops (e.g., miscanthus and short rotation coppice willow) • Lignocellulosic biomass (e.g., wheat straw, sugarcane bagasse, woody biomass) • Waste streams (e.g., municipal solid waste, waste vegetable oil, used cooking oil) 	<ul style="list-style-type: none"> • Biomethanol • Bioethanol • Biobutanol • Bio-oil • Biocrude • Biosyngas • Fischer-Tropsch gasoline and diesel • Dimethyl ether • Biogas • Biochar • Bioelectricity 	<ul style="list-style-type: none"> • Pretreatment • Hydrolysis and fermentation • Anaerobic digestion • Gasification • Pyrolysis • Hydrothermal liquefaction • Fischer-Tropsch synthesis • Chemical synthesis 	<ul style="list-style-type: none"> • No food-energy competition • Abundance of feedstocks at lower prices compared with vegetables oil and oilseeds • Availability of commercial-scale equipment • Need for lower amounts of fertilizer and pesticides compared with the first-generation feedstocks 	<ul style="list-style-type: none"> • Need for arable lands • High water consumption in the cultivation phase • Ecological destruction due to deforestation issue • Relatively laborious harvesting process • Need for the precise control of environmental conditions such as humidity and temperature • Complex and expensive processing, upgrading, and production technologies • Need for novel and advanced technologies to reduce the cost of conversion
Third-generation	<ul style="list-style-type: none"> • Algae (e.g., blue-green algae, water hyacinth, microalgae, macroalgae) 	<ul style="list-style-type: none"> • Biodiesel • Biomethanol • Bioethanol • Biobutanol • Bio-oil • Biocrude • Biosyngas • Biogas • Biohydrogen • Biochar • Bioelectricity 	<ul style="list-style-type: none"> • Cultivation • Harvesting • Oil extraction • Transesterification • Hydrolysis and fermentation • Anaerobic digestion • Gasification • Pyrolysis • Hydrothermal liquefaction 	<ul style="list-style-type: none"> • No food-energy competition • Minimum conflict with traditional agriculture • Fast algae growth rate • Producing algal biomass with high amounts of lipids (up to 80% of dry weight) as well as proteins and carbohydrates • Reducing greenhouse gas level through carbon dioxide fixation in the algae cultivation phase • Ability of algae to tolerate and use a high level of carbon dioxide (i.e., 150,000 ppmv) • Capable of yielding higher algal oil per unit land area compared with terrestrial oilseed crops • Feasibility of cultivating algae in non-arable land, wastewater, and saline water • Possibility of cultivating algae in harsh environmental conditions such as pH at the range 4–9 • Feasibility of treating wastewater using algae through removing the hazardous elements mostly N and P • Compatibility with co-production through biorefinery concept 	<ul style="list-style-type: none"> • No well-established markets for trading • Expensive large-scale cultivation • Complex and expensive algae harvesting process • Difficult scaling up of lab-scale production rate to commercial quantities • Need for massive carbon and nitrogen sources • Need for day-time availability of solar energy • Lack of research and technological development • No well-established markets for trading

(continued on next page)

Table 1 (continued)

Biofuel class	Feedstocks	Biofuels	Main production and processing technologies	Merits	Drawbacks
Fourth-generation	<ul style="list-style-type: none"> Genetically modified algae 	<ul style="list-style-type: none"> Similar to the third-generation biofuels 	<ul style="list-style-type: none"> Metabolic engineering of algae for increasing their carbon entrapment ability Cultivation Harvesting Oil extraction Transesterification Hydrolysis and fermentation Anaerobic digestion Gasification Pyrolysis Hydrothermal liquefaction 	<ul style="list-style-type: none"> Similar to the third-generation biofuels 	<ul style="list-style-type: none"> Expensive large-scale cultivation Complex and expensive algae harvesting High human health and environmental risks Hazardous water residue and by-products containing plasmid or chromosomal Risk of lateral gene transfer Lack of research and technological development

three different hydroxycinnamyl alcohol monomers (i.e., monolignols) including p-coumaryl, coniferyl, and sinapyl alcohols [33,35] (Fig. 4). The monolignols are linked together through a variety of couplings, mainly ether linkage (e.g., α -O-4, β -O-4, and 4-O-5) and C-C linkage (e.g., β - β , β -5, and 5-5) [36]. The most abundant type of inter-connections in the structure of lignin is β -O-4 aryl ether that is responsible for the highly branched aromatic structure. For instance, hardwood and softwood lignins are accounted for 60–62% and 45–50% β -O-4 aryl ether linkage of the total bonds, respectively [37]. In lignocellulosic biomass, cellulose and hemicellulose are sugars-rich resources that are suitable for biofuels production such as ethanol, whereas lignin is a useful feedstock for synthesizing aromatic-based chemicals [38,39].

1.3. Lignocellulosic biofuel production pathways

There is a wide range of processing technologies for converting lignocellulosic biomass into biofuels including primarily biological methods (e.g., fermentation and aerobic/anaerobic digestion) and thermochemical methods (e.g., hydrothermal liquefaction, pyrolysis, conventional/advanced gasification) (Table 2) [40–42]. Due to the refractory property of lignin polymer in lignocellulosic materials, thermochemical conversion routes can be more promising through thermal degrading the recalcitrant structure to produce biofuels. However, thermal-based transformations are essentially capital-expensive processes because of their harsh reaction conditions, hindering their widespread application for sustainable biofuels production. In this regard, biological approaches have attracted more attention for converting lignocellulosic materials into biofuels because of their mild operation conditions [43].

1.4. Lignocellulose pretreatment methods

There are various kinds of pretreatment methods used for facilitating biofuel production, including biological, physical, chemical, physicochemical, and combined methods as illustrated in Fig. 5 [76]. The merits and drawbacks of the developed pretreatment methods are tabulated in Table 3. Each pretreatment method imposes a certain influence on the cellulose, hemicellulose, and lignin proportion [77]. Accordingly, the selection of a suitable pretreatment strategy depends on the process configurations employed in the downstream hydrolysis and fermentation [78].

It should be noted that various factors like feedstock logistics, pretreatment process, enzyme supply, hydrolysis/fermentation or anaerobic digestion process, and separation and purification processes can significantly affect the economic viability and environmental sustainability of lignocellulose bioconversion into biofuel [43]. Among the above-mentioned items, the lignocellulose pretreatment process has been reported to be a more crucial step in affecting the viability and sustainability of biofuel systems because of its capital-expensive, energy-intensive, and chemical-consuming nature. For instance, da Silva et al. [94] techno-economically evaluated the effects of different pretreatment methods including diluted acid, liquid hot water, and ammonia fiber explosion on the lignocellulosic bioethanol production process. The authors claimed that the cost of pretreatment alone could be as high as the overall cost of the production process (e.g. hydrolysis, fermentation, or recovery/purification).

In addition, the formation of inhibitory compounds is inevitable in the pretreatment of lignocellulosic feedstocks which adversely affects the performance of the entire conversion [95]. The major groups of inhibitors include (a) furan compounds (i.e., furfural, hydroxymethylfurfural), (b) weak acids (i.e., formic acid, acetic acid, levulinic acid), and (c) phenolic derivatives which could hamper the activity of microorganisms and consequently cease fermenting the pretreated hydrolysate [96].

Overall, an ideal pretreatment of lignocellulosic materials is to (a) increase the surface area accessibility, (b) breakdown the lignin-

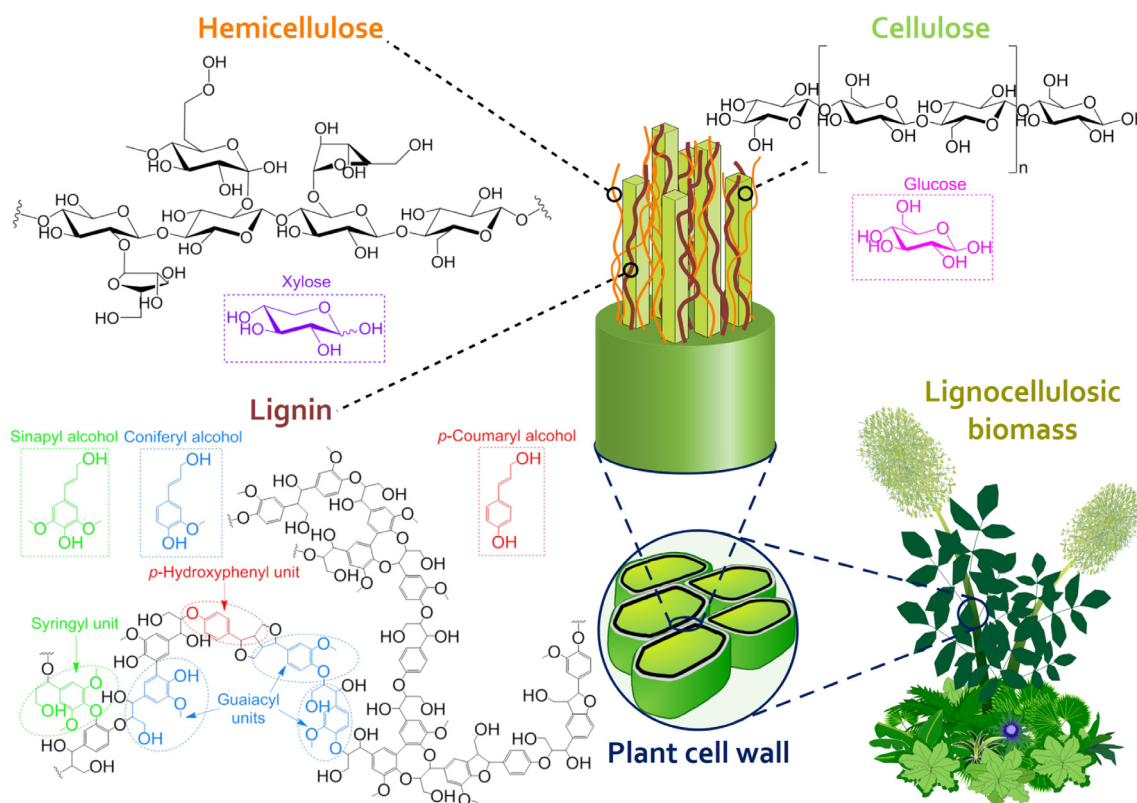


Fig. 4. Schematic structure of lignocellulosic materials.

hemicellulose cross-linkage impeding the enzymatic activity, (c) decrease cellulose crystallinity, (d) depolymerize cellulose and hemicellulose partially, (e) increase the solubility of hemicellulose and lignin, (f) alter the structure of lignin, (g) promote the enzymatic digestibility, (h) diminish the sugar loss, (i) preserve the pentose fraction of hemicellulose, (j) minimize the formation of inhibitors negatively affecting the activity of fermentation microorganisms, (k) reduce energy demand, and (l) discount capital and operating costs [78,84].

1.5. Biofuel sustainability assessment methods

Several approaches have been developed to date for measuring the efficiency, productivity, envirosafety, and sustainability issues of energy conversion systems, namely: life cycle assessment [97,98], techno-economic analysis [99,100], emergy analysis [101], energy analysis [102,103], and exergy analysis [104].

Life cycle assessment approach is a suitable method for evaluating a product in terms of environmental issues and human health over the entire life cycle of the product [26,105,106]. This technique is able to provide a much broader view for a systematic analysis of biofuel production processes by coupling material/energy consumptions with waste streams and pollutant emissions. However, life cycle assessment as an environmental impact assessment approach is subjected to drawbacks like arbitrariness and uncertainties [107].

Techno-economic analysis is a methodology often used for appraising the economic feasibility and specifying the short- and long-term economic success of energy projects [108,109]. This method identifies technical and economic bottlenecks and offers remedies for attaining the most favorable scenarios [110,111]. Nevertheless, techno-economic analysis might lead to misconclusions since it analyzes energy systems on the basis of technical and economic criteria while disregarding the thermodynamic and environmental aspects [112].

Emergy quantifies the amounts of energies and resources used in the biosphere in direct or indirect form for making a specific product or

service [113]. In this approach, all flows of energy, matter, and money entering the system under investigation are expressed on the basis of solar energy joule (sej) since it is hypothesized that solar energy is the main driving force in creating and sustaining life in the biosphere [114]. Despite the promising features of emergy analysis, it not only suffers from the uncertainty associated with transformity values but also needs some allocation decisions [114,115].

Energy analysis, as the most widely used approach for analyzing energy systems, takes into consideration all energetic streams involved in a process (i.e., input energy, output energy, energy generation) in order to measure its first-law efficiency [116]. However, conventional energy analysis is not sufficiently reliable for making decisions on the sustainability of energy systems because it is only based on the principle of energy conservation [117].

In contrast to the energy analysis which measures just the quantity of an energy stream, exergy analysis has been emerged to consider both the quality and quantity of energy and material flows [118,119]. In fact, exergy is a systematic integration of the first and second laws of thermodynamics to cope with the shortcomings of energy analysis. Simply speaking, exergy manifests the maximum useful work that a thermodynamic system can produce when it gets equilibrium with a reference environment through reversible processes [120]. Exergy analysis can precisely discover the quantities, locations, and reasons of thermodynamic losses (called also irreversibility or exergy destruction) of energy systems [121]. Notably, exergy destruction is directly associated with economic loss/resource depletion [122] as schematically illustrated in Fig. 6.

Among the approaches explained above for sustainability assessment of energy systems, exergy is a universally accepted concept for analyzing energy systems since it is based on a well-defined methodology [115]. This approach allows precise measurement of resource destruction and economic loss due to the fact that it is rooted in thermodynamics. In addition, the exergy concept can be enhanced by integrating with economic and environmental constraints, providing

Table 2
Comparison of different conversion pathways for biofuel production from lignocellulosic materials.

Conversion pathway	Description	Merits	Drawbacks	Refs.
<i>Biological</i> Anaerobic digestion	A process of converting organic matter into biogas (i.e., a mixture of mainly methane, carbon dioxide, hydrogen) using bacterial consortiums in an oxygen-free environment	<ul style="list-style-type: none"> ● Ability to process high-moisture containing biomass ● Producing solid and liquid biofertilizers with value-added agronomical features ● Less energy-intensive compared to the thermal conversion process ● Mild reaction conditions 	<ul style="list-style-type: none"> ● Long processing time ● Low production rate ● Need for feedstock pretreatment ● High pretreatment cost ● Complexity of the process because of involving several parameters like temperature, total solid content, volatile solid content, ultimate and proximate properties of feedstocks, carbon/nitrogen ratio, chemical oxygen demand, alkalinity, organic loading rate, hydraulic retention time, volatile fatty acid, pH, co-feed inputs, pretreatment type, and reactor type 	[44–51]
Fermentation	A microorganism-assisted process converting sugars, such as glucose and fructose into ethanol	<ul style="list-style-type: none"> ● Ability to process high-moisture containing biomass ● Less energy-intensive compared to the thermal conversion process ● Mild reaction conditions 	<ul style="list-style-type: none"> ● Long processing time ● Low production rate ● Need for pretreatment ● High pretreatment cost 	[52,53]
<i>Thermochemical</i> Hydrothermal liquefaction	A process carried out in the presence of a solvent such as water and ethanol at a temperature in the range of 250–370 °C and a pressure in the range of 5–25 MPa with or without using a catalyst in order to produce biocrude or bio-oil as the main product along with aqueous, gaseous (mainly carbon dioxide), and solid by-products	<ul style="list-style-type: none"> ● Ability to process moist feedstocks or aquatic biomass such as microalgae ● Ability to process lipid-poor biomass ● Producing energy-dense biocrude ● Producing biocrude with higher carbon contents compared with pyrolysis technology ● Fast processing time ● High production rate ● No need for pretreatment ● Fast processing time ● High production rate ● No need for pretreatment 	<ul style="list-style-type: none"> ● Energy- and water-intensive process ● Expensive upgrading process ● Production of biocrude with a high content of nitrogen-containing compounds ● Harsh reaction conditions 	[25,45,54–63]
Pyrolysis	A thermal decomposition process in an oxygen-depleted environment to produce bio-oil, syngas, and biochar	<ul style="list-style-type: none"> ● No need for pretreatment ● Fast processing time ● High production rate ● No need for pretreatment ● Fast processing time ● High production rate ● No need for pretreatment 	<ul style="list-style-type: none"> ● Energy-intensive process ● Expensive upgrading process ● Harsh reaction conditions ● Energy-intensive process ● Expensive upgrading process ● Complexity of the process as affected by several parameters including particle size, biomass type, moisture content, gasifying medium flow rate, feedstock flow rate, gas residence time, temperature, pressure, and reactor type 	[45,62,64–67]
Gasification	A partial oxidation converting solid carbonaceous feedstocks into syngas along with condensable tar compounds and charcoal	<ul style="list-style-type: none"> ● No need for pretreatment 	<ul style="list-style-type: none"> ● Formation of a high amount of tar, requiring extensive clean-up process prior to its utilization in downstream facilities such as internal combustion engines and gas turbines ● Unable to process moist feedstocks ● Low calorific value of the produced syngas 	[45,62,64,68–75]

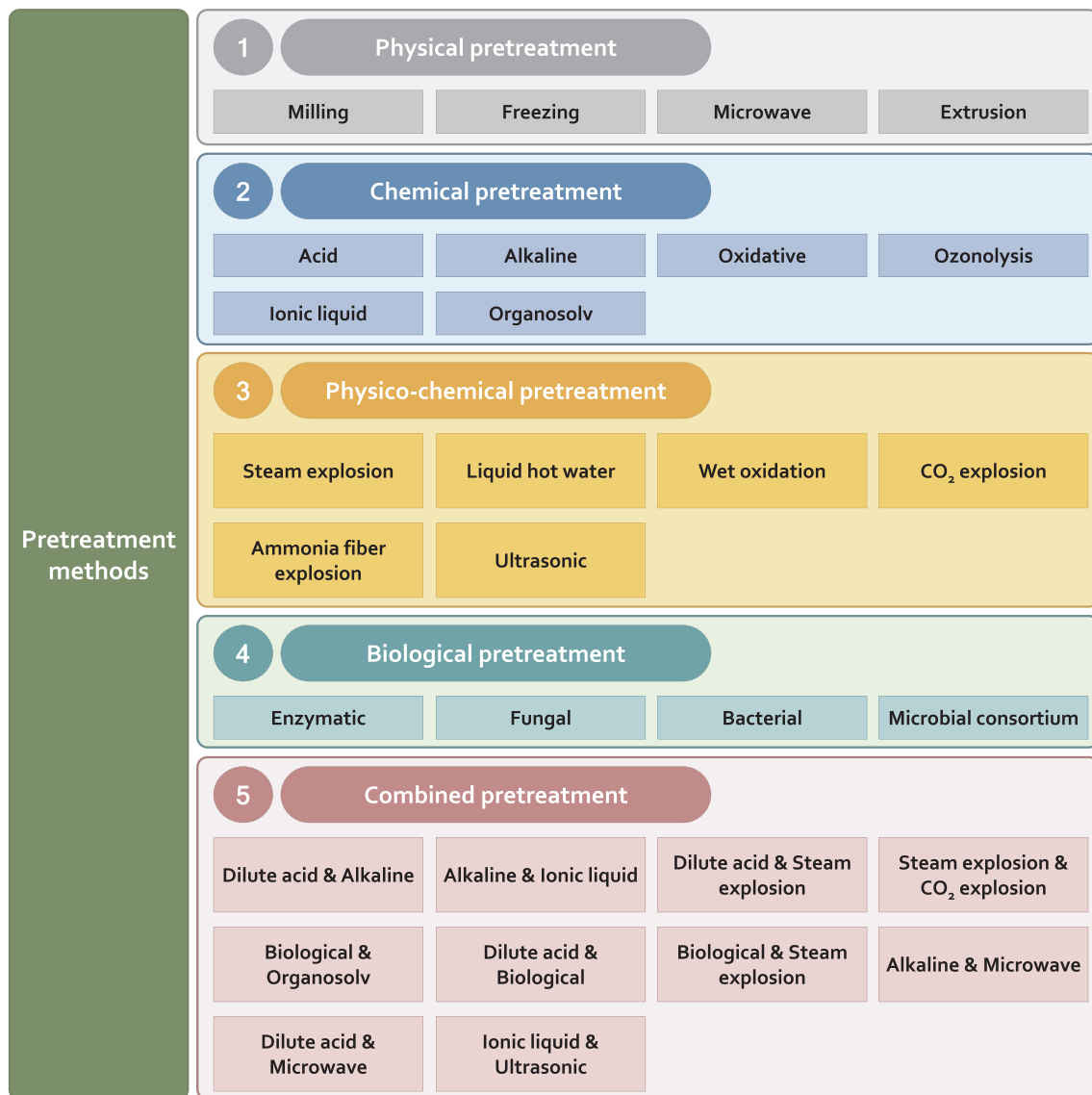


Fig. 5. Different types of pretreatment methods used for lignocellulosic biomass feedstocks. Inferred from Mood et al. [79] and Zabed et al. [43].

more practical tools for diagnosing how a process interacts with the economy and environment [112]. Fig. 6 portrays the interactions among exergy, economy, and environment.

However, exergy/economy/environmental analysis alone is not a comprehensive decision-making tool for investigating energy systems. In addition, even though exergoeconomic and exergoenvironmental methods can be effective and reliable tools for analyzing energy systems from productivity and envirosafety viewpoints, these approaches might still yield misleading results [112]. This can be ascribed to the fact that exergoeconomic method can assess energy systems based on thermodynamic and economic principles while the obtained information does not satisfy the environmental targets provided by exergoenvironmental approach, and vice versa. This issue can be effectively addressed through harmonizing exergoeconomic and exergoenvironmental approaches using the emergy concept as elaborated by Aghbashlo and Rosen [113]. Exergoeconomic method proposed by Aghbashlo and Rosen [112] can also be an effective tool for sustainability assessment of energy systems.

In general, exergy-based analyses are informative tools for assessing the sustainability of energy systems as such methods can reliably quantify their efficiency, productivity, envirosafety, and sustainability (Fig. 7). In addition, exergetic approaches can provide effective and

practical solutions to overcome technical, economic, and environmental problems associated with energy systems. Hence, exergy-based methods have become increasingly popular over recent years for evaluating bioenergy projects.

2. Key theoretical considerations

2.1. Exergy analysis

The mass, energy, and exergy balance equations for the k th component of a biofuel system as a steady-state control volume can be expressed as follows:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \quad (1)$$

$$\sum_i \dot{Q}_i + \sum_i \dot{m}_i h_i = \dot{W} + \sum_e \dot{m}_e h_e \quad (2)$$

$$\sum_i \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) + \sum_i \dot{m}_i e_i = \dot{W} + \sum_e \dot{m}_e e_e + \dot{E}_d \quad (3)$$

where \dot{m}_i and \dot{m}_e denote the mass flow rates of the inlet and exit streams, h_i and h_e the specific enthalpies of the inlet and exit streams,

Table 3
Merits and drawbacks of different pretreatments used for lignocellulosic biomass feedstocks.

Pretreatment method	Merits	Drawbacks	Refs.
Physical			
Milling	<ul style="list-style-type: none"> ● Reduction of particle size, degree of polymerization, and cellulose crystallinity of feedstock ● Ability to work at high-solids loadings ● No inhibitory formation 	<ul style="list-style-type: none"> ● High power and energy consumption ● Limited enzymatic digestibility 	[80]
Extrusion	<ul style="list-style-type: none"> ● Ability to work at high-solids loadings ● Good mixing and heat transfer capability ● No inhibitory formation ● Good process monitoring and simple control of all variables ● Low cost ● Simply adaptable to process modifications 	<ul style="list-style-type: none"> ● High power and energy consumption ● Limited enzymatic digestibility ● Need for chemical agents for efficient process ● Mostly suitable for herbaceous-type feedstocks 	[14,81,82]
Freezing	<ul style="list-style-type: none"> ● Increase the glucose accessibility and enzymatic digestibility ● No generation of inhibitors 	<ul style="list-style-type: none"> ● Cost-intensive process 	[79]
Microwave	<ul style="list-style-type: none"> ● Simple operation ● Fast heating rate ● Low energy requirement ● Degradation of the structural configuration of cellulose fraction 	<ul style="list-style-type: none"> ● Expensive operation ● Difficulty of scaling up ● Inadequate delignification ● Formation of some inhibitors 	[83–85]
Chemical			
Acid	<ul style="list-style-type: none"> ● Short residence time (1–90 min) ● Mild temperature pretreatment ● No need for enzymatic hydrolysis in some cases because of hydrolyzing the pretreated feedstock into fermentable sugars 	<ul style="list-style-type: none"> ● High generation of inhibitors such as furfurals, 5-hydroxymethylfurfural, phenolic acids, and aldehydes ● Requirement for washing/neutralization in order to remove/neutralize acid prior to enzymatic hydrolysis or fermentation ● High cost of the reactors because of using acid-resistant materials ● Use of highly corrosive and toxic acids ● Need for recovering the acid used ● Environmental pollution 	[14,84]
Alkaline	<ul style="list-style-type: none"> ● Less sugar degradation compared with acid pretreatment ● Low temperature and pressure requirements ● Enhanced enzymatic hydrolysis 	<ul style="list-style-type: none"> ● Suitable for the biomass with low lignin content ● High generation of inhibitors ● Relatively long reaction time ● Neutralization difficulties ● High cost ● Environmental pollution 	[14,43,76]
Oxidative	<ul style="list-style-type: none"> ● Lower formation of by-products ● Lower generation of toxic species ● Efficient delignification 	<ul style="list-style-type: none"> ● Partially cellulose degradation ● High costs of oxidizing chemicals ● Generation of inhibitors 	[14,76,83]
Ionic liquid	<ul style="list-style-type: none"> ● High environmental compatibility ● High thermal stability ● Negligible vapor pressure ● No release of toxic or explosive gases 	<ul style="list-style-type: none"> ● High pretreatment temperatures ● Long processing times ● High costs of ionic liquids ● Recovery requirement of ionic liquids 	[14,86,87]
Ozonolysis	<ul style="list-style-type: none"> ● Low generation of inhibitors ● Operating at room temperature and pressure 	<ul style="list-style-type: none"> ● High costs for on-site ozone production and utilization ● Flammability and toxicity of ozone 	[43]
Organosolv	<ul style="list-style-type: none"> ● No need for neutralization ● No need for size reduction ● Formation of high purity and quality lignin ● Low temperature and pressure requirements ● Low cellulose loss and relatively pure cellulose yield 	<ul style="list-style-type: none"> ● Suitable for high lignin-containing materials ● High capital costs ● Recovery requirement of solvents ● Generation of inhibitors 	[14,43,88,89]
Biological			
Fungal	<ul style="list-style-type: none"> ● High efficiency and downstream yields (3–72% delignification and maximum 120% growth in the biofuel yield using white-rot fungi) ● No or minimum inhibitor generation ● Low energy consumption ● Simple operating conditions and equipment ● Low downstream facilities costs ● No need for chemicals recovery and treatment ● Ability to tolerate harsh environmental conditions 	<ul style="list-style-type: none"> ● Long pretreatment time (weeks to months) ● Loss of carbohydrates ● Low downstream yields ● Need for the continuous control of the fungi growth 	[43,76,90]
Bacterial	<ul style="list-style-type: none"> ● Faster growth than fungi ● Simpler genetic manipulation than fungi ● Less costly than fungi ● No or minimum inhibitor generation 	<ul style="list-style-type: none"> ● Long pretreatment time (a few hours to days) ● Loss of carbohydrates ● Low downstream yields 	[43]
Enzymatic	<ul style="list-style-type: none"> ● Low energy consumption ● Simple operating conditions and equipment ● No or minimum inhibitor generation ● Low downstream facilities costs ● No need for chemicals recovery and treatment 	<ul style="list-style-type: none"> ● Long pretreatment time (a few hours to days) ● Loss of carbohydrates ● Low downstream yields ● High costs of enzyme production and purification 	[43,76]
Microbial consortium	<ul style="list-style-type: none"> ● Ability to degrade both cellulose and hemicellulose ● Fairly lower pretreatment time than fungal ● Increasing the enzymatic accessibility ● Enhanced productivity 	<ul style="list-style-type: none"> ● Sensitive to the environmental fluctuations ● Need for stable metabolites generation for lignin decomposition 	[43,76]
Physico-chemical			
Ultrasonic	<ul style="list-style-type: none"> ● Fast operation 	<ul style="list-style-type: none"> ● Need for expensive equipment 	[91,92]

(continued on next page)

Table 3 (continued)

Pretreatment method	Merits	Drawbacks	Refs.
Liquid hot water	<ul style="list-style-type: none"> • Reducing particle size • Increasing the solubility of organic matter • No need for size reduction • High sugars recovery • No need for catalysts and chemicals • No or minimum formation of inhibitors 	<ul style="list-style-type: none"> • High energy consumption and poor energy efficiency • High energy consumption • High demand for water • High cost • Suitable for feedstock having a low lignin content • Low yield of fermentable sugars 	[14,43,76]
Steam explosion	<ul style="list-style-type: none"> • No need for size reduction • Increasing hemicellulose and lignin solubilization • Higher production of glucose and hemicellulose • No recovery requirements • Short processing time 	<ul style="list-style-type: none"> • Formation of inhibitors • Incomplete hemicellulose degradation 	[43]
Ammonia fiber explosion	<ul style="list-style-type: none"> • High efficiency and selectivity • No or minimum formation of inhibitors 	<ul style="list-style-type: none"> • Less suitable for softwood • High cost of ammonia • Health concerns about using ammonia 	[14,88]
Wet oxidation	<ul style="list-style-type: none"> • Good lignin removal • Good carbohydrate recovery • Enhanced enzymatic digestibility 	<ul style="list-style-type: none"> • High energy consumption • High capital cost • High operating costs • Low hemicellulose recovery 	[43,79]
CO ₂ explosion	<ul style="list-style-type: none"> • Low carbon dioxide cost • No generation of toxic compounds • Low-temperature condition • Handling high amounts of solids 	<ul style="list-style-type: none"> • Need for expensive materials for reactor • High capital cost 	[93]

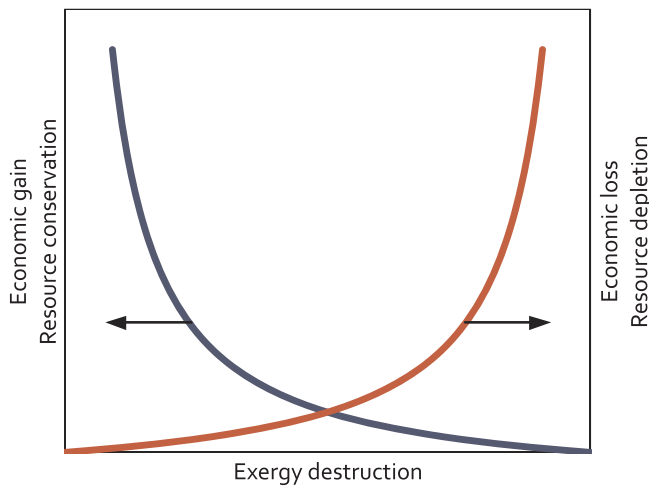


Fig. 6. Relationship between exergy destruction and economic loss/resource depletion. Inferred from references [112–114,123–130].

and e_i and e_e the specific exergies of the inlet and exit streams, respectively. \dot{W} denotes the work rate, \dot{Q} the heat transfer rate, and \dot{E}_d the exergy destruction rate. In a thermodynamic system, total exergy can be broken down into four components including (a) physical exergy, (b) chemical exergy, (c) kinetic exergy, and (d) potential exergy [131]. Accordingly, the total specific exergy of such streams can be obtained by summing their specific physical exergy (e^{ph}), specific chemical exergy (e^{ch}), specific kinetics exergy (e^{ke}), and specific potential exergy (e^{pe}) as follows [132]:

$$e = e^{ph} + e^{ch} + e^{ke} + e^{pe} \quad (4)$$

2.1.1. Physical exergy

The specific enthalpy (h) and entropy (s) of the majority of pure streams can be found in the published literature. Using these data, the specific exergies of such streams can be determined as follows [133]:

$$e^{ph} = h - h_0 - T_0(s - s_0) \quad (5)$$

where h_0 and s_0 denote the specific enthalpy and entropy of the reference state, respectively, and T_0 represents the absolute temperature

of the reference state. The specific physical exergies of the mixed or even pure liquid streams can be assessed using the following equation [134]:

$$e^{ph} = C \left(T - T_0 - T_0 \ln \left(\frac{T}{T_0} \right) \right) \quad (6)$$

where C is the specific heat capacity.

In addition, the specific physical exergies of the mixed or even pure gaseous streams can be estimated as follows [135,136]:

$$e^{ph} = C \left(T - T_0 - T_0 \ln \left(\frac{T}{T_0} \right) \right) + RT_0 \ln \left(\frac{P}{P_0} \right) \quad (7)$$

where P denotes the absolute pressure, P_0 the absolute pressure of the reference state, and R the gas constant. The specific heat capacities of the mixed liquid and gaseous streams can be determined as follows [137]:

$$C = \sum_{j=1}^n x_j C_j \quad (8)$$

where x_j and C_j denote the mass fraction and specific heat capacity of the j th stream, respectively. The gas constants of the mixed gaseous streams can be obtained as follows:

$$R = \frac{\bar{R}}{\sum_{j=1}^n y_j M_j} \quad (9)$$

where \bar{R} is the universal gas constant (i.e., 8.314 kJ/mol K) and y_j and M_j are the molar fraction and molar mass of the j th stream, respectively.

2.1.2. Chemical exergy

The specific chemical exergies of the streams involved in a biofuel production system can be determined using the equation given below:

$$e^{ch} = \sum_j \frac{1}{y_j M_j} \left(\sum_j y_j \varepsilon_j + \bar{R} T_0 \sum_j y_j \ln(y_j) \right) \quad (10)$$

where ε_j is the standard chemical exergy of the j th stream. The standard chemical exergies of the majority of inorganic and organic compounds involved in the biofuel production processes can be found in the related

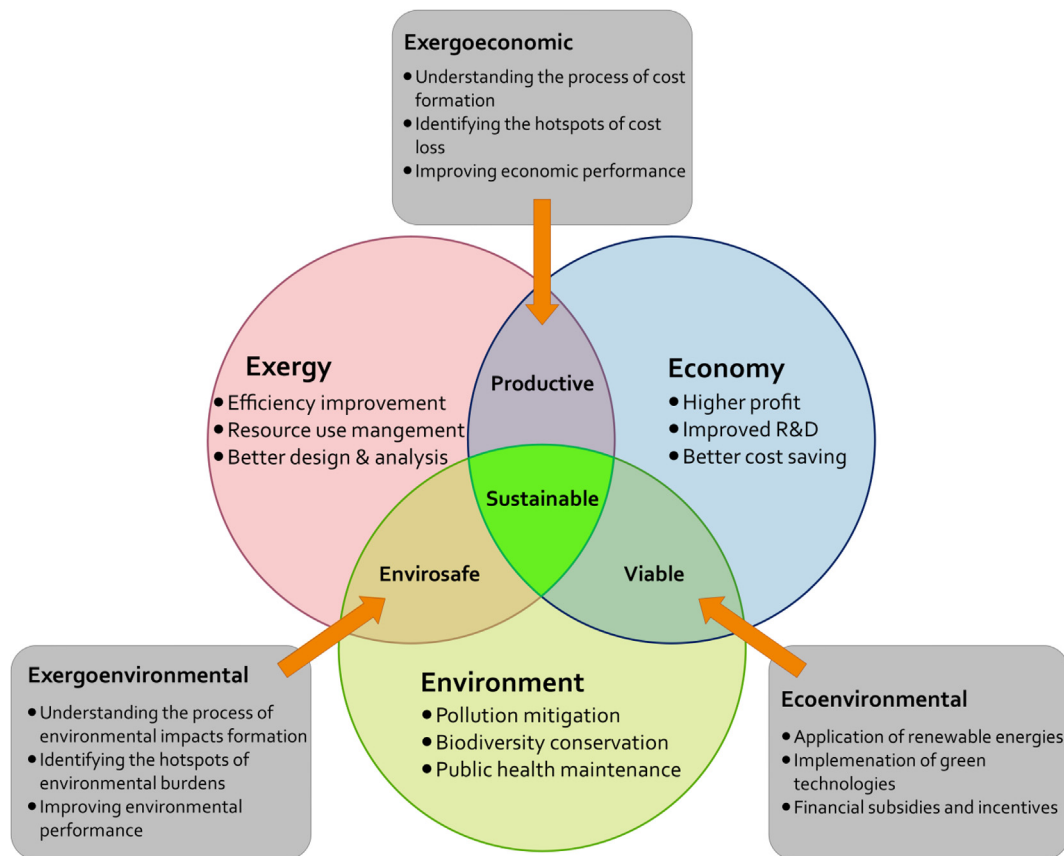


Fig. 7. The interactions among exergy, economy, and environment. Inferred from references [112–114,124,126–130].

literature [138,139]. The unavailable standard chemical exergies of inorganic compounds can be obtained as follows:

$$\varepsilon = -\Delta G + \sum_{\text{Product}} n_k \varepsilon_k - \sum_{\text{Reactant}} n_l \varepsilon_l \quad (11)$$

where G is the Gibbs free energy.

The specific or standard chemical exergies of organic compounds can be evaluated using various theoretical or semi-theoretical relations available in the published literature. For instance, the specific chemical exergies of the structurally complicated solid organic compounds can be obtained as follows [140]:

$$e^{ch} = 4.1868\{8, 177.79[C] + 5.25[N] + 27, 892[H] - 3, 173.66[O] + 0.15 [O](7, 837.677[C] + 33, 888.889[H] - 4, 236.1[O])\} \quad (12)$$

In addition, the following formula can be used to compute the specific chemical exergies of both liquid and solid organic compounds [141,142]:

$$e^{ch} = 100\{363.439[C] + 1075.633[H] - 86.308[O] + 4.14[N] + 190.798 [S] - 21.1[A]\} \quad (13)$$

where $[C]$, $[H]$, $[O]$, $[N]$, $[S]$, and $[A]$ are the weight fractions of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash in the biomass structure, respectively.

2.1.3. Kinetics and potential exergies

The specific kinetics and potential exergies of the streams involved in a biofuel system can be measured as follows [143]:

$$e^{ke} = \frac{1}{2} V^2 \quad (14)$$

$$e^{pe} = gz \quad (15)$$

where V denotes the velocity, g the gravitational constant, and z the height from the earth's surface. Notably, the values obtained from the equations above should be divided by 1000 in order to make their units kJ/kg.

2.1.4. Exergy of living organisms

Jørgensen et al. [144] stated that the genetic information of living organisms should be taken into consideration during exergetic calculations. Accordingly, they developed the eco-exergy concept that can be used for estimating the exergetic contents of living microorganisms including fungal, bacteria, and microbes involved in the biofuel production process. The exergetic contents of living organisms can be computed by multiplying their chemical exergetic contents by the eco-exergy/chemical exergy ratios (β). This ratio for different living organisms can be obtained as follows [145,146]:

$$\beta = 1 + \frac{\ln 20(\text{numberofnucleotides}(1 - \text{numberofrepeatinggenes}))}{3 \times 7.34 \times 10^5} \quad (16)$$

Since $\ln 20 \approx 3$, accordingly, the above equation can be written as follows:

$$\beta = 1 + \frac{\text{numberofnucleotides}(1 - \text{numberofrepeatinggenes})}{7.34 \times 10^5} \quad (17)$$

2.1.5. Humid air exergy

The humidity term should be considered in computing the specific physical exergy of air streams where the humidity difference with the reference environment is relevant. The specific physical exergies of such air streams (e_a) can be computed as follows [147,148]:

$$e_a = [C_a + \omega_a C_v](T_a - T_0) - T_0 \left\{ [C_a + \omega_a C_v] \ln \left(\frac{T_a}{T_0} \right) - (R_a + \omega_a R_v) \ln \left(\frac{P_a}{P_0} \right) \right\} + T_0 \left\{ (R_a + \omega_a R_v) \ln \left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega_a} \right) + 1.6078\omega_0 R_a \ln \left(\frac{\omega_a}{\omega_0} \right) \right\} \quad (18)$$

where C_a and C_v denote the specific heat capacities of air and water vapor, R_a and R_v the gas constants of air and water vapor, T_a and P_a the absolute temperature and pressure of air, ω_a and ω_0 the humidity ratio of air and reference state, respectively.

2.1.6. Exergetic indicators

After determining the exergetic contents of all streams involved in the process, some dimensional or dimensionless indices are defined and computed for comparison purposes. Notably, the dimensionless exergetic indicators are more contextually relevant over the dimensional ones since they are independent of the processing capacity of the developed biofuel systems. The exergetic efficiency of a biofuel system can be defined in two different forms: universal (ψ_U) and functional (ψ_F) exergetic efficiencies. In the universal definition, the degree of exergy loss of a given biofuel system or its related units as a result of both thermodynamic non-ideality and heat rejection is measured as follows [149]:

$$\psi_U = \frac{\dot{E}_e}{\dot{E}_i} = 1 - \frac{\dot{E}_d}{\dot{E}_i} \quad (19)$$

where \dot{E}_i and \dot{E}_e are the total inlet and outlet and exergy values, respectively.

The universal exergetic efficiency of a biofuel system nears zero on which the majority of its input exergy is lost owing to both irreversibility and heat loss and vice versa. The functional exergetic efficiency is the ratio of the exergy content of the useful product(s), the exergy sought, to the exergy invested for its (their) production, the exergy that costs [149].

$$\psi_F = \frac{\text{Exergysought}}{\text{Exergythatcosts}} = \frac{\text{Exergycontent(s)ofusefulproduct(s)}}{\text{Exergyinvestedforproduct(s)formation}} \quad (20)$$

The functional exergetic efficiency weighs how profitably and efficiently the provided exergies into a biofuel system are invested within the process with respect to its purpose. In general, the functional exergetic efficiency showing the exergetic effectiveness of a thermodynamic system is a perceptually meaningful objective measure over the universal one.

In addition to the above-mentioned efficiency definitions, various exergetic indices can be calculated for a biofuel production system. For example, the exergy destruction ratio (γ) that ranks the units of a biofuel system with respect to their contribution to the total irreversibility can be defined as follows:

$$\gamma = \frac{\dot{E}_{d,k}}{\dot{E}_{d,tot}} \quad (21)$$

where $\dot{E}_{d,k}$ is the exergy destruction rate of the k th unit and $\dot{E}_{d,tot}$ is the total exergy destruction rate of the whole system.

The depletion number (DP) that indicates the relationship between the exergy destruction rate and the input exergy rate can be defined as follows:

$$DP = \frac{\dot{E}_{d,tot}}{\dot{E}_i} \quad (22)$$

The exergetic sustainability index (SI) of biofuel production systems can be defined as follows [150]:

$$SI = \frac{1}{DP} = \frac{1}{1 - \psi_U} \quad (23)$$

The exergetic improvement potential rate ($\dot{I}P$) of a biofuel system or its subunits from exergy viewpoint can be determined as follows [148]:

$$\dot{I}P = (1 - \psi_U)(\dot{E}_i - \dot{E}_e) \quad (24)$$

2.2. Exergoeconomic analysis

Among the various methods developed for exergy-based economic analysis of energy conversion systems, Specific Exergy Costing (SPECO) approach elaborated by Lazzaretto and Tsatsaronis [151] attracted a great deal of interest because of its unique conceptual features. In this method, the cost balance equations are first defined at component- or unit-level once the exergetic contents of all streams of the energy system being investigated are quantified. This analysis can be carried out by taking into consideration either the total exergetic contents of streams or the discrete exergetic contents of streams, i.e., thermal, mechanical, and chemical exergy values. Even though the discrete form of exergoeconomic analysis can marginally improve the accuracy of the results achieved, it makes the analysis computationally-intensive [103]. Hence, in most of the research works published using the SPECO approach, the total exergetic contents of the streams involved in the process are considered in order to simplify the calculation procedure.

The cost balance equation for the k th component of a biofuel system can be expressed as follows:

$$\sum_i c_q \dot{Q}_i \left(1 - \frac{T_0}{T_i} \right) + \sum_i c_i \dot{m}_i e_i + \dot{Z}_k = c_w \dot{W} + \sum_e c_e \dot{m}_e e_e \quad (25)$$

where c_i and c_e denote the unitary exergy costs of the inlet and exit streams and c_w and c_q the unitary exergy costs associated with the work and heat transfer, respectively. \dot{Z}_k is the investment cost rate of the k th component.

There are N unknowns for an energy system having N streams while only one equation, i.e., the cost balance equation is available [151]. Accordingly, $N-1$ auxiliary equation should be defined using the F and P principles of SPECO approach. Notably, the unitary exergy costs of external input streams reduce the number of required auxiliary equations. It should be emphasize that the F and P principles are expressed for each component of the system according to its exergetic purposes. In better terms, the F and P principles for productive and dissipative components are different from each other. Readers are referred to Lazzaretto and Tsatsaronis [151] where the SPECO approach has been comprehensively explained covering all cases that might be faced.

The investment cost rate of the k th component/unit of a biofuel system can be roughly determined by dividing its capital, operation, and maintenance costs by the accumulative lifetime working hours. However, the following equation is the most widely used formula for computing the investment cost rate of a given component/unit of a system [152]:

$$\dot{Z}_k = \frac{Z_k CRF \phi}{H_k} \quad (26)$$

where Z_k denotes the capital cost of the k th component, H_k the annual working hour of the k th component; CRF the capital recovery factor, and ϕ the maintenance factor.

The capital recovery factor can be obtained as follows [153]:

$$CRF = \frac{I(1+I)^N}{(1+I)^N - 1} \quad (27)$$

where I denotes the interest rate and N the plant lifetime.

Once the unitary exergy costs of all the streams involved in the process are determined, the fuel and product costs of all components of the system being analyzed are computed in order to their calculate exergoeconomic parameters. The relative cost difference ($r_{c,k}$) identifying the ease or complicity of discounting the unitary exergy cost of the product for a given component can be computed as follows:

$$r_{c,k} = \frac{c_{p,k} - c_{f,k}}{c_{f,k}} \quad (28)$$

where $c_{f,k}$ and $c_{p,k}$ are the unitary exergy costs of fuel and product, respectively.

Exergoeconomic factor ($f_{c,k}$) that indicates the way of improving the exergoeconomic performance of a given component either by increasing its capital cost or augmenting its exergy-related cost can be defined as follows:

$$f_{c,k} = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{d,k}} = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k}\dot{E}_d} \quad (29)$$

where $\dot{C}_{d,k}$ is the cost rate related to the exergy destruction of the k th component.

In addition to the exergoeconomic indicators mentioned above, Soltanian et al. [154] recently introduced a new complementary exergoeconomic index for exergoeconomic factor so-called "economic modification requirement index" ($m_{c,k}$) that manifests the degree of balance between component- and exergy-related cost rates of a given component.

$$m_{c,k} = \frac{\frac{\dot{Z}_k}{\dot{C}_{d,k}} - 1.5}{1.5} = \frac{\frac{\dot{Z}_k}{c_{f,k}\dot{E}_d} - 1.5}{1.5} \quad (30)$$

2.3. Exergoenvironmental analysis

Exergoenvironmental analysis for a biofuel system can be conducted using the SPECO approach in the same way explained above for exergoeconomic analysis. The environmental impact balance equation for the k th component of an energy system can be defined as follows:

$$\sum_i b_q \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) + \sum_i b_i \dot{m}_i e_i + \dot{Y}_k = b_w \dot{W} + \sum_e b_e \dot{m}_e e_e \quad (31)$$

where b_i and b_e denote the unitary exergy environmental impacts of the inlet and exit streams and b_w and b_q the unitary exergy environmental impacts associated with the work and heat transfer, respectively. \dot{Y}_k is the component-related environmental impact rate of the k th component.

The F-rules and P-rules developed in the exergoeconomic analysis can be used in exergoenvironmental analysis only by changing their notations and values. The environmental impact rate of the components or units of a biofuel system can be determined by dividing their associated total environmental impacts (Y_k) by accumulative lifetime working hours (H_k) as follows:

$$\dot{Y}_k = \frac{Y_k}{H_k} \quad (32)$$

The construction, operation, and dismantling phases of an energy system should be considered in determining its associated environmental impact. However, the construction phase is the main step taken into consideration in most of the research works published in this domain [155]. The unitary exergy environmental impacts of external input streams should also be determined before solving the developed set of equations. The environmental impacts associated with components and inputs of an energy system can be determined using various environmental impact assessment methods such as Eco-indicator 99 and IMPACT 2002+. Notably, the weighted environmental impacts obtained using these methods are used in exergoenvironmental analysis. The weighted environmental impacts are computed by summing the weighted environmental impacts of all damage categories considered in the analysis. Various life cycle assessment software such as SimaPro, TEAM, and GABi can be used for measuring the weighted environmental impacts of the components and streams of an energy system.

Once the unitary exergy environmental impacts of all the streams

involved in the process are computed, the fuel and product environmental impacts of all components of the system being analyzed are determined in order to calculate their exergoenvironmental indicators. The relative environmental impact difference ($r_{b,k}$) that shows the ease or complicity of mitigating the unitary exergy environmental impact of the product for a given component can be determined as follows:

$$r_{b,k} = \frac{b_{p,k} - b_{f,k}}{b_{f,k}} \quad (33)$$

where $b_{f,k}$ and $b_{p,k}$ are the unitary exergy environmental impacts of fuel and product, respectively.

Exergoenvironmental factor ($f_{b,k}$) that reveals the way of boosting the exergoenvironmental performance of a given component either by increasing its component-related environmental impacts or elevating its exergy-related environmental impacts can be defined as follows:

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{d,k}} = \frac{\dot{Y}_k}{\dot{Y}_k + b_{f,k}\dot{E}_d} \quad (34)$$

where $\dot{B}_{d,k}$ is the environmental impact rate related to the exergy destruction of the k th component.

Similar to the economic modification requirement index, a new complementary exergoenvironmental index called "environmental modification requirement index" ($m_{b,k}$) is introduced herein that shows the degree of balance between component- and exergy-related environmental impact rates of a given component.

$$m_{b,k} = \frac{\frac{\dot{Y}_k}{\dot{B}_{d,k}} - 1.5}{1.5} = \frac{\frac{\dot{Y}_k}{b_{f,k}\dot{E}_d} - 1.5}{1.5} \quad (35)$$

Notably, the component-related environmental impact rates of a given component are adequately balanced with its irreversibility-related environmental impact rates on which environmental modification requirement index approaches zero. The component-related environmental impact rate of a given component should be mitigated by replacing an environment-friendly component even with low exergetic performance when this indicator gains a positive value. However, a negative value of this indicator suggests that the irreversibility rate of the corresponding component should be minimized even by using an environmentally detrimental component.

3. Exergetic analysis of lignocellulose bioconversion into biofuel

In lignocellulose bioconversion into biofuel, the pretreatment process used for disrupting the robust structure of lignocellulosic feedstocks requires substantial amounts of energy and chemicals. Accordingly, a significant amount of exergy is destroyed in this process because of heat and mass transfer phenomena, mixing processes, and chemical reactions. Hence, the choice of an optimum pretreatment method depends not only on its potential sugar yield but also on its thermodynamic performance [156,157]. The exergetic performance can be a fair basis for comparing different pretreatment methods used in lignocellulosic biofuel systems. Using the exergy concept, the pretreatment methods along with their associated biofuel systems are reliably compared in terms of their capability to generate useful bioproducts and bioenergy.

Unlike the other sustainability assessment methods such as technoeconomic analysis, energy analysis, and life cycle assessment, all the produced products are expressed on a consolidated basis (i.e., J) using the exergy concept. This in turn greatly facilitates the comparison of the obtained results. The following subsections detail the research works where exergy-based analyses have been used for assessing lignocellulose bioconversion into biofuel, with the main focus on understanding the effects of pretreatment methods on the sustainability of the resultant product(s).

Table 4
Effects of different pretreatment methods on the exergetic aspects of single-product lignocellulosic biofuel systems.

Pretreatment	Pretreatment conditions	Raw material (s)	Main product (s)	Main production stages	Exergy efficiency of the pretreatment process (%); [SI (-)]	Overall exergy efficiency (%); [SI (-)]; [IP (MJ)]	Remarks	Ref.
Chemical Acid (dilute sulfuric acid)	<ul style="list-style-type: none"> • H₂SO₄ = 1.5 wt% • T = 160 °C 	Sugarcane bagasse	Ethanol*	PT/NT/SSF/PF/D&R/DH	67.27 ^F	-	<ul style="list-style-type: none"> • Simultaneous heat and mass integration in the distillation process could recover the majority of waste exergy of the plant. 	[140]
	<ul style="list-style-type: none"> • H₂SO₄ = 1.5 wt% • T = 165 °C 	Sugarcane bagasse	Ethanol*	PT/NT/SSF/D&R/DH	67.71 ^F	-	<ul style="list-style-type: none"> • Thermal integration, material recycling, and SSF design modification could be promising ways of improving the exergetic efficiency of the system. 	[162]
	<ul style="list-style-type: none"> • H₂SO₄ = 1.5 wt% • T = 165 °C • P = 0.4 MPa 	Sugarcane bagasse	Ethanol*	PT/SHF or SSF or SSF	53.50 ^F	-	<ul style="list-style-type: none"> • The SSF process could be the most efficient strategy for cellulosic ethanol production from the exergetic standpoint. 	[163]
	<ul style="list-style-type: none"> • H₂SO₄ = 1.5 wt% • T = 165 °C 	Sugarcane bagasse	Ethanol*	PT/NT/SSF/PF/D&R/DH	54.43 ^F	73.98 ^F ; [3.843]; [60.5]	<ul style="list-style-type: none"> • Improving the pretreatment process and saccharification/fermentation unit technologically could significantly boost the system exergetically. • The pretreatment and SSF stages should be exergetically enhanced in order to improve the overall performance of the system. 	[164]
Alkaline (sodium hydroxide)	<ul style="list-style-type: none"> • H₂SO₄ = 0.5 wt% • T = 190 °C • P = 13 atm • SC = 22 wt% 	Rice husks	Ethanol*	PT/NT/SSF/D&R/DH	35.48 ^F	-	<ul style="list-style-type: none"> • The heat integration design could lead to an improved exergetic performance of the system. • The pretreatment process should be technologically improved in order to reduce the exergy destruction rate of the system and improve its exergetic efficiency. • Implementing the heat integration methodology into the ethanol production process as well as annexing cogeneration systems could reduce the external energy dependence which in turn could mitigate the associated environmental impact and operational costs of the system. 	[165]
	Not reported	Flower stalk of banana tree	Syrup (glucose and water mixture)	PP/PT/HY	-	20.30–55.00 ^{F,a}	<ul style="list-style-type: none"> • Reducing water-to-biomass ratio through diminishing biomass moisture content could improve the exergy efficiency of the system. 	[166]
	<ul style="list-style-type: none"> • Ethanol = 65.0 wt% • NaOH = 2.5 wt% • Water = 32.5 wt% 	Sugarcane bagasse	Ethanol*	PT/SHF/DT/PF/D&R/ET	-	64.27–68.12 ^{F,b} 65.21–72.06 ^{F,c}	<ul style="list-style-type: none"> • The generated inhibitors could result in a marked reduction in the enzyme activity at low substrate concentrations and, consequently, could lead to a decrease in the exergy efficiency of the system. 	[167]
	<ul style="list-style-type: none"> • Ethanol^a = 34 wt% • T = 185 °C 	Sugarcane bagasse	Ethanol*	PT/SSF/PF/D&R/DH	83.13 ^F	-	<ul style="list-style-type: none"> • Simultaneous heat and mass integration in the distillation process could regenerate the major portion of waste exergy of the system. 	[140]
Organosolv	<ul style="list-style-type: none"> • Ethanol = 58.5 wt% • H₂SO₄ = 1.5 wt% • Water = 40 wt% • T = 185 °C • P = 2.0 MPa • Ethanol^a = 34 wt% • T = 185 °C • P = 2.0 MPa 	Sugarcane bagasse	Ethanol*	PT/NT/SSF/D&R/DH	25.64 ^F	-	<ul style="list-style-type: none"> • Thermal integration, material recovery, and SSF design improvement could promisingly improve the exergy efficiency of the system. 	[162]
	<ul style="list-style-type: none"> • Ethanol^a = 40–70 wt% • NaOH^a = 1.0 wt% • T = 140–160 °C • RT = 40–60 min 	Oil palm fronds	Pretreated substrate	PP/M/PT	90.26 ^F ; [7.43]	78.37 ^F ; [4.621]; [624.1]	<ul style="list-style-type: none"> • The exergetic improvement of the system could be achieved by enhancing the pretreatment and SSF stages thermodynamically and implementing the heat integration methodology. 	[164]
	<ul style="list-style-type: none"> • Ethanol^a = 40–70 wt% • NaOH^a = 1.0 wt% • T = 140–160 °C • RT = 40–60 min 	Oil palm fronds	Pretreated substrate	PP/M/PT	90.26 ^F ; [7.43]	90.30 ^F	<ul style="list-style-type: none"> • Ethanol solvent should be recovered in order to reduce the exergy rates associated with waste streams. • The conversion of hemicellulose, lignin, and other extractives into added-value products could increase the overall exergetic efficiency and sustainability of the system. 	[168]
	<ul style="list-style-type: none"> • Ethanol^a = 40–70 wt% • NaOH^a = 1.0 wt% • T = 140–160 °C • RT = 40–60 min 	Oil palm fronds	Pretreated substrate	PP/M/PT	90.26 ^F ; [7.43]	90.30 ^F	<ul style="list-style-type: none"> • Ethanol solvent should be recovered in order to reduce the exergy rates associated with waste streams. • The conversion of hemicellulose, lignin, and other extractives into added-value products could increase the overall exergetic efficiency and sustainability of the system. 	[168]

(continued on next page)

Table 4 (continued)

Pretreatment	Pretreatment conditions	Raw material (s)	Main product (s)	Main production stages	Exergy efficiency of the pretreatment process (%); [SI (-)]; [IP (MJ)]	Overall exergy efficiency (%); [SI (-)]; [IP (MJ)]	Remarks	Ref.
	<ul style="list-style-type: none"> Ethanol⁰ = 34 wt% T = 185 °C P = 2.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Pretreated substrate 	PT	83.30 ^{F,8} -85.40 ^{F,8}	-	<ul style="list-style-type: none"> Low lignin fraction could facilitate the delignification process and increase the exergetic efficiency of the pretreatment process. 	[156]
	<ul style="list-style-type: none"> Ethanol⁰ = 34 wt% T = 185 °C P = 2.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SHF	-	56.54 ^{F,8}	<ul style="list-style-type: none"> The inhibitory effect of high glucose concentration on the hydrolyzing enzymes could limit cellulose hydrolysis and could reduce the bioethanol yield, lowering the exergetic efficiency of the system. 	[169]
	<ul style="list-style-type: none"> Ethanol⁰ = 34 wt% T = 185 °C P = 2.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SSF	-	58.32 ^{F,8}	<ul style="list-style-type: none"> The synergetic effects of hydrolyzing and fermenting microorganisms could increase the bioethanol yield and, consequently, could augment the exergetic efficiency of the plant. 	[169]
Physicochemical								
	Steam explosion	<ul style="list-style-type: none"> T = 220 °C P = 23.2 bar 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SSF/PF/D&R/DH	89.39 ^F	<ul style="list-style-type: none"> Simultaneous heat and mass integration in the distillation process could improve the system energetically by recovering its waste exergy. 	[140]
		<ul style="list-style-type: none"> T = 200–250 °C P = 3.0 MPa RT = 5–20 min H₂SO₄ = 2.25 wt% P = 0.6 MPa 	Oil palm fronds	<ul style="list-style-type: none"> Pretreated substrate 	PP/PT	42.48 ^F ; [1.56]	66.65 ^F	<ul style="list-style-type: none"> Wastewater treatment could increase the overall exergetic sustainability of the system.
Acid-catalyzed steam explosion	<ul style="list-style-type: none"> T = 188 °C P = 0.6 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/NT/SSF/D&R/DH	89.63 ^F	-	<ul style="list-style-type: none"> The exergetic performance of the plant could be effectively boosted by thermal integration, material recycling, and improving SSCF design. 	[162]
	<ul style="list-style-type: none"> H₂SO₄ = 2.25 wt% T = 188 °C P = 0.6 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/NT/SSF/PF/D&R/DH	87.53 ^F	79.58 ^F ; [4.897]; [27.2]	<ul style="list-style-type: none"> The system could be exergetically enhanced by improving the pretreatment and SSF processes as well as performing heat integration. 	[164]
	<ul style="list-style-type: none"> SO₂ = 2.0 wt% T = 190 °C P = 1.25 MPa S/B = 0.55–0.65 w/w 	Sugarcane bagasse	<ul style="list-style-type: none"> Pretreated substrate 	PT	91.00 ^{F,8} -93.20 ^{F,8}	-	<ul style="list-style-type: none"> Low lignin content of lignocelluloses could facilitate the delignification process, improving the exergetic performance of the pretreatment process. 	[156]
SO ₂ -catalyzed steam explosion	<ul style="list-style-type: none"> SO₂ = 2.0 wt% T = 190 °C P = 1.25 MPa S/B = 0.55–0.65 w/w 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SHF	-	60.03 ^{F,8}	<ul style="list-style-type: none"> The bioethanol yield was decreased because of the inhibitory effect of high glucose concentration on the cellulose hydrolyzing enzymes which in turn could negatively influence the exergetic efficiency of the system. 	[169]
	<ul style="list-style-type: none"> SO₂ = 2.0 wt% T = 190 °C P = 1.25 MPa S/B = 0.55–0.65 w/w 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SSF	-	62.48 ^{F,8}	<ul style="list-style-type: none"> The exergetic performance of the system could be raised due to the synergetic effects of hydrolyzing and fermenting microorganisms. 	[169]
		<ul style="list-style-type: none"> T = 200 °C P = 5.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SSF/D&R/DH	78.67 ^F	-	<ul style="list-style-type: none"> The exergetic sustainability of the system could be improved through thermal integration, material recycling, and SSCF design modification.
Liquid hot water	<ul style="list-style-type: none"> T = 188 °C P = 6.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Pretreated substrate 	PT	93.30 ^{F,8} -94.10 ^{F,8}	-	<ul style="list-style-type: none"> Low lignin fraction of biomass could enhance the exergetic efficiency of the pretreatment process by facilitating the delignification process. 	[156]
	<ul style="list-style-type: none"> T = 200 °C P = 5.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SHF	-	58.34 ^{F,8}	<ul style="list-style-type: none"> The exergetic efficiency of the system was negatively influenced by the inhibitory effect of high glucose dosage on the cellulose hydrolyzing enzymes and its subsequent detrimental effect on the bioethanol yield. 	[169]
	<ul style="list-style-type: none"> T = 200 °C P = 5.0 MPa 	Sugarcane bagasse	<ul style="list-style-type: none"> Ethanol* 	PT/SSF	-	60.72 ^{F,8}	<ul style="list-style-type: none"> The bioethanol yield could be enhanced due to the synergetic effect of hydrolyzing and fermenting microorganisms, which in turn could increase the exergetic efficiency of the system. 	[169]

Biological

(continued on next page)

Table 4 (continued)

Pretreatment	Pretreatment conditions	Raw material (s)	Main product (s)	Main production stages	Exergy efficiency of the pretreatment process (%); [SI (-)]	Overall exergy efficiency (%); [SI (-)]; [IP (MJ)]	Remarks	Ref.
Microbial (white-rot fungi)	<ul style="list-style-type: none"> • $T_s = 28\text{--}29\text{ }^\circ\text{C}$ • $RT = 8\text{ weeks}$ 	Oil palm fronds	<ul style="list-style-type: none"> • Pretreated substrate 	PP/M/PT	91.06 ^F ; [9.32]	90.93 ^F	<ul style="list-style-type: none"> • The microbial-treated waste stream could be converted into added-value chemicals in order to increase the overall exergy efficiency of the system. [168] 	[168]
Combined								
Steam explosion and liquid hot water	<ul style="list-style-type: none"> • $T_s = 190\text{ }^\circ\text{C}$ • $P_s = 1.25\text{ MPa}$ • $T_L = 265\text{ }^\circ\text{C}$ • $P_L = 5.1\text{ MPa}$ • $T_s = 190\text{ }^\circ\text{C}$ • $P_s = 1.25\text{ MPa}$ • $T_L = 265\text{ }^\circ\text{C}$ • $P_L = 5.1\text{ MPa}$ 	Sugarcane bagasse	<ul style="list-style-type: none"> • Pretreated substrate 	PT	94.40 ^{F,δ} ; 95.10 ^{F,ε}	–	<ul style="list-style-type: none"> • Low lignin fraction could augment the exergy efficiency of the pretreatment process by promoting the delignification process. [156] 	[156]
		Sugarcane bagasse	<ul style="list-style-type: none"> • Ethanol* 	PT/SHF	–	59.74 ^{F,ε}	<ul style="list-style-type: none"> • The inhibitory effect of high glucose concentration on the hydrolyzing enzymes could lower the glucose yield which in turn could lead to a reduction in the exergetic performance of the system because of decreasing the bioethanol yield. [169] 	[169]
		Sugarcane bagasse	<ul style="list-style-type: none"> • Ethanol* 	PT/SSF	–	61.79 ^{F,ε}	<ul style="list-style-type: none"> • The synergetic effect of hydrolyzing and fermenting microorganisms could increase the exergetic efficiency of the system owing to an increase in the bioethanol yield. [169] 	[169]

*: Single second generation ethanol; a: Aqueous; B: Biomass; D&R: Distillation and rectification; DH: Dehydration; DT: Detoxification; ET: Effluent treatment; F: Functional exergy efficiency; HY: Hydrolysis; IP: Exergetic improvement potential; M: Milling; NT: Neutralization; P: Pressure; P_L : Liquid pressure; P_s : Steam pressure; PF: Pentose fermentation; PP: Preliminary processing; PT: Pretreatment; RT: Residence time; S: Steam; SC: Solid concentration; SHF: Separate hydrolysis and fermentation; SI: Sustainability index; SSCF: Simultaneous saccharification and co-fermentation; SSF: Simultaneous saccharification and fermentation; T: Temperature; T_L : Liquid temperature; T_s : Steam temperature; α : Dependent on the variable process conditions; β : Based on hydrolysis type of continuous stirred-tank reactor; γ : Based on hydrolysis type of plug-flow reactor; δ : Based on weight-based chemical composition of cellulose 47.5%, hemicellulose 20%, lignin 30%, and ash 2.5%; ϵ : Based on weight-based chemical composition of cellulose 43.38%, hemicellulose 25.63%, lignin 23.24%, ash 2.94%, and extractives 4.81%.

3.1. Single-product lignocellulosic biofuel systems

The biological conversion of lignocellulosic feedstocks into biofuels involves six main chemical processes including (a) preliminary processing such as washing, drying, and milling, (b) pretreatment, (c) cellulose/hemicellulose hydrolysis and detoxification, (d) hexoses/pentose fermentation, (e) product separation and purification, and (f) effluent treatment [158–160]. Due to the energy-intensive, time-consuming, chemical-dependent nature of the pretreatment process, it can remarkably affect the thermodynamic, economic, environmental aspects of biologically-derived biofuels [161]. Accordingly, exergy-based analyses have been used in several research works to evaluate the effects of different pretreatment methods on the exergetic aspects of single-product lignocellulosic biofuel systems (Table 4).

Ojeda et al. [140] assessed three lignocellulosic bioethanol schemes with different pretreatment methods, i.e., dilute sulfuric acid, steam explosion, and organosolv. The authors found that the most exergy-efficient pretreatment was steam explosion, followed by organosolv and dilute acid techniques. Ojeda et al. [164] also exergetically compared three sugarcane bagasse-based bioethanol production systems. In the developed scenarios, different pretreatment methods including steam explosion, dilute sulfuric acid, and organosolv were considered along with the SSF process. It was observed that the steam explosion-assisted scenario had the highest overall exergy efficiency and sustainability index. In addition, the highest unit-level exergy efficiency was obtained for the steam explosion compared with those of dilute acid and organosolv [164]. Accordingly, the steam explosion showed the lowest environmental burden. In this scenario, the greatest amount of entropy was generated in the pretreatment process compared with the neutralization/pentose fermentation, SSF, and purification processes. The dilute acid-assisted scenario had the lowest overall exergy efficiency and sustainability index due to the lower unit-level exergy efficiency of the pretreatment process. Interestingly, although the organosolv-assisted scenario did not have the lowest overall exergy efficiency, its renewability index (i.e., bioethanol energy content/net consumed fossil energy) was lower than unity because this pretreatment consumed a high amount of energy for recovering the used solvent [164].

Ojeda et al. [162] exergetically compared four different pretreatment methods including dilute sulfuric acid, liquid hot water, acid-catalyzed steam explosion, and acid organosolv used for pretreating sugarcane bagasse as shown in Fig. 8. The pretreated biomass was then fed to a SSCF process for bioethanol production. The acid-catalyzed steam explosion showed the highest unit-level exergy efficiency, while the lowest value of this index was found for the acid organosolv pretreatment. Due to the higher pressure of the liquid hot water process, its unit-level exergy efficiency was lower than that of the steam explosion. In addition, the high amount of exergy destroyed in the sulfuric acid neutralization process might be the main reason for the lower unit-level exergy efficiency of the acid organosolv pretreatment method. Notably, the pretreatment type not only could influence its own unit-level exergetic efficiency but also could affect the exergetic performance of the corresponding downstream processes such separation/neutralization, hydrolysis/fermentation, and purification (Fig. 8). Accordingly, the overall exergy efficiency should be computed for lignocellulosic biofuel systems in order to make the right decisions on the pretreatment type.

Ofori-Boateng and Lee [168] conducted exergy analysis for assessing the thermodynamic sustainability of three different pretreatment techniques, i.e., including steam explosion, organosolv, and microbial methods used for oil palm fronds processing. Among the investigated pretreatment methods, the microbial approach showed the highest exergy efficiency while the lowest value of this index was determined for the steam explosion. The organosolv pretreatment had the highest exergy destruction, which might be due to the consumption of huge amounts of energy and chemicals. Surprisingly, the exergy efficiency value attained for the organosolv pretreatment was very close to that calculated by Ojeda et al. [164]. The organosolv pretreatment showed

the highest amount of waste exergy (emitted through external non-useful or non-exploited exergy streams), followed by the microbial pretreatment approach. The large amounts of ethanol and chemicals vented to the effluent stream after organosolv and microbial pretreatment methods, respectively, might be responsible for the high waste exergy values in these processes. Overall, microbial pretreatment was the most thermodynamically sustainable approach compared with the steam explosion and organosolv methods.

Meramo-Hurtado et al. [165] analyzed a rice husk-based bioethanol production plant using the exergy concept. The exergy loss rates and exergy efficiencies were determined for dilute sulfuric acid pretreatment, simultaneous saccharification and co-fermentation, and purification processes. The pretreatment step had the highest irreversibility rate, showing the fact that this process should be technically and thermodynamically improved and optimized. The fermentation and product purification processes were not mainly responsible for the overall exergy destruction of the plant.

The compositions of lignocellulosic biomass could considerably affect the exergetic performance of pretreatment methods. In this regard, Ortiz and de Oliveira Jr [156] considered two types of sugarcane bagasse with different chemical compositions subjected to various pretreatment methods, i.e., steam explosion, organosolv, liquid hot water, as well as a combination of steam explosion and liquid hot water. They concluded that the exergy destruction rates and exergy efficiencies of all the investigated pretreatment methods were significantly affected by the chemical constituents of the utilized sugarcane bagasse. The lignin content was the most influential component in the exergetic performance of pretreatment methods [156]. More specifically, sugarcane bagasse having lower lignin content could lead to higher exergetic efficiency in the pretreatment process over the lignin-rich counterpart. The combined steam and liquid hot water pretreatment had the highest exergy efficiency [156]. In fact, this combined pretreatment benefited from the high exergetic efficiencies of both steam explosion and liquid hot water methods. The organosolv pretreatment strategy showed the lowest exergy efficiency because it was highly dependent on the effectiveness of hemicellulose and lignin recovery. Interestingly, the exergy efficiencies obtained by Ortiz and de Oliveira Jr [156] for both steam explosion and organosolv pretreatments were well-agreed with those reported by Ojeda et al. [164].

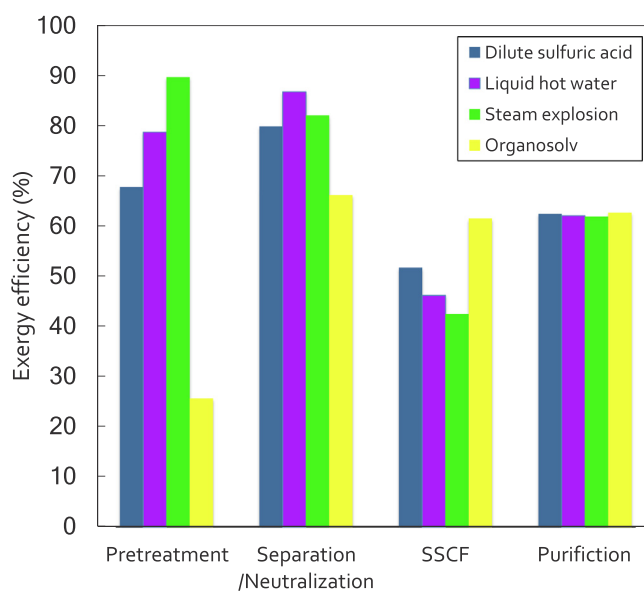


Fig. 8. Unit-level exergy efficiencies of different pretreatment methods as well as their effects on the exergetic performance of the corresponding downstream processes in a lignocellulosic bioethanol production system. Redrawn with permission from Ojeda et al. [162]. Copyright© 2011 Elsevier.

Hammond and Mansell [170] compared the key stages of four different wheat straw-based bioethanol production scenarios from energetic and exergetic viewpoints. The three first scenarios were assisted by steam explosion pretreatment, while the lime solution (alkaline) pretreatment was used in the remaining scenario. All the steam explosion pretreatment-assisted scenarios had positive net energy values. This study showed that the boundary expansion negatively affected the net energy values of all the investigated scenarios due to the huge amount of energy consumed in the feedstock harvesting phase. In the steam explosion pretreatment-assisted scenarios, the exergetic efficiencies of the pretreatment units were found to be in the range of 60–75% which were markedly lower than those of the other steps involved (~90%). Due to the higher exergy destruction rates in the steam pretreatment steps, the higher exergetic improvement potential rates were found for these processes. Overall, this study demonstrated that the definition of system boundary is a crucial factor that substantially affects the sustainability indices of biofuel systems.

Different components involved in the organosolv pretreatment of olive tree pruning were evaluated by Mabrouk et al. [171] using the component-level exergy analysis. The components involved in the delignification of feedstock accounted for 44% of the total exergy destruction, out of which 63.6% and 36.4% were associated with the heater and reactor, respectively. The condensation and separation processes had the second highest exergy destruction rates in the whole process. Therefore, improvement efforts should be concentrated on the components involved in the delignification process in order to increase the exergetic efficiency of the organosolv pretreatment process. It should be noted that the component-level exergy analysis of such complex biological systems could provide detailed information regarding their thermodynamic performance and lead to better decision-making compared with the unit-level exergy analysis.

Using the exergy and economic concepts, Mabrouk et al. [172] analyzed the catechols production process utilizing the lignin fractionated from olive tree pruning. The developed process consisted of the main three units including (a) lignocellulose decomposition/fractionation through ethanolic organosolv pretreatment, (b) depolymerization of lignin fraction, and (c) separation of different products. The lignocellulose fractionating unit had the highest contribution (i.e., 44%) to the total non-idealities of the whole process, in which the heater and pretreatment reactor were primarily to blame for the large portion of its irreversibilities (Fig. 9). The lignin depolymerization unit and products separation unit amounted to 35% and 21% of the total irreversibility of the whole process, respectively. The price of the produced catechols was estimated to be 1100 USD/ton with a valorization ratio (value of useful product/cost of feedstock) of 3.02. Overall, this study showed the importance of the lignocellulose pretreatment process on the exergetic performance of the developed catechol production process.

Despite the key role of the pretreatment process on the exergetic efficiency of biofuel systems, the importance of downstream hydrolysis and fermentation process in this index should also be highlighted. Ortiz and de Oliveira Jr [169] analyzed the exergetic performance of eight bioethanol production systems where four pretreatment methods (steam explosion, organosolv, liquid hot water, as well as a combined steam explosion and liquid hot water) and two bioethanol production methods (SHF and SSF) were taken into consideration. The SSF configuration exergetically outperformed the SHF approach. This occurred due to the synergetic effect of saccharifying enzymes and fermenting microorganisms in the SSF configuration which could lead to more efficient use of the exergy provided into the system.

Ojeda and Kafarov [167] compared two types of reactors, i.e., stirred-tank and plug-flow reactors used for the enzymatic hydrolysis of the organosolv-pretreated lignocellulosic materials from exergetic viewpoint. The plug-flow reactor outperformed the continuous stirred-tank reactor in terms of exergy efficiency. The inhibitory effect of xylose was one of the major sources of irreversibilities in both reactors so that an increase in the xylose concentration from 0 to 40 g/kg unfavorably

reduced their exergy efficiencies by around 30%. Moreover, the hydrolysis temperature had a considerable effect on the exergetic performance of the reactors. Increasing the process temperature from 40 to 50 °C boosted the exergetic efficiencies of both types of reactors, while further increase in the hydrolysis temperature deteriorated their exergetic performance. This could be explained by the fact that the process temperature beyond 50 °C could markedly inactivate the cellulase enzyme.

Even though lignocellulosic bioethanol production can be regarded as a stepping stone for sustainable biofuel production, its superiority over other biofuel production techniques from the exergetic standpoint remains a debate. To address this issue, Tan et al. [138] exergetically compared palm-based biodiesel and bioethanol production systems. The bioethanol production plant including dilute sulfuric acid pretreatment step was fed by empty palm fruit bunch, while palm oil was used as feedstock in the biodiesel production plant. In the bioethanol plant, direct steam injection was considered in order to solubilize hemicellulose fraction and break it down into fermentable sugars. The second-generation bioethanol had an overall 10% higher net exergy value compared with the palm methyl ester, confirming its thermodynamic sustainability [138]. It is interesting to note that the net energy value of the bioethanol production system was 9% lower than the biodiesel production process. Moreover, the product recovery/waste treatment unit contributed to the majority of the exergy destroyed in the bioethanol plant, followed by the pretreatment step. The higher irreversibility rate of the distillation process in the product recovery/waste treatment unit because of massive mass transfer and large heat loss was the main reason for that finding [138]. On the other hand, the higher irreversibility rate due to intensive chemical reaction and rapid heat transfer in the pretreatment unit was responsible for its higher exergy destruction rate [138]. Unlike the SSF unit, exergy loss rates of both the pretreatment and product recovery/waste treatment units were lower than their corresponding energy loss rates. This could be ascribed to the fact that the energy types lost in the pretreatment and product recovery/waste treatment units were low-grade quality flows. However, the energy types lost in the SSF process were high-grade quality energy streams [138]. Accordingly, the pretreatment and distillation processes should be retrofitted using advanced heat integration approaches.

Velásquez-Arredondo et al. [166] compared a bioethanol

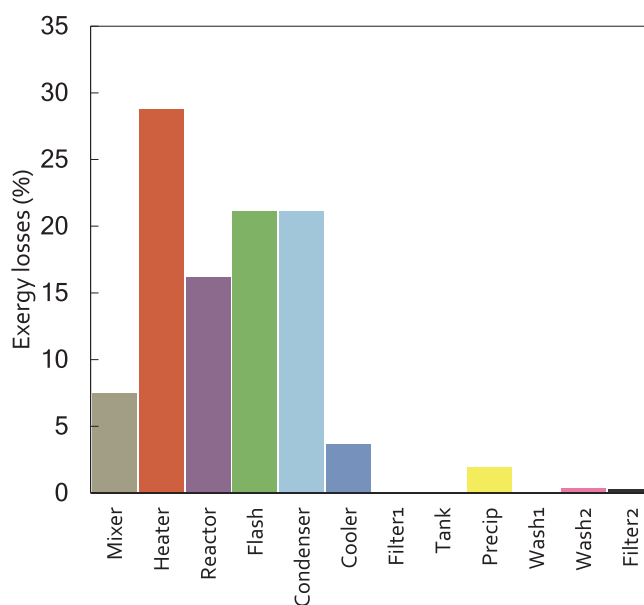


Fig. 9. Component-level exergy losses percentage of delignification (pretreatment) unit in a lignocellulosic catechol production plant. Redrawn with permission from Mabrouk et al. [172]. Copyright© 2018 Elsevier.

Table 5
Effects of different pretreatment methods on the exergetic aspects of multi-product lignocellulosic biofuel systems.

Pretreatment	Pretreatment conditions	Raw material(s)	Main product(s)	Main production stages	Exergy efficiency of the pretreatment process (%); [SI (-)]	Overall exergy efficiency (%); [SI (-)]; [IP (MJ)]	Remarks	Ref.								
Chemical Acid (dilute sulfuric acid)	<ul style="list-style-type: none"> • $H_2SO_4 = 1.1$ wt% • $T = 268$ °C • $P = 13$ atm 	Empty fruit bunch	<ul style="list-style-type: none"> • Ethanol* • Electricity 	PT/SSF/D&R/DH/ET	82.32 ^F	-	<ul style="list-style-type: none"> • Heat integration in the distillation process could reduce the irreversibility rate of the system. • The recovered heat and steam could be utilized for preheating the feedstock as well as heating the distillation column, which in turn could boost the exergetic performance of the system. 	[138]								
									<ul style="list-style-type: none"> • $T < 200$ °C 	Wood chip	<ul style="list-style-type: none"> • Ethanol* • Electricity 	TR/PT/SSCF/D&R/DH/AD/UT	93.70 ^F	34.70 ^F	<ul style="list-style-type: none"> • Lignin utilization/exploitation was found to be a promising strategy for augmenting the overall exergy efficiency of the plant. 	[173]
	<ul style="list-style-type: none"> • $H_2SO_4 = 2.0$ wt% 	Sugarcane bagasse	<ul style="list-style-type: none"> • Octane* • Nonane* • Octane* • Nonane* 	PT/HY/OP/NP	15.04 ^F	-	-	[174]								
									<ul style="list-style-type: none"> • $H_2SO_4 = 2.0$ wt% 	Sugarcane bagasse	<ul style="list-style-type: none"> • Octane* • Nonane* • Syngas • Electricity 	PT/HY/OP/NP/GAS/UT	11.55 ^F	-	-	[174]
	<ul style="list-style-type: none"> • $NaOH = 1.2$ wt% 	The hanging cluster of banana fruit	<ul style="list-style-type: none"> • Ethanol* • Electricity • Steam • Fertilizer 	GR/FT/PP/PT/NT/YP/SHE/D&R/DH/UT/ET	-	15.30 ^U	-	<ul style="list-style-type: none"> • The process design should be improved in order to optimize the use of H_2SO_4, $NaOH$, steam, and electricity. Such improvements could increase the overall exergy efficiency of the system to 22.30%. 								
									<ul style="list-style-type: none"> • $NaOH = 1.2$ wt% 	Banana skin	<ul style="list-style-type: none"> • Ethanol* • Electricity • Steam • Fertilizer 	GR/FT/PP/PT/NT/YP/SHE/D&R/DH/UT/ET	-	10.60 ^U	-	<ul style="list-style-type: none"> • Optimizing the use of H_2SO_4, $NaOH$, steam, and electricity could boost the overall exergy efficiency of the system to 17.10%.
	<ul style="list-style-type: none"> • $T = 180$ °C • $P = 10$ bar 	Wheat straw	<ul style="list-style-type: none"> • Ethanol* • Biogas 	PT/SHE/YP/D&R/DH/AD/UT	-	74.00 ^U ; 41.80 ^F ; [3.846]; [7.8]	-	<ul style="list-style-type: none"> • The use of the lignin fraction of the wheat straw could increase the overall exergetic efficiency of the system to 68.70%. 								
									<ul style="list-style-type: none"> • $T = 180$ °C • $P = 10$ bar 	Wheat straw	<ul style="list-style-type: none"> • Ethanol* • Electricity • District heat 	PT/SHE/YP/D&R/DH/AD/UT	-	65.40 ^U ; 30.90 ^F ; [2.890]; [16.6]	-	<ul style="list-style-type: none"> • Optimizing the design of biogas combustion chamber could avoid the major portion of the irreversibilities occurred in the plant.
	<ul style="list-style-type: none"> • $T = 210$ °C • $P = 12.5$ bar • $RT = 5$ min 	Sugarcane	<ul style="list-style-type: none"> • Ethanol** • Electricity • Steam 	PP/PT/FER/PT/SHE/PE/D&R/DH/UT	-	53.40 ^F ; 58.90 ^{F-A}	-	<ul style="list-style-type: none"> • The economic viability of the system could be increased through power generation. 								
<ul style="list-style-type: none"> • $H_2SO_4 = 0.50$ wt% • $T = 192$ °C • $P = 13$ bar 									Wood chip	<ul style="list-style-type: none"> • Ethanol* • Electricity • Single-cell proteins 	PT/DT/HY/FER/ES/HYD/SR/UT	-	38.00 ^F	-	<ul style="list-style-type: none"> • Heat integration could improve the renewability and exergetic efficiency of the system while reducing its unitary exergy cost and exergy-based GHG emissions. 	[178]
	<ul style="list-style-type: none"> • $H_2SO_4 = 0.50$ wt% • $T = 160$ °C • $P = 6$ atm • $SC = 20$ wt% • $SO_2 = 1.0$ wt% 	Corn cob	<ul style="list-style-type: none"> • Ethanol* • Electricity • Steam • Xylose • Ethanol* 	PT/DT/NT/XP/SSF/D&R/DH/WT/UT	-	62.80 ^U ; 36.60 ^F ; [2.688]	-	<ul style="list-style-type: none"> • Heat integration could reduce the need for external utilities, improving the exergetic efficiency of the process. 								
<ul style="list-style-type: none"> • $T = 180$ °C • $P = 10$ bar 									Wheat straw	<ul style="list-style-type: none"> • Ethanol* 	-	66.60 ^U ; 44.10 ^F	-	-	-	[180]

(continued on next page)

Table 5 (continued)

Pretreatment	Pretreatment conditions	Raw material(s)	Main product(s)	Main production stages	Exergy efficiency of the pretreatment process (%); [SI (-)]	Overall exergy efficiency (%); [SI (-)]; [IP (MD)]	Remarks	Ref.
SO ₂ -catalyzed steam explosion	<ul style="list-style-type: none"> T = 190 °C 		<ul style="list-style-type: none"> Methane** Electricity 	PT/EP/YP/SSF/D&R/DH/AD/UT/UT			<ul style="list-style-type: none"> Heat integration could shrink the use of steam and cooling water up to 40%, substantially discounting the utility costs. Fertilizer production from sludge and sludge incineration could increase the exergy efficiency of the system. Replacing the pretreatment methods with more efficient ones could be a good solution for improving the exergetic sustainability of the process. 	[181]
	<ul style="list-style-type: none"> SO₂ = 2.0 wt% T = 190 °C P = 12.5 bar S/B = 0.55 w/w T = 266 °C P = 13 atm 	Sugarcane and residual bagasse	<ul style="list-style-type: none"> Ethanol** Bogas Electricity 	PP/PT/PT/SHF/D&R/DH/AD/UT	59.00–66.00 ^{U,α}	34.70–36.60 ^{U,α}	<ul style="list-style-type: none"> Recovering the physical and chemical exergy of the exhaust combustion gas could significantly enhance the exergy efficiency of the biorefinery. Replacing the conventional chiller with high-performance hybrid refrigerators like combined supercritical CO₂ recompression Brayton/adsorption refrigeration cycles could promote the exergetic performance of the plant. 	[182]
	<ul style="list-style-type: none"> SO₂ = 2.0 wt% T = 160–240 °C P = 6.0–34.0 bar RT = 1–15 min 	Sugarcane bagasse and brown leaves	<ul style="list-style-type: none"> Lactic acid Electricity Fertilizer 	PT/EP/HY/LS/WT/AD/UT	98.73 ^U 98.71 ^F	52.71 ^U , 44.73 ^F	<ul style="list-style-type: none"> Although the second-generation bioethanol plant showed 6% higher exergy loss compared with the conventional first-generation bioethanol technology, its overall exergy efficiency was 7.87% higher than the first-generation bioethanol system because of a considerable increase in the rate of bioethanol production. 	[183]
H ₃ PO ₄ -catalyzed steam explosion	<ul style="list-style-type: none"> T = 190 °C RT = 5 min 	Sugarcane and sugarcane leaves	<ul style="list-style-type: none"> Ethanol** Electricity 	M/PT/1GP/2GP/UT	–	43.87 ^F	<ul style="list-style-type: none"> The second-generation bioethanol system had 9% higher exergy efficiency compared with the conventional first-generation bioethanol plant due to the production of single-cell proteins (vinasse-yeast). Even though the supercritical water hydrolysis technology had lower total investment cost compared with enzymatic hydrolysis technique, this method showed lower ethanol production rate, electricity generation rate, and exergetic efficiency. 	[184]
	<ul style="list-style-type: none"> SO₂ = 2.0 wt% T = 160–240 °C P = 6.0–34.0 bar RT = 1–15 min 	Sugarcane	<ul style="list-style-type: none"> Ethanol** Electricity Single-cell proteins 	M/PT/1GP/2GP/UT/YP	–	45.03 ^F	<ul style="list-style-type: none"> Increasing the exergetic efficiency of the system might significantly increase its capital cost. 	[185]
	<ul style="list-style-type: none"> T = 190 °C RT = 5 min 	Sugarcane and sugarcane leaves	<ul style="list-style-type: none"> Ethanol** Electricity 	PP/JT/FER/M/PT/SHF/D&R/DH/UT	–	28.32 ^{F,H} , 35.05 ^{F,α}	<ul style="list-style-type: none"> Optimization of heat integration network could remarkably improve the exergetic performance of the system. The load of CHP plant had a slight impact on the exergetic performance of the bioethanol production plant. 	[186]
Hydrothermal	Not reported	Sugarcane, sugarcane bagasse, and leaves	<ul style="list-style-type: none"> Ethanol** Electricity 	M/JT/PT/HY/FER/D&R/DH/UT	–	39.20–44.40 ^F		[187]
	<ul style="list-style-type: none"> S/B = 2.0 w/w T = 195 °C P = 13 bar 	Wheat straw	<ul style="list-style-type: none"> Ethanol* Molasses Solid biofuel Electricity District heat 	PT/SSF/D&R/UT	99.00 ^F	85.50 ^F		
Combined								
Combined Organosolv and dilute acid	<ul style="list-style-type: none"> Ethanol¹⁸ = 75.0 wt% H₂SO₄ = 0.25–0.50 wt% T = 180–200 °C P = 25–28 bar 	Sugarcane	<ul style="list-style-type: none"> Ethanol** Electricity 	PP/PT/SHF/D&R/UT	–	40.90 ^F	<ul style="list-style-type: none"> Fermenting six-carbon sugars (hexose) alone in the integrated first- and second-generation bioethanol production system could not increase the exergy efficiency of the system when compared with the single first-generation bioethanol production system. 	[187]

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production plant fed by banana pulp, fruit, and flower stalk with a biodiesel palm oil-based biodiesel plant. The subsections of bioethanol production plant were as follows: (1) starch acid hydrolysis unit that was used for preliminary processing and acid hydrolysis of banana fruit or banana pulp, (2) lignocellulose enzymatic hydrolysis unit that was considered for preliminary processing, alkaline delignification (pre-treatment), and enzymatic hydrolysis of banana flower stalk, and (3) sugar fermentation unit. Unlike the findings of Tan et al. [138], the flower stalk-based bioethanol production plant (i.e., second-generation bioethanol systems) had the lowest exergetic efficiency, while the palm oil-based biodiesel production showed the highest exergetic efficiency. The effects of several variables including water-to-biomass ratio, pH, hydrolysis efficiency, and glucose conversion were also investigated on the exergetic efficiency of bioethanol plant. It was reported that these variables could significantly affect the exergetic efficiency and sustainability level of bioethanol production plant. This in turn showed the fact that the bioethanol production conditions should be exergetically optimized before real-world implementation of such biofuel production systems.

3.2. Multi-product lignocellulosic biofuel systems

One of the most efficient strategies for enhancing the exergetic efficiency of lignocellulosic biofuel systems and reducing their associated production costs and environmental impacts is to use multi-generation or biorefinery systems. These systems have emerged as efforts to utilize biomass feedstocks more efficiently by providing various types of energy and material fluxes like bioheat, bioelectricity, biofuels, biochemicals, and biomaterials from a single biomass while minimizing or even eliminating any waste stream. Exergy analysis offers a promising framework for sustainability assessment of lignocellulosic-based biorefinery systems by quantifying the waste streams generated and diagnosing the hotspots of energy quality loss. Therefore, exergy-based methods have been increasingly drawing much attention in order to assess the sustainability aspects of biorefinery systems. Table 5 tabulates the research attempts in which exergetic methods have been used for analyzing the sustainability aspects of multi-product lignocellulosic biofuel systems with an emphasis on the pretreatment methods.

Bösch et al. [176] assessed five poly-generation scenarios converting wheat grain and wheat straw into various products including first- and second-generation ethanol, biogas, electricity, district heat, dried distillers grains, and fertilizer from exergetic standpoint. Among the investigated cases, two scenarios were only fed by wheat straw in order to produce second-generation bioethanol with/without the co-generation of electricity and district heat. In both scenarios, only hexose-type sugars were fermented for bioethanol production, while pentose-type sugars were processed through an anaerobic digestion unit. The robust structure of the wheat straw was broken down using a steam explosion pretreatment unit. The stillage left from the ethanol separation process and a stream of the pretreated wheat straw were mixed and fed into an anaerobic digestion reactor to produce biogas [176]. The evolved biogas was then used in a combustion engine or a combustion chamber to generate utility steam with/without power and district heat. In the scenario without power and heat generation, there was a surplus of biogas which remained intact and, accordingly, did not have any contribution to irreversibilities (Fig. 10a). In contrast, due to the irreversibilities associated with the evolved biogas combustion, the scenario including the gas engine generated higher exergy destruction as shown in Fig. 10b. Moreover, it was found that the evolved biogas combustion through either the combustion chamber or the gas engine was responsible for the majority of thermodynamic imperfection occurred in the developed biorefinery [176].

Palacios-Bereche et al. [181] evaluated an integrated first- and second-generation ethanol production plant using the conventional exergy and exergetic cost methods. Overall, integrating the second-generation bioethanol system with the conventional first-generation

Table 5 (continued)

Pretreatment	Pretreatment conditions	Raw material(s)	Main product(s)	Main production stages	Exergy efficiency of the pretreatment process (%); [SI (-)]	Overall exergy efficiency (%); [SI (-)]; [P (MD)]	Remarks	Ref.
	<ul style="list-style-type: none"> Ethanol^a = 75.0 wt% H₂SO₄ = 0.25–0.50 wt% T = 180–200 °C P = 25–28 bar 	Sugarcane	<ul style="list-style-type: none"> Ethanol^{**} Electricity 	PP/PT/SSCF/D&R/ UT	-	42.00 ^f	<ul style="list-style-type: none"> The integrated first- and second-generation bioethanol production system with pentose fermentation might have a higher exergy efficiency compared with the single first-generation bioethanol production plant. 	[187]

*: Single second generation ethanol; **: Integrated first and second generation ethanol; ***: Biogas is upgraded to nearly pure methane; 1GP: First generation ethanol plant; 2GP: Second generation ethanol plant; a: Aqueous; AD: Anaerobic digestion; B: Biomass; D&R: Distillation and rectification; DH: Dehydration; DT: Detoxification; EP: Enzyme production; ES: Esterification; ET: Effluent treatment; F: Functional exergy efficiency; FER: Fermentation; FP: Furfural production; GAS: Gasification; GR: Growing; HMF: Hydroxymethylfurfural; HP: Hydroxymethylfurfural production; HY: Hydrolysis; HYD: Hydrogenation; IP: Exergetic improvement potential; JT: Juice treatment and concentration; LS: Lactic acid synthesis; M: Milling; NP: Nonane production; OP: Octane production; P: Pressure; PF: Pentose fermentation; PP: Preliminary processing; PT: Pretreatment; RT: Residence time; S: Steam; SC: Solid concentration; SHF: Separate hydrolysis and fermentation; SI: Sustainability index; SR: Steam reforming; SSCF: Simultaneous saccharification and co-fermentation; SSF: Simultaneous saccharification and fermentation; T: Temperature; TR: Transportation; U: Universal exergy efficiency; UP: Upgrading; UT: Utility or CHP; WT: Wastewater treatment; XP: Xylose production; YP: Yeast production; α: Dependent on the variable process conditions; λ: The process with heat integration; μ: Based on supercritical water hydrolysis; σ: Based on enzymatic hydrolysis.

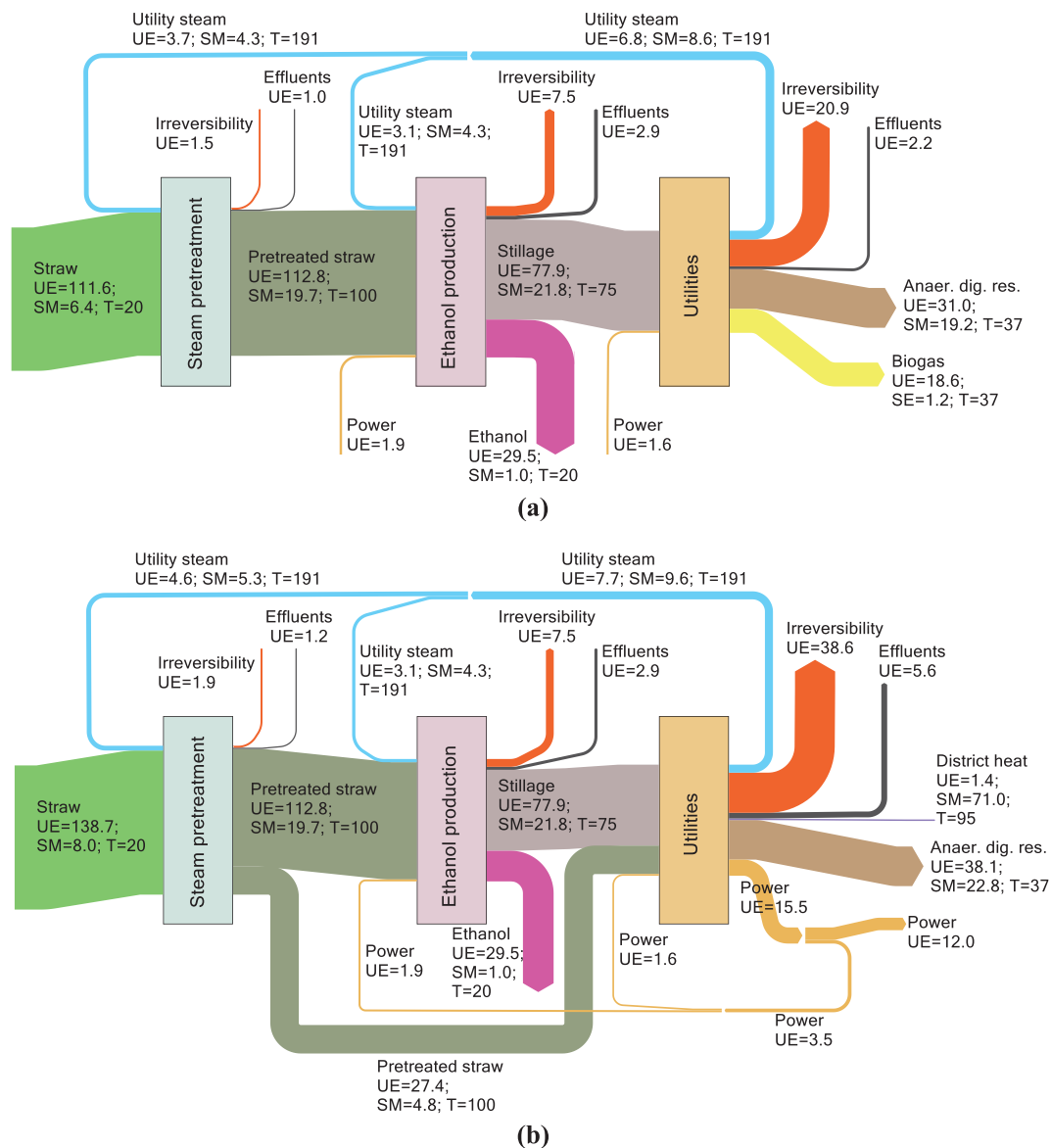


Fig. 10. Sankey diagrams of wheat straw-based multi-product bioethanol production system without (a) and with (b) electricity generation [176]. UE: Unitary exergy (MJ/kg ethanol); SM: Specific mass (kg/kg ethanol); T: Temperature ($^{\circ}\text{C}$). Redrawn with permission from Bösch et al. [176]. Copyright© 2012 Elsevier.

ethanol production technology could raise the unitary exergetic cost associated with ethanol production from 12% to 15%. Despite the increase in the exergetic cost, the integrated plant had higher overall exergy efficiency compared to the conventional first-generation ethanol plant. This study indicated that the utility production unit contributed to the largest proportion of the irreversibility rate occurred in the plant [181]. This could be attributed to the intensive combustion reaction, fast heat transfer, and rapid phase change in the steam production unit. The second highest irreversibility rate was found for the fermentation process due to the reactions occurred in the fermenter as well as the heat dissipated for the reaction exothermicity. In addition, the SO_2 -catalyzed steam explosion pretreatment was blamed for the lower exergy efficiency of its hydrolysis unit [181]. It appeared that substituting the applied pretreatment method with energy-efficient pretreatment approaches such as microbial consortium would be a good solution for boosting the exergetic efficiency of the hydrolysis stage.

Lythcke-Jørgensen et al. [186] used the exergy concept for scrutinizing a second-generation bioethanol production system integrated with a CHP plant. The hydrothermally-pretreated wheat straw was used for bioethanol production. The developed system was exergetically

analyzed at six different operation modes covering various loads of CHP plant, integrated/separate operation of CHP plant, and the incorporation of district heating into the bioethanol facility. The integrated bioethanol system incorporating district heating at lower CHP load showed the highest exergy efficiency, while the exergy efficiency of the separate bioethanol system without district heating was found to be the lowest value. The highest exergy loss and destruction in the bioethanol facility for the most exergetically-efficient operation mode occurred in the SSF process as shown in Fig. 11 [186]. This could be attributed to the fact that the heat released from the exothermic fermenting reactions in the SSF process was used only to keep the temperature of the fermenting process in the desired operating range without an efficient recovery in the heat network. In addition, the exergy loss and destruction in the separation process was substantial due to large quantities of heat transfer and mechanical separation of streams [186].

The poly-generation system developed by Lythcke-Jørgensen et al. [186] was then further investigated by Lythcke-Jørgensen and Haglind [188] in order to optimize its design and operation parameters. The optimization process was conducted to minimize the specific ethanol production cost by considering a quasi-static hourly time-scale

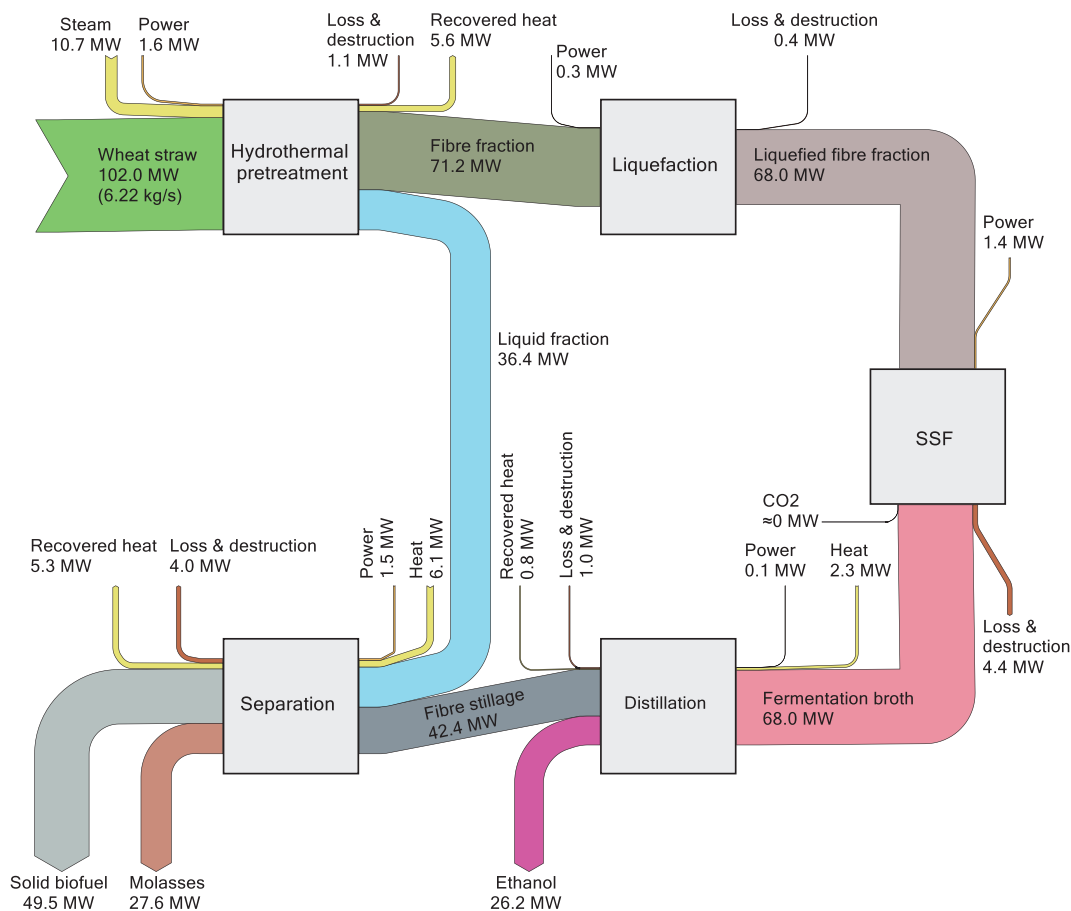


Fig. 11. Exergy flow diagram of the wheat straw-based bioethanol facility for the most exergetically-efficient operation mode, i.e., the integrated bioethanol system incorporating district heating at lower CHP load. Redrawn with permission from Lythcke-Jørgensen et al. [186]. Copyright© 2014 Elsevier.

operation over a year. Different lignocellulose processing capacities in the range of 5–12 kg/s were considered in the bioethanol production process in order to scrutinize the effect of plant scale on its exergetic and economic performance. The plant was restricted by two operational constraints including a fixed hourly heat generation and an upper hourly power export threshold. The average hourly exergy efficiency over a year was computed in order to assess the exergetic performance of the plant for the optimal solutions found. The results indicated that

the specific ethanol production cost was continuously increased from 0.958 Euro/L to more than 1.100 Euro/L as the lignocellulose processing capacity elevated [188]. In addition, increasing the lignocellulose processing capacity prolonged the annual working hour of the CHP plant during the separate operation mode, leading to an increase in the specific energy cost of the plant. The average exergy efficiency showed a descending trend with increasing the lignocellulose processing capacity, mainly due to the prolonged annual working hour during the

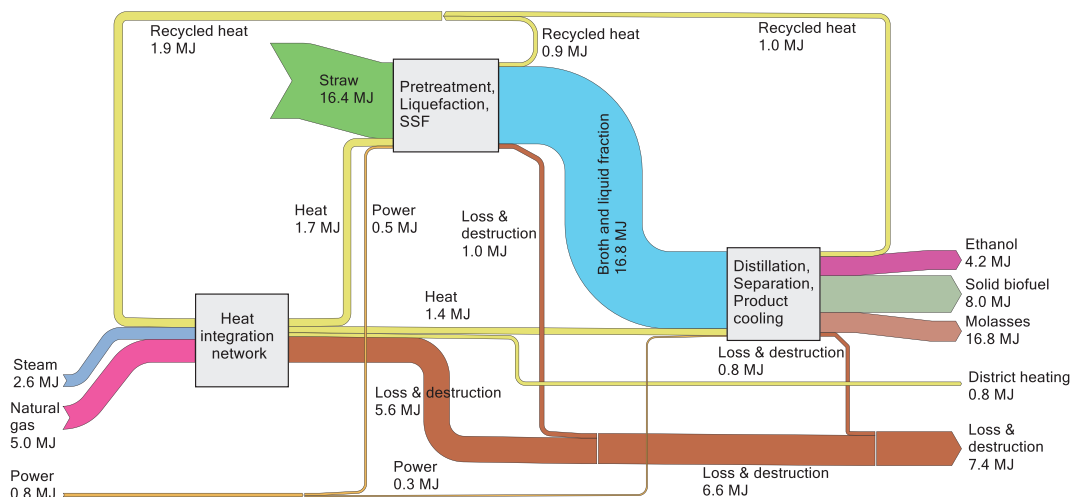


Fig. 12. Exergy flow diagram for the wheat straw-based bioethanol production unit under the optimal lignocellulose processing capacity of 5 kg/s. Redrawn with permission from Lythcke-Jørgensen and Haglind [188]. Copyright© 2015 Elsevier.

separate operation mode. More specifically, the maximum average exergy efficiency (i.e., 74.6%) was found for the lignocellulose processing capacity of 5 kg/s [188]. Fig. 12 presents the exergy flow diagram for the lignocellulose processing capacity of 5 kg/s as the optimal solution. Overall, it could be concluded that the plant scale-up could be an inefficient strategy from both economic and thermodynamic viewpoints.

Flório and Junior [187] exergetically, thermoeconomically, and exergoeconomically analyzed three sugarcane-based first- and second-generation bioethanol production systems integrated with CHP plant. Notably, unlike the monetary exergy cost (monetary/kJ) obtained using exergoeconomic method, thermoeconomic analysis determines the exergy cost (kJ/kJ) or the amount of input exergy required to make one kJ of product exergy. The developed scenarios were as follows: (a) sugarcane juice-based first-generation bioethanol production, (b) integrated sugarcane juice/bagasse-based first- and second-generation bioethanol production with only hexose fermentation technology, and (c) integrated sugarcane juice/bagasse-based first- and second-generation bioethanol production with both hexose/pentose fermentation technologies. The third scenario attained the highest exergy efficiency, while the second scenario showed the lowest exergy efficiency [187]. Based on the internal rate of return results, it was concluded that the first-generation bioethanol production was the most economically-viable scenario compared with the other scenarios. This stemmed from the fact that the more second-generation bioethanol produced in the second and third scenarios could not compensate for the fixed and operating costs of the hydrolysis process [187]. Overall, it could be concluded that the rapid development in bioethanol production technologies would make second-generation bioethanol production more economically viable in the near future over the first-generation counterpart.

Using the exergy concept, Palacio et al. [183] analyzed three case studies including (a) cane juice-based plant co-producing first-generation bioethanol and electricity, (b) cane juice- and sugarcane bagasse-based plant co-producing first-generation bioethanol, second-generation bioethanol, and electricity, and (c) cane juice- and sugarcane bagasse-based plant co-producing first-generation bioethanol, second-generation bioethanol, fodder yeast (single-cell proteins), and electricity. The pretreatment process used for sugarcane bagasse was steam explosion method. The second and third case studies generated higher irreversibilities compared with the first case study. This could be related to the chemical reactions occurred in the pretreatment process of the sugarcane bagasse. However, the exergy rates of products evolved in the second and third case studies could compensate for their higher exergy destruction rates and, consequently, could lead to higher exergy efficiencies for these scenarios compared with the first case study.

Arredondo et al. [175] attempted to assess the exergetic renewability of four different bioethanol systems based on banana fruit and its non-edible residues. The boundaries of the developed scenarios were extended to cover all the processes from the plant cultivation to the residue treatment. In addition to exergy efficiency, an index called "Renewability Performance Indicator" was introduced to compare the level of renewability of the developed scenarios. Overall, the lignocellulosic-based second-generation ethanol production scenarios had lower exergy efficiencies and renewability performance indicators compared with the fruit-based first-generation counterparts. This might be ascribed to the consumption of higher amounts of energy and chemicals for breaking down the robust structure of lignocellulosic residues.

In continuation, Velásquez et al. [189] compared the exergy-based renewability level of three liquid biofuel production schemes using the renewability performance indicator. The investigated biofuel production processes included (a) sugar and ethanol production scheme from sugarcane, (b) ethanol production scheme from banana fruit, banana pulp, and hanging cluster, and (c) biodiesel production scheme from palm oil. The highest exergy efficiency (i.e., 74.7%) and renewability indicator (i.e., 1.2) were found for the biodiesel production plant,

followed by the first ethanol production scheme with exergy efficiency of 45.70% and renewability indicator of 0.72. The ethanol production scenario based on lignocellulosic material (i.e., hanging cluster) had the lowest exergy efficiency (i.e., 12.2%) and renewability indicator (0.13). Overall, it could be inferred that the use of renewable energy and material sources could not necessarily guarantee the renewability of biofuel production processes since the exergy destruction of chemical and biochemical reactions could significantly affect their renewability indices.

One of the effective strategies for boosting the exergetic efficiency of lignocellulosic bioethanol production systems is to convert the hemicellulose extracted from the pretreatment process into added-value products. In this context, Ojeda et al. [163] compared different strategies for hydrolysis and fermentation including the SSF, SSCF, and SHF from exergetic point of view. Dilute sulfuric acid pretreatment was adopted for all of the fermentation methods. The results showed that the maximum exergy destruction occurred in the pretreatment stage (more than 25 MJ/kg bioethanol). However, the pretreatment process had lower exergy emission compared with all the of the hydrolysis and fermentation processes investigated. Among the hydrolysis and fermentation methods used, the highest exergy destruction and emission were found for the SHF approach, while the SSCF approach had the lowest values of these two measurements [163]. The higher exergy destruction of the SHF process was due to the lower rates of enzyme activity and ethanol evolution as a result of the accumulation of glucose in the hydrolysis reactor acting as an inhibitor for cellobiose hydrolysis. Overall, the SSCF process was the most exergetically efficient strategy in comparison with the SHF and SSF processes [163]. However, the microorganisms fermenting both pentoses and hexoses into ethanol (e.g., *Zymomonas mobilis*) not only have lower activity than those fermenting hexoses only but also tend to ferment hexoses more than pentoses. Therefore, there is an open room for further improving the exergetic efficiency of such plants by switching from pentose-based bioethanol to added-value products.

Liu et al. [179] proposed a corn cob-based multi-product system for the simultaneous generation of bioethanol, xylose, electricity, and steam and examined the developed biorefinery using exergy analysis. The system comprised of several subunits including pretreatment, xylose and ethanol production, wastewater treatment, and CHP subunits. The pretreatment process was performed using steam in the presence of dilute sulfuric acid. After pretreating the corn cob, the cellulose fraction was used for ethanol production through the SSF method, whereas the hemicellulose proposition was applied for xylose crystalline production. The highest exergy efficiency was obtained for the ethanol + xylose production subunit, while the CHP subunit showed the lowest exergy efficiency. The developed biorefinery was competitive with the conventional cellulosic ethanol systems due to the high price of xylose (i.e., 2989.5 USD/t). Notably, the xylose crystalline could be utilized as the chemical platform for producing many valuable compounds such as lactic acid.

Using the exergy concept, Aghbashlo et al. [182] assessed a lignocellulosic biorefinery co-producing lactic acid, utility electricity, surplus electricity, utility steam, and fertilizer from sugarcane bagasse and brown leaves. The investigated system consisted of nine subunits including biomass pretreatment, cellulase enzyme supply, saccharification, steam generation, wastewater treatment, power generation and steam distribution, lactic acid synthesis, chiller, and cooling tower subunit. The steam explosion process catalyzed by SO_2 was considered for the feedstock pretreatment. The pretreatment subunit was found to exergetically-efficient process among the subunits of the biorefinery system. The highest exergy destruction rate occurred in the boiler subunit due to the huge amount of entropy generated in the combustion reaction. However, the lowest exergy efficiency was obtained for the chiller subunit due to its high power consumption.

Using the data reported by Aghbashlo et al. [182], Soltanian et al. [154] exergoeconomically analyzed the lignocellulosic-based

developed biorefinery. The feedstock pretreatment and saccharification units had minimum relative cost difference, while the chiller unit had the maximum value of this indicator. Accordingly, unlike the chiller subunit, the unitary exergy cost could not be easily discounted for the feedstock pretreatment and saccharification subunits. The total cost rates of the feedstock pretreatment, enzyme production, and saccharification units were dominated by component-related cost rate and, therefore, their economic improvement should be centered on reducing the component-related cost rate.

The use of the lignin extracted from the pretreatment process could also be another way for enhancing the exergetic efficiency and improving the sustainability aspects of lignocellulose-based biorefineries. Soheli and Jack [173] showed that the overall exergetic efficiency of a wood chip-based bioethanol plant integrated with a CHP system was remarkably dependent on how the extracted lignin fraction was exploited. After dilute sulfuric acid pretreatment of wood chips, the obtained lignin was combusted in the CHP system. Despite the highest exergy destruction of the lignin combustion process, this strategy could recover the major portion of lignin exergy content through producing electrical exergy.

Restrepo-Serna et al. [174] used the exergy concept for investigating three different sugarcane bagasse-based systems co-producing various value-added products. The products of the developed scenarios were as follow: (a) furfural and hydroxymethylfurfural, (b) octane and nonane, and (c) octane, nonane, syngas, and electricity. The acid pretreatment process was used in all the developed scenarios adopted for breaking down the recalcitrant structure of bagasse. The third scenario attained the highest exergy efficiency among the developed systems because of upgrading the remained lignin into useful products, i.e., syngas and electricity. Among the different stages involved in the developed schemes, the gasification process showed the highest exergy destruction, followed by the detoxification and furfural production processes [174]. The gasification step was a highly irreversible process because of rapid heat and mass transfer processes as well as intensive chemical reactions. The main reason for the high exergy destruction rate of the detoxification step was ascribed to the neutralization process in which stabilized salts were formed. The huge amount of energy used in converting pentoses into value-added furfural through dehydration process was the main cause of thermodynamic non-idealities in the furfural production process. The pretreatment process of the first scenario showed the highest exergetic efficiency while the lowest value was obtained for the third scenario [174].

Soheli and Jack [178] analyzed a new biochemical system co-producing bioethanol, bioelectricity, and single-cell proteins from wood chip using the exergy concept. Unlike the conventional bioethanol production process, the developed system first converted biomass-based sugars into acetic acid and then produced bioethanol through consecutive esterification and hydrogenation processes of the evolved acetic acid. Despite the high yield of the developed system, its exergy efficiency was not significantly higher than the conventional counterpart. Accordingly, there was no direct association between the process yield and its exergy efficiency. It was found that the pretreatment and detoxification processes did not have an important role in the overall thermodynamic imperfection of the system, while power generation and hydrogenation units destroyed the major portion of the supplied exergy. The higher chemical exergy of the hydrogen consumed in the hydrogenation process was the main reason for its higher irreversibility rate. Unlike the authors' previous work [173], lignin utilization through supercritical water gasification for providing the required hydrogen in the hydrogenation process could not considerably improve the overall exergetic performance of the system.

As previously underlined, the technologies applied for the hydrolysis and fermentation processes significantly influence the exergetic, economic, and environmental performances of bioethanol production systems. Using exergy analysis, economic assessment, and water intake measurement, Albarelli et al. [184] compared two supercritical water

hydrolysis approaches and one enzymatic hydrolysis method in a sugarcane-based biorefinery co-producing bioethanol (first- and second-generation) and electricity. In the first supercritical water hydrolysis-assisted scenario, the produced steam was cooled down through a heat exchanger. However, the produced steam was decompressed through a steam turbine in the second scenario. In order to produce second-generation bioethanol, the residual bagasse along with sugarcane leaves were pretreated through a SO_2 -catalyzed steam explosion unit [184]. The exergy efficiency of the second supercritical water hydrolysis-assisted scenario was higher than that of the first counterpart owing to the electricity generated by the steam turbine during decompression of the produced steam. However, both of the developed supercritical water hydrolysis-assisted scenarios were exergetically inefficient compared with the enzymatic hydrolysis-assisted scenario owing to their higher energy demand [184]. Nevertheless, the total investment and manufacturing costs of the biorefinery with enzymatic hydrolysis were significantly higher than those of supercritical water hydrolysis-assisted scenarios. In addition, the biorefineries with supercritical water hydrolysis had lower water intake compared with the enzymatic hydrolysis-assisted biorefinery, indicating lower water footprint of the supercritical water hydrolysis approach over the enzymatic one [184].

There are complex relationships among the factors affecting the exergetic performance of lignocellulosic biofuel systems. Accordingly, process optimization needs to be further explored in order to identify the optimal process configurations and operating conditions. Bechara et al. [185] strived to optimize the design of a sugarcane bagasse/juice-based co-generation system producing bioethanol (first- and second-generation) and power from economic and exergetic viewpoints. Four different scenarios were selected from the published literature and subjected to the optimization process where the phosphoric acid-catalyzed steam explosion process was used for pretreating the utilized sugarcane bagasse. It was found that only two scenarios were economically justified on which their exergetic efficiency values and hydrolysis levels were low. Based on the Pareto solutions found, a slight increase in the exergetic efficiency negatively elevated the capital cost as shown in Fig. 13. It was claimed that the optimal configuration could present the highest hydrolyzed bagasse fraction and ethanol evolution rate as well as the lowest cooling water demand and power generation rates.

Quiroz-Ramírez et al. [190] energetically, exergetically,

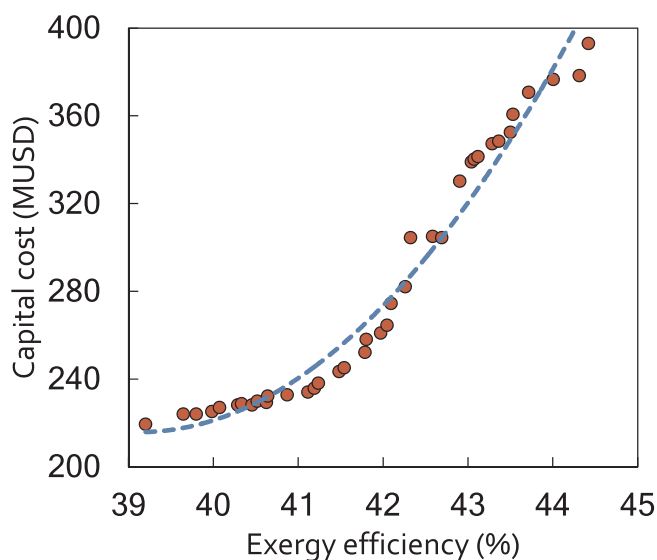


Fig. 13. The relation of capital cost with exergetic efficiency for a sugarcane bagasse/juice-based co-generation system producing bioethanol (first- and second-generation) and power. Redrawn and modified with permission from Bechara et al. [185]. Copyright© 2016 Elsevier.

economically, and environmentally optimized a multi-product lignocellulosic-based plant producing acetone, ethanol, and butanol. The enzymatic hydrolysis process was chosen for pretreating the considered lignocellulosic biomass. All the saccharification, fermentation, and separation processes were simultaneously carried out within a reactor. Three different purification scenarios, i.e., a conventional system with a side stream, a thermally-coupled design, and a thermodynamic equivalent design were considered for purifying the effluent leaving the reactor. According to the results obtained, the thermally-coupled design with corn grain, wheat, and wheat straw was found as the best scenario. The total annual cost, global Eco-indicator 99, exergy efficiency, net present value, and annual production of the optimal configuration of the selected scenario were found to be 0.138 USD/kg, 0.132 points/kg butanol, 66.8%, 266.4 MUSD, and 2586 ton/year, respectively [190]. Similar to Bechara et al. [185], the total annual cost and environmental impact of the selected scenario showed direct associations with its exergetic efficiency [190]. This further showed the fact that exergy, economy, and environmental analyses in the separate forms could not present a comprehensive decision-making criterion. To address this issue, exergy-based economic and environmental analyses, i.e., exergoeconomic and exergoenvironmental should be applied for analyzing thermodynamic systems.

The process integration can substantially improve the renewability and sustainability levels of biorefinery systems. The process integration can be implemented in two different ways, i.e., heat integration and mass integration. The heat integration is a useful method to reduce the energy consumption, to achieve the desired utility demand targets, and to optimize the process thermal design in bioenergy systems. The most popular heat integration method is pinch technology in which the heat exchangers network is optimized through determining the maximum heat recovery potential between hot and cold streams with respect to a desired minimum temperature difference [191].

Tan et al. [138] stated that recovering the waste thermal energy of the leftover vapor in the distillation column and stillage cooling process and their use for preheating the raw material and beer could lead to an improvement in the overall exergetic efficiency of lignocellulosic bioethanol system. Ojeda et al. [163] thermally integrated the SSCF process of lignocellulosic bioethanol production plant using pinch technology. They succeeded to reduce the cooling and heating demands of the system by more than 26% and 95%, respectively, using the optimized heat exchanger network.

Using pinch technology and exergy analysis, Modarresi et al. [180] scrutinized a wheat straw-based poly-generation plant co-producing bioethanol, methane, heat, and electricity. The pinch analysis was applied to obtain the minimum steam and cooling water demands. The utilities demand could be discounted up to 40% (i.e., 45 MW) through the optimized heat exchanger network that regenerated thermal energy from steam explosion pretreatment, drying, and distillation product cooling subunits and used the recovered thermal energy to preheat the raw materials and SSF-produced mash. After identifying the optimal heat exchanger network topology using the pinch concept, exergy analysis was applied to further investigate the optimal plant. Overall, the plant optimized using the pinch technology had higher exergy efficiency than the base case due to the reductions in hot and cold utility demands [180]. Among the various subunits investigated (i.e., bioethanol production, biogas production, and CHP subunits), the bioethanol production process attained the highest exergy efficiency. This could be ascribed to the fact that the stillage stream leaving the distillation column was considered as a useful product since it was then digested in the anaerobic digestion process to produce biogas. The evolved biogas was combusted to generate electrical power in the CHP unit. In addition, intensive chemical reactions and rapid heat transfer in the CHP and biogas production subsystems could result in an increase in their irreversibility rate, collectively lowering the exergetic efficiency of these subunits [180].

Silva Ortiz et al. [177] assessed three different sugarcane-based

biorefineries using several exergetic indicators, i.e., exergy efficiency, average unitary exergy cost, exergy-based CO₂-equivalent emissions, and exergy-based renewability index. The developed biorefineries were as follows: (a) conventional first-generation bioethanol production scheme, (b) combined first- and second-generation bioethanol production plant with mass integration, and (c) combined first- and second-generation bioethanol production plant with mass-heat integration. In the second and third scenarios, the steam explosion technique was employed for pretreating the sugarcane bagasse before enzymatic hydrolysis. Based on the results obtained, the third scenario had the highest exergy efficiency (50%) with the lowest average unitary exergy cost (i.e., 1.61 USD/kJ). For all the developed schemes, the most irreversible unit was the cogeneration system accounting for 58–60% of the total exergy destruction, followed far behind by fermentation system amounting to 12–14% of the total irreversibility. The exergy-based CO₂-equivalent emissions index was lower for the third configuration (94.10 gCO₂/MJ product) in comparison with the second (108.12 gCO₂/MJ product) and first (160.56 gCO₂/MJ product) routes [177]. Despite the fact that the exergy-based renewability index for the third scenario was higher than those of the other scenarios, all the obtained renewability indices were below than unity. This in turn indicated that all the developed configurations were environmentally unsustainable. However, the third scenario could be an environmentally-friendly option if the useful exergy of the byproducts (i.e., filter cake, lignin, vinasse, and pentoses liquor) was considered [177].

4. Challenges and future directions

Overall, the exergy-based methods can be applied as effective tools to scrutinize the efficiency, productivity, envirosafety, and sustainability aspects of energy-intensive and material-consuming biofuel production systems from a thermodynamically, economically, and environmentally unbiased viewpoints. In spite of the unique conceptual features of the exergy concept in valuing and weighing energy and material flows involved in the biofuel systems in a reliable way, it cannot be regarded as a “magic wand” to resolve all the issues associated with sustainability of such complicated processes. Like the other existing sustainability assessment tools, exergy-based methods suffer from some drawbacks like the sensitivity of their outcomes to the choice of the reference state, i.e., temperature, pressure, and compositions [142]. Readers are referred to Maes and Van Passel [192] for further information concerning the pros and cons of the exergetic indices used to evaluate the sustainability aspects of bioenergy and biomaterials production processes. As a guide, the most appealing application of the exergy concept is to integrate it with real-world constraints or to consolidate it with available economic accounting and environmental impact assessment approaches for enhancing the quality of the resultant conclusions.

Exergy analysis alone used in most of the research works published in this field cannot provide useful information about the economic and environmental aspects of lignocellulosic biofuel systems. Accordingly, exergoeconomic and exergoenvironmental approaches as the most popularized methods consisting of actual economic and environmental constraints should be considered as complementary tools for analyzing lignocellulosic biofuel systems in order to make comprehensive decisions. In addition, in order to facilitate multi-objective optimization, energy-based exergoeconomic and exergoenvironmental methods introduced by Aghbashlo and Rosen [114] that bridge the objectives of both approaches concurrently can be used for exploring a global optimal point. In order to better understand biofuel production systems from thermodynamic, economic, and environmental viewpoints simultaneously, exergoeconomic and exergoenvironmental method proposed by Aghbashlo and Rosen [112] can be taken into consideration as well. Furthermore, exergy analysis accounts only for the physical flows of energy systems while disregarding their nonphysical flows. This issue can be effectively addressed using the concept of extended exergy accounting

method elaborated by Sciubba [193] in which all physical and non-physical inputs to energy systems are expressed on a common exergy basis (Joules) [7].

Universal exergy efficiency that determines the level of exergy loss (because of both irreversibility and heat loss) of a biofuel system has been used in almost all the reported studies to date. However, this indicator cannot reliably and objectively measure the exergetic effectiveness of lignocellulosic biofuel systems. To address this issue, functional exergy efficiency that measures the level of usefulness and productiveness of biofuel systems in accordance with their purpose could be regarded. Moreover, the contribution of chemical exergy to the total exergy of the streams involved in biofuel production systems was usually much higher than that of physical exergy. In addition, unlike the physical exergy, various approaches and formulas have been used for computing the chemical exergy of organic components which in turn could affect the accuracy and reliability of the obtained exergetic indicators. Accordingly, these approaches and formulas should be further assessed and the most accurate one should be introduced.

The conventional exergy analysis widely applied for analyzing lignocellulosic biofuel systems not only cannot provide information regarding the thermodynamic interactions among the components of systems but also cannot quantify the avoidable portion of the thermodynamic inefficiencies. These issues can be satisfactorily addressed using advanced exergy-based methods developed by Tsatsaronis and Morosuk [126]. Using these advanced analyses, exergy destruction along with its associated costs and environmental consequences can be fractionated into avoidable endogenous, avoidable exogenous, unavoidable endogenous, and unavoidable exogenous parts. Similarly, component-related cost and environmental impact rates of the system under investigation can be split into the above-mentioned categories. Accordingly, the quality and accuracy of the conclusions derived from exergy, exergoeconomic, and exergoenvironmental approaches can be significantly and substantially improved.

There is no unanimous consensus about terminologies used for describing the exergetic indicators used in lignocellulosic biofuel systems. The lack of standardized terminologies not only might make difficult comparisons among different studies but also might lead to misunderstanding and misinterpretation of the reported data. For example, Arredondo et al. [175] introduced a new exergetic parameter, namely "Renewability Performance Indicator", as an exergo-environmental indicator. By taking a quick glance at the paper published by Velásquez et al. [189], one could conclude that the introduced indicator could be an exergetic index, not an exergo-environmental indicator. In fact, exergoenvironmental approach is a systematic combination of the exergy concept and life cycle assessment method through the SPECO method elaborated by Meyer et al. [128]. A similar argument could be mentioned for the symbols and notations used in the exergetic formulation of biofuel systems. Therefore, future study appears merited to harmonize and standardize the terminologies, symbols, and notations used in the exergetic formulation of biofuel systems in order to facilitate understanding and interpretation of the obtained results.

The majority of the works published have focused on the mainstream processes (feedstock pretreatment and biofuel production), while a limited number of researchers have incorporated the upstream (feedstock production) and downstream (effluents remediation) processes into their analyses. Accordingly, all upstream, mainstream, and downstream processes should be considered in implementing exergy-based analyses for the evaluation of lignocellulosic biofuel systems in order to provide reliable and objective measures. A promising strategy for solving this issue is to use "exergetic life cycle assessment" method that accounts for all the exergy inputs required by a biofuel production process. Moreover, most of the research works exergetically analyzing biofuel production plants have focused on a single product objective, mainly bioethanol. However, bioethanol production as a single product from lignocellulosic biomass is not energetically efficient, economically profitable, and environmentally sound. In order to address the

shortcomings of the single-product plants, the biorefinery concept that tries to maximize energy recovery from given biomass by providing multiple biofuels and bioproducts analogous to today's petroleum refinery should be further considered.

Strictly speaking, a precise comparison of the data reported in different studies is not likely to be attained because of fundamental discrepancies in the biofuel systems modeled, processing conditions considered, exergetic formulations implemented, simulation procedures applied, assumptions made, simplifications adopted, boundaries considered, and scales used. Furthermore, the majority of the studies published in this domain have used the simulated databases for performing exergy analysis. Even though simulation studies could provide more detailed information about lignocellulosic biofuel systems, it is difficult to judge about their real-world applicability without taking into consideration experimental uncertainties and repeatability errors. Accordingly, reliable and valid experimental data should be used for simulating such processes.

Lignocellulosic biofuel systems are energy-intensive operations requiring a huge amount of utilities. Thus, such processes should be designed based on advanced heat integration methods like pinch technique with the aim to decrease their utility consumption and operating costs. In addition, advanced waste heat recovery systems should be annexed to biofuel production systems in order to boost their efficiency, productivity, envirosafety, and sustainability. Integrating freely available renewable energy sources such as solar and wind energy systems into biofuel systems could also boost these plants from thermodynamic, economic, and environmental perspectives simultaneously. In addition, the utilities consumed in biofuel production and refining processes have been taken into account as exogenous inputs in the many of the research works published. This could negatively affect the reliability and validity of the exergetic indicators determined since the thermodynamic inefficiencies associated with the utility production have been excluded from the calculation. Accordingly, future work should be directed towards developing biofuel production systems including utility production units in order to provide reliable and valid exergetic indicators.

Single pretreatment cannot achieve all the main goals of biomass pretreatment, i.e., maximizing fermentable sugars economically while minimizing the formation of inhibitors satisfactorily. In contrast with this fact, single pretreatment has been considered in almost all the investigations conducted in this subject. In spite of the fact that multiple pretreatments can make biofuel production processes more complex and expensive, future work deserves to examine such pretreatments on their exergetic indices. The main challenging issue in biomass pretreatment is the generation of some inhibitory compounds which in turn hinders the subsequent enzymatic hydrolysis and fermentation steps. However, the formation of these detrimental compounds which negatively affect the process efficiency and economic viability have not been properly considered or even irrationally overlooked in the simulation process. To resolve this issue, precise lab-based databases should be collected and used in simulating such processes in order to mimic real-world conditions as much as possible. In addition, although various pretreatment methods have been introduced and used to restructure lignocellulosic materials to date, the effects of a limited number of them on the exergetic performance indices of the resultant biofuels have been investigated in the published literature. This suggests that there is room for further investigation into the effect of various pretreatment techniques on the exergetic sustainability indicators of lignocellulosic biofuel systems.

The developed lignocellulosic biofuel systems have been exergetically analyzed at the unit-level in almost all the research works conducted in this field. In spite of the fact that investigating such complex systems at unit-level could reduce the computational efforts required, this strategy could not provide more detailed information concerning the sources of thermodynamic inefficiencies occurred. However, component-level analysis enables conducting performance

analysis of biofuel plants with the added value of detailed thermodynamic modeling for all the components involved in the process. In addition, the variations in feedstocks compositions have rarely been considered in the published papers. Simple chemical formulas have usually been taken into consideration for the biomass components as well. In order to enhance the realizability of the simulated biofuel systems in real-world situations, feedstocks variations and their chemical formulas should be further explored. Finally, it could be concluded that exergy-based methods have the potential to be used in almost every area of the lignocellulosic biofuel industry more effectively and informatively than their current status.

5. Concluding remarks

This paper is aimed at thoroughly reviewing and critically discussing the effects of various pretreatment methods on the exergetic performance indices of lignocellulose bioconversion into biofuel. The following main concluding remarks could be drawn from the works published in this domain:

- The pretreatment process is the main cause of exergy destruction in lignocellulose bioconversion into biofuel.
- Unlike dilute acid and organosolv pretreatment methods, steam explosion and microbial pretreatment techniques appear to be efficient approaches from the exergetic viewpoint.
- Combining exergetically-efficient pretreatment techniques can lead to higher exergetic efficiency compared with single original methods.
- The majority of exergy destruction occurred in the pretreatment process is associated with the heating of the process streams.
- Exergy destruction rate of lignocellulose pretreatment process can be substantially prevented through its technological improvements and innovations.
- There is a direct relationship between the lignocellulose composition and exergetic efficiency of the pretreatment process. The lower the lignin, the higher the exergy efficiency of the lignocellulose pretreatment process is.
- Recovering chemical exergy of the remained waste lignin stream through its direct combustion or gasification can boost the exergetic performance of lignocellulosic biofuel systems.
- Utilizing the stillage stream leaving distillation tower as biogas feedstock can improve the lignocellulosic biofuel production processes exergetically.
- Formation of inhibitory compounds can deteriorate the exergetic efficiency of lignocellulose pretreatment process due to their negative effects on enzyme activity.
- The overall exergetic efficiency of lignocellulose bioconversion into biofuel can be enhanced by the use of SSF and SSCF approaches.
- The multi-generation or biorefinery concept can promisingly improve the exergetic efficiency of lignocellulosic biofuel systems.
- Heat integration and waste stream recycling can significantly boost the lignocellulosic biofuel production processes from the exergetic standpoint.
- Exergoeconomic and exergoenvironmental approaches can provide more informative results regarding lignocellulose bioconversion into biofuel in comparison with the conventional exergy analysis.
- Complementary advanced exergetic approaches should be applied for improving the sustainability of lignocellulosic biofuel production processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates



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ABSTRACT

A key challenge for black soldier fly larvae (BSFL) treatment is its variable reliability and efficiency when applied to different biowastes. Similar to other biowaste treatment technologies, co-conversion could compensate for variability in the composition of biowastes. Using detailed nutrient analyses, this study assessed whether mixing biowastes to similar protein and non-fibre carbohydrate (NFC) contents increased the performance and reduced the variability of BSFL treatment in comparison to the treatment of individual wastes. The biowastes examined were mill by-products, human faeces, poultry slaughterhouse waste, cow manure, and canteen waste. Biowaste formulations had a protein-to-NFC ratio of 1:1, a protein content of 14–19%, and a NFC content of 13–15% (dry mass). Performance parameters that were assessed included survival and bioconversion rate, waste reduction, and waste conversion and protein conversion efficiency. In comparison to poultry feed (benchmark), vegetable canteen waste showed the best performance and cow manure performed worst. Formulations showed significantly improved performance and lower variability in comparison to the individual wastes. However, variability in performance was higher than expected for the formulations. One reason for this variability could be different fibre and lipid contents, which correlated with the performance results of the formulations. Overall, this research provides baseline knowledge and guidance on how BSFL treatment facilities may systematically operate using biowastes of varying types and compositions.

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1. Introduction

The treatment of biowaste by black soldier fly larvae (BSFL) is an emerging waste management technology (Čičková et al., 2015; Gold et al., 2018b; Zurbrügg et al., 2018). This process converts waste into larval biomass, reduces waste dry mass and generates the raw materials for the production of soil conditioner and fertilizer (Setti et al., 2019), lubricants and biodiesel (Leong et al., 2016; Li et al., 2011), pharmaceuticals (Vilcinskis, 2013)

and animal feeds (Barragán-Fonseca et al., 2017; Makkar et al., 2014; Sánchez-Muros et al., 2014; Wang and Shelomi, 2017).

A key challenge for BSFL biowaste treatment is its variable reliability and efficiency. Currently, performance—as measured by bioconversion rate, larval weight, and larval biomass composition (e.g. protein and lipid content)—varies both when using the same type of biowaste (e.g. different vegetable wastes) and when treating different types (e.g. vegetable waste compared to mill by-products) (as summarised by Gold et al., 2018a). The sustainable operation of BSFL biowaste treatment facilities likely depends on the use of different waste types of varying quantity and composition. Homogenous or highly nutritious biowastes such as food industry

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by-products (e.g. bread and mill by-products) or canteen and restaurant wastes are often already used elsewhere (e.g. as animal feeds and for energy recovery). In addition, poor waste management practices, such as a lack of organic waste segregation, incentives for landfill disposal, and complex collection and transport logistics, often hinder access to high-quality wastes. Importantly, the use of different wastes from different sources will adversely affect the day-to-day operation (e.g. running over or under capacity) of BSFL treatment facilities with concurrent impacts on BSFL growth and waste treatment performance. This affects the sustainability (Mertenat et al., 2019; Smetana et al., 2019, 2016) and scalability of this technology and the down-stream application of products (e.g. live-feed for aquaculture) (Gold et al., 2018a).

Similar to other animal species used for production, the nutrient content of biowaste is hypothesised to have the largest influence on performance under similar operating conditions (e.g. feeding rate, larval density and temperature) (Nguyen et al., 2013; Ooninx et al., 2015a; Tindler et al., 2017). Factors determining the nutritional quality of biowaste include the density, ratio and type of nutrients it contains. Nutrients considered to be decisive include the sum of all macronutrients, organic matter, protein, non-fibre carbohydrates (NFC), fibre and lipids (Barragán-Fonseca et al., 2018a, 2018b; Gold et al., 2018a; Lalander et al., 2018). For example, manures are typically low in organic matter and fibre, restaurant and canteen wastes are rich in NFC and lipids, and fruit and vegetable wastes are low in proteins (Gold et al., 2018a). In response to these different nutritional conditions, fly larvae adjust their growth rate and nutrient accretion, with the main goal of accumulating enough reserves to complete the non-feeding life-stages of metamorphosis and adulthood (Danielsen et al., 2013; Gold et al., 2018a). Similar to other animals, an insufficient amount or an unfavourable ratio of nutrients prolongs development, reduces growth and related biomass production, and limits the efficiency of waste reduction (Danielsen et al., 2013).

BSFL feeding experiments and assessments of the midgut (the main organ involved in digestion) suggest that protein, NFC and lipids are highly digestible by BSFL and, therefore, their supply enhances performance (Barragán-Fonseca et al. 2018a; Beniers and Graham, 2019; Bonelli et al., 2019; Lalander et al., 2018). In contrast, fibre including cellulose and lignin are less digestible and tend to decrease larval growth rates (Liu et al., 2018). Among these nutrients, several studies have concluded that the protein (and amino acid) content of biowastes is most important. For example, Lalander et al. (2018) concluded that protein has the greatest impact on the development time to prepupa. Beniers and Graham (2019) also observed that protein has greater importance for larval weight than NFC. As amino acids allow larvae to proceed to the next instar (Gold et al., 2018b) and BSFL accumulate lipids during later instars (as energy reserves for later life-stages) (Liu et al., 2017), waste with a greater protein content can also increase larval lipid content. Research on the common fruit fly larvae (*Drosophila melanogaster*) indicates that fly larvae control their feeding with respect to protein and may overfeed on other nutrients such as NFC (Almeida de Carvalho and Mirth, 2017). This further emphasises that protein is so essential for development. For BSFL, protein supply may influence larval weight and lipid content when receiving low-protein and high-carbohydrate feeds as carbohydrates may be converted into body lipids (Pimentel et al., 2017; Spranghers et al., 2017). By contrast, lipids in biowaste can impede or promote larval development. Nguyen et al. (2013) suspected that excess lipids in fish offal may decrease larval development; however, results from Ooninx et al. (2015a) for food industry by-products and from Nguyen et al. (2013) for liver and kitchen waste suggest that lipids can also increase performance as the energy density of the feed is increased (Brouwer, 1965). Ooninx et al. (2015a) also observed high feed-conversion efficiencies for

feeds with a high lipid and protein content. The ash content of biowaste positively correlates with larval ash content (Spranghers et al., 2017) and negatively with bioconversion rates (Lalander et al., 2018).

A reliable high-performance BSFL treatment for biowaste requires strategies that build on existing knowledge of the influence of variable waste nutrient compositions on larval performance. Similar to other biowaste treatment options such as anaerobic digestion or composting, co-conversion, i.e. the treatment of a mixture of several biowastes, could increase performance and reduce variability (Li et al., 2009). Specifically, mixing multiple biowastes can provide a more nutritious and balanced feed for larval growth. Rehman et al. (2017) and Nyakeri et al. (2019) observed that mixing cow and human manure with food wastes and food production by-products (e.g. soybean curd residue and banana peels) increased larval weight compared to these individual wastes. Similar to composting (i.e. carbon-to-nitrogen ratio) and anaerobic digestion (e.g. methane potential), a systematic approach to co-conversion based on biowaste nutrients could compensate for the variability in biowaste composition.

The formulation of appropriate biowaste mixtures based on nutrients requires the reliable determination of composition using parameters that are relevant for BSFL growth. Such an approach—and also incorporating cost considerations—is widely applied for feed formulation in commercial livestock production (McDonald et al., 2011). Barragán-Fonseca et al. (2018b) were the first to formulate feeds for BSFL with similar protein and NFC contents using combinations of food industry by-products; however, larvae still performed significantly different between these waste mixtures. These authors concluded that nutrient quality (e.g. amino acid content, type of NFC and fibre) must be considered to reduce this variability. Previous studies have not considered this sufficiently when determining biowaste composition. For example, biowaste has been characterised based on its carbon, nitrogen and protein content (using generic nitrogen-to-protein conversion factors) or the sum of other nutrients to estimate its NFC content (Barragán-Fonseca et al. 2018b; Lalander et al., 2018). Nitrogen may not, however, be an accurate measure as it may also include non-protein nitrogenous compounds of low nutritional value such as urea, ammonia, nitrate and nitrite (Chen et al., 2017). Similarly, carbon includes digestible fibre such as cellulose and lignin. The importance of these compounds is difficult to assess as the extent to which non-protein nitrogen and fibre are used by the gut microbes of BSFL is not yet known. Thus, generic nitrogen-to-protein conversion factors may overestimate protein content. In addition, carbon may greatly overestimate NFC when the ash, lipid, protein and fibre content is subtracted from 100% rather than the sum of digestible carbohydrates such as glucose and starch.

This study aimed to assess the performance of BSFL treatment as applied to different waste formulations prepared from six types of biowaste following the determination of their respective nutritional composition. It was hypothesised that biowaste formulations with a similar protein and NFC content would increase performance and reduce variability in comparison to the individual wastes. Thereby, this research sought to generate knowledge and advice on how BSFL treatment facilities may best operate with biowaste of varying type and composition.

2. Materials and methods

2.1. Biowastes used in the feeding experiments

Six different types of biowaste were used in feeding experiments, namely mill by-products, human faeces, poultry slaughterhouse waste, cow manure, and canteen and vegetable canteen

waste. Two different batches of human faeces were used as BSFL treatment performance was unexpectedly high with the first batch. Mill by-products were obtained from a Swiss wheat-milling company. The human faeces were obtained from dry toilets separating urine and faeces at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) in Dübendorf, Switzerland. The poultry slaughterhouse waste consisted of discarded body parts (feet, head, liver, stomach, and intestine) from a poultry slaughterhouse of Micarna, a leading meat processing company in Switzerland. The cow manure was obtained from a farm near Zurich, Switzerland. The vegetable waste was obtained from the Eawag canteen and consisted of a mixture of vegetables with and without salad dressing. The difference between the vegetable canteen waste and the canteen waste was that the latter had the addition of sausage and other meat offal.

Following their collection, the wastes were homogenised with a kitchen blender to mimic the pre-treatments used in BSFL treatment facilities (Dortmans et al., 2017), and moisture content was determined in duplicate with a halogen moisture analyser (BM-65, Phoenix instrument, Garbsen, Germany) The wastes were then portioned into plastic bags, frozen and stored at -20°C until the start of the feeding experiments (Diener et al., 2009; Lalander et al., 2018; Myers et al., 2008; Nguyen et al., 2015). The wastes were thawed at 4°C for 24 h and brought to the experimental temperature of 28°C prior to each feeding experiment.

2.2. Composition of the experimental biowastes

Oven-dried (105°C) wastes and poultry feed (used as a high-performance benchmark) were analysed for gross nutrient composition, moisture content and pH using standard procedures (AOAC 1997; Van Soest et al., 1991). The second batch of human faeces was only analysed for protein, lipid and organic matter content. Moisture and organic matter were determined in quintuplicate with an automatic thermogravimetric determinator (TGA-701, Leco, St. Joseph, MI, USA). Nitrogen content was determined in triplicate using a C/N analyser (Type TruMac CN, Leco Cooperation, St. Joseph, MI, USA). Fibre fractions including neutral (NDF) and acid detergent fibre (ADF) were assessed in duplicate using a fibrebag system (Fibretherm, Gerhardt Analytical Systems, Germany) according to methods 6.5.1 and 6.5.2 of the Association of German Agricultural Analytic and Research Institutes (Naumann et al., 2012). Lipids were analysed from ether extracts from freeze-dried samples by Eurofins Scientific, Schönenwerd, Switzerland, according to Regulation (EC) No 152/2009 (European Commission (EC) 2009). The extraction solvent used was petroleum ether at $40\text{--}60^{\circ}\text{C}$ following hydrolysis with 3 M hydrochloric acid. pH was analysed with a portable meter and pH probe (HQ40d, Hach Lange GmbH, Switzerland).

Amino acids were analysed in triplicate in freeze-dried samples (Çevikkalp et al., 2016; Kwanyuen and Burton, 2010; White et al., 1986; Zhang et al., 2009). The samples were hydrolysed at 110°C for 16–24 h with 5 M sodium hydroxide (tryptophan) or 6 M hydrochloric acid containing 0.1% phenol (for all other amino acids). For tryptophan, the hydrolysed samples were subsequently neutralised, diluted and analysed by RP-HPLC-FLD using an Agilent 1200 series LC-system including a fluorescent detector (FLD) (Agilent Technologies, Santa Clara, USA) and a C18 analytical Pico Tag amino acid analysis column (3.9×150 mm) in combination with a Nova-Pak C18 guard column (3.9×20 mm) (Waters AG, Baden, Switzerland). The fluorescence detector was operated at an excitation wavelength of 280 nm and an emission wavelength of 340 nm. For all other amino acids, the hydrolysed amino acids were transformed into their phenylthiocarbonyl derivatives with phenyl isocyanate and analysed by RP-HPLC using an Agilent 1100 series LC-system including a diode array detector (DAD) operated at

254 nm (Agilent Technologies, Santa Clara, USA) and the same column as above. α -methyl-DL-tryptophan and L-norleucine was used as an internal standard. The HPLC results were corrected with the respective recovery rates of the internal standards. Only results with an internal standard recovery $>70\%$ were considered further. More details on amino acid analyses are included in the [Supplementary Material](#).

Glucose and starch were determined in triplicate using freeze-dried samples with a commercial enzyme assay (Megazyme, 2019). In brief, glucose was removed from each sample with ethanol. Then, following centrifugation, the glucose concentration was determined in the supernatant and the pellet was used for starch analysis. Resistant starch was converted into maltodextrins in potassium hydroxide. Amylase and amyloglucosidase were used to hydrolyse the remaining starch into glucose. Glucose was then quantified with a spectrometer (Genesys 10S, Thermo Fisher Scientific, USA) in comparison to a glucose standard.

Protein was calculated by multiplication of the nitrogen results with specific conversion factors, namely 5.6 for poultry feed (based on results for maize and soybean meal) (Sriperm et al., 2011), 4.3 for cow manure (Chen et al., 2017), 5.4 for mill by-products (based on results for cereals) (Mariotti et al., 2008), 5.4 for canteen waste, 5.0 for vegetable canteen waste, and 5.0 for poultry slaughterhouse waste (based on results for meat, fish, cereals and vegetables) (Mariotti et al., 2008). No conversion factors were available for human faeces and so this was estimated as the ratio of the sum of all amino acids divided by the nitrogen content. Samples of human faeces (mixed with sawdust) (Nyakeri et al., 2019) and pit latrine sludge provided by Sanergy, Nairobi, Kenya, were also included in the analysis to cover the typical variability of human faeces and faecal sludge (Gold et al., 2017b, 2017a). Caloric content was estimated by multiplying the mean results for lipids, NFC and protein with their gross caloric content of 9.4, 5.4, and 4.1 kcal/g, respectively (Merrill, 1973; Wu, 2016). Hemicelluloses were determined as the difference between NDF and ADF. ADF was assumed to be a reliable estimate of cellulose and lignin content. The sum of glucose and starch was assumed to reflect the total NFC.

2.3. Formulation of the biowaste mixtures

For the feeding experiments, either the six individual wastes or six mixtures of the wastes (Table 1) were used. The mixtures were based on the composition of the biowastes and aimed to achieve a protein-to-NFC ratio of approximately 1:1 (DM) considering the low content of NFC (Barragán-Fonseca et al. 2018b; Cammack and Tomberlin, 2017). In contrast to Barragán-Fonseca et al. (2018b), no high-value ingredients such as sunflower oil or cellulose were added to balance the unavoidable variability in fibre and lipid content as this is not typically practicable for cost reasons.

The formulations were generated using Visual Basic for Applications in Microsoft Excel and were always based on mill by-products complemented with two to three other wastes. The formulations were prepared from thawed wastes on the day of feeding and were mixed thoroughly. Formulation 3 was prepared with two different batches of human faeces based on the nutrient composition of the first batch. These batches appeared to have a similar composition based on their lipid (20.9 and 19.3% DM), crude protein (20.5 and 21.8% DM) and ash (13.7 and 15.8% DM) content. In the following discussions, the two human faeces formulations are referred to as formulation F3 (1) and formulation F3 (2), respectively.

Table 2 shows the realised nutrient composition of the six formulations, calculated based on the proportions shown in Table 1 and the results of the analyses of the individual biowastes. The

Table 1
Dry mass proportion of individual wastes in the biowaste formulations (F1–F6).

Formulation	F1	F2	F3	F4	F5	F6
Mill by-products	23	37	51	60	33	65
Canteen waste	–	7	–	20	33	–
Human faeces	16	–	14	20	–	–
Poultry slaughterhouse waste	–	–	–	–	–	22
Cow manure	11	35	34	–	–	12
Vegetable canteen waste	50	21	–	–	33	–

Table 2
Mean dry mass nutrient contents of the different biowaste formulations (F1–F6) based on the percent dry mass proportion of individual wastes in the biowaste formulations (Table 1) and the composition of their constituent wastes (Table 3).

	Proteins	Non-fibre carbohydrates	Fibres	Lipids	Organic matter	Moisture content
Formulation 1 (F1)	13.8	13.6	38.5	19.0	90.5	80.8
Formulation 2 (F2)	14.0	13.0	48.7	11.2	88.9	81.5
Formulation 3 (F3)*	14.0	12.7	50.1	5.9	88.4	79.9
Formulation 4 (F4)	19.1	15.8	43.8	13.0	92.1	72.5
Formulation 5 (F5)	19.6	15.4	39.8	22.3	93.1	76.9
Formulation 6 (F6)	19.0	15.4	45.8	12.0	92.1	73.9
Mean	16.6 (2.9)	14.3 (1.4)	44.5 (4.7)	13.9 (5.9)	90.7 (2.2)	77.6 (3.7)

In parentheses: standard deviation.

* Formulation (3) 1.

formulations contained between 14 and 19% DM of protein and between 13 and 15% DM of NFC.

2.4. Feeding experiments

Feeding experiments were designed as outlined by Lalander et al. (2018) and Liu et al. (2018). Three individual sets of experiments with different batches of larvae were carried out. First with the individual wastes (experiment 1) and then with formulations 1 to 3 (experiment 2) and finally with formulations 4 to 6 (experiment 3). Larvae were obtained from the BSFL research colony at Eawag maintained according to Dortmans et al. (2017). The BSFL hatched within 24 h and were first fed *ad libitum* with poultry feed (UFA 625, UFA AG, Switzerland) for 12–14 d until they reached a mean individual weight of 3.8 ± 0.5 mg DM. The larvae had a similar content of carbon (55–56% DM), protein (36–38% DM) and ash (13–14% DM) across the experiments (Section 2.5). From these populations, 4 to 5 × 80 randomly selected larvae per treatment were manually counted and placed in plastic containers (7.5 cm diameter, 11 cm height) with individual wastes or waste formulations, giving a larval density of approximately 2 larvae/cm². Larvae were also freeze-dried for the analysis of larval composition. The experimental containers were covered with paper towels or mosquito nets and randomly arranged in a climate chamber (HPP 260, Memmert GmbH, Germany) providing a steady microclimate of 28 °C and 70% relative humidity. Feed was provided every 3 d. Considering the increase in the nutrient requirements of BSFL with growth (Nyakeri et al., 2019), the feeding rate was increased over the 9-day experiment from 15 to 25 and 40 mg DM/larva per day on days 0, 3 and 6, respectively. Due to the expected improved nutritional quality of the formulations, the feeding rate was lowered by 25% for each feeding in experiment two and three.

In contrast to previous studies, which have typically terminated experiments after the first appearance of prepupae (Bosch et al., 2019; Lalander et al., 2018), all experiments were terminated after 9 d, before the appearance of prepupae. Prepupae are richer in chitin and lipids and, therefore, not optimal for animal feed applications (Nyakeri et al., 2019). Larvae were manually separated from the residue, cleaned with tap water, and dried with paper towels. Subsequently, larvae were manually counted, weighed

and freeze-dried. Residues were dried in a laboratory oven at 80 °C. Both the dried larvae and the residues were then weighed and stored at 4 °C.

2.5. Analysis of larval composition

The dried larvae were milled and treatment replicates were combined equally by mass. Samples were then analysed in triplicate for DM, carbon and nitrogen content using the same analysers as for the wastes. Larval protein content was calculated as the nitrogen content × 4.67 following Janssen et al. (2017). Carbon content was divided by the total amount of organic matter; as lipids typically contain more carbon than proteins and carbohydrates (Brouwer, 1965), the ratio of carbon-to-organic matter was used as an indicator of larval lipid content.

2.6. Determination of the performance of BSFL treatment

Larval counts, and residue and larvae dry weights, were used to calculate five BSFL performance parameters. First, larval survival rates were calculated using Eq. (1) as the ratio of larvae at the end (larvae_{end}) and the beginning (larvae_{beg}) of the experiments (Van Der Fels-Klerx et al., 2016).

$$\text{Survival rate (\%)} = \frac{\text{larvae}_{\text{end}}}{\text{larvae}_{\text{beg}}} \times 100 \quad (1)$$

Waste reduction was calculated using Eq. (2) as the ratio of residue dry mass (residue_{mass}) to the dry mass of total feed (feed_{mass}) provided (Diener et al., 2009):

$$\text{Waste reduction (\% DM)} = \left(1 - \frac{\text{residue}_{\text{mass}}(\text{g})}{\text{feed}_{\text{mass}}(\text{g})}\right) \times 100 \quad (2)$$

The bioconversion rate was calculated using Eq. (3), for which the larval dry weight gain (larval_{gain}) was calculated as the difference between the final larval dry weight and the initial larval dry weight multiplied by the number of larvae at the end of the experiment:

$$\text{Bioconversion rate (\% DM)} = \frac{\text{larvae}_{\text{gain}}(\text{g})}{\text{feed}_{\text{mass}}(\text{g})} \times 100 \quad (3)$$

Waste conversion efficiency (Liu et al., 2018), also called efficiency of conversion of ingested/digested food (Diener et al., 2009; Oonincx et al., 2015b), was calculated using Eq. (4):

Waste conversion efficiency (% DM)

$$= \frac{\text{larvae}_{\text{gain}}(\text{g})}{\text{feed}_{\text{mass}}(\text{g}) - \text{residue}_{\text{mass}}(\text{g})} \times 100 \quad (4)$$

Finally, the protein conversion efficiency was calculated using Eq. (5) as the ratio of the amount of larval protein accumulated (protein_{gain}) to feed provided (feed_{mass}). Larval protein accumulated was calculated as the difference between the amount of final larval protein and the initial larval protein multiplied by larvae_{end}. The amount of larval protein was calculated by multiplying the larval protein content with the larval weight:

$$\text{Protein conversion efficiency (\% DM)} = \frac{\text{protein}_{\text{gain}}(\text{g})}{\text{feed}_{\text{mass}}(\text{g})} \quad (5)$$

2.7. Performance benchmark

As in previous research, poultry feed (60% moisture content) was fed to larvae in parallel to the individual biowastes and biowaste formulations as a high-performance benchmark (Lalander et al., 2018). As shown in Fig. 1, the results for poultry feed varied between experiments but no single experiment stood out as being different across all of the performance parameters. Even though larvae had a similar weight and composition at the start of the experiment, variability between experiments could be due to differences in age, feeding rates or other confounding factors (e.g. differences in airflow in the climate chamber due to varying numbers of containers).

To ensure a consistent basis for comparison between the three experiments, and between the individual wastes and waste formulations, performance parameters were also expressed as percentage differences (Fig. 1) in comparison to the results for the poultry feed using Eq. (6). For this, the results for each performance parameter (Performance_{treatment}) were subtracted from the median result obtained using the poultry feed (performance_{benchmark}) over all three experiments:

Performance in % to benchmark

$$= \frac{\text{performance}_{\text{treatment}} - \text{median performance}_{\text{benchmark}}}{\text{median performance}_{\text{benchmark}}} \times 100 \quad (6)$$

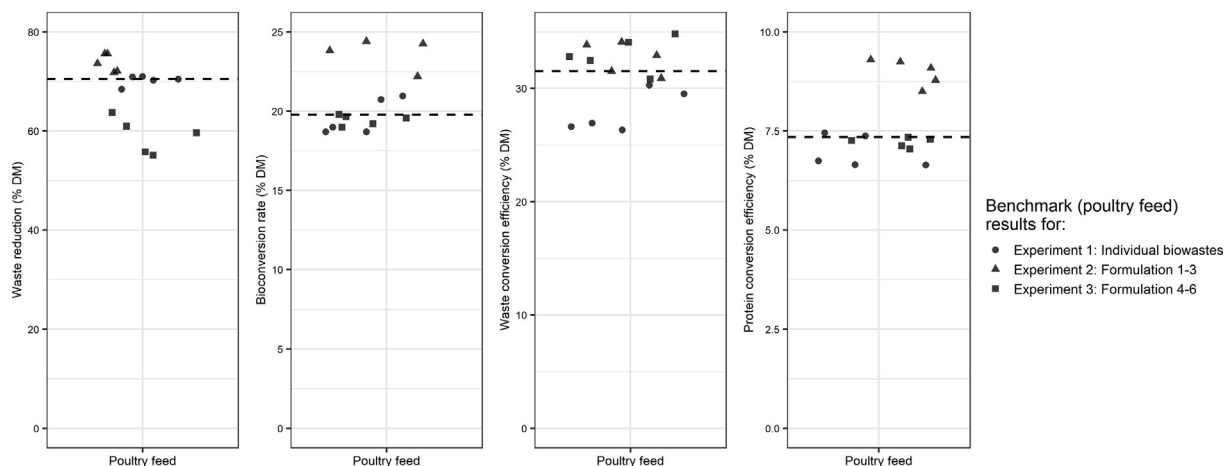


Fig. 1. Performance of BSFL fed on poultry feed used as a high-performance benchmark in the three experiments. Medians are shown as dashed lines. Performance results of the biowastes and formulations were expressed relative to these medians using Eq. 6.

Even though all of the parameters were corrected by the mass of total feed provided, variations in feeding rate, which differed between experiments, could influence performance results. Therefore, poultry feed and mill by-products were also fed to larvae at two different feeding rates: 27 mg DM/larva per day as used in experiment 1 and 20 mg DM/larva per day as used in experiments 2 and 3. This comparison, included in Supplementary Fig. S1, did not reveal an influence of feeding rate on performance, thus justifying the comparisons across the experiments.

2.8. Data analyses and statistics

Data were analysed using R software and RStudio version 1.1.463 (RStudio Inc., Boston, MA, USA). The mean, median, standard deviation, and range (difference of maximum and minimum) of the biowaste composition and performance parameters were calculated. Significance of differences in mean nutrient composition and mean performance parameters between the individual wastes and the waste formulations were tested using analysis of variance (ANOVA) followed by pairwise Tukey post-hoc comparisons. Due to the small size sample size per group ($n = 3-5$), normality and homogeneity of variance were assessed visually by residuals versus fits and Q-Q plots (Ricci et al., 2019). These graphs are shown in Supplementary Figs. S2–S4. A conservative p-value of <0.01 was chosen to declare significance due to the small sample size per group, which could lead to misinterpretation of model assumptions. The Mann–Whitney U test ($p < 0.05$) used to identify significant differences between the distributions of performance parameters of all the individual wastes ($n = 29$) in comparison to all the waste formulations ($n = 29$). The Levene and Shapiro–Wilk test ($p < 0.05$) identified that the data in those two groups violated the assumptions for parametric tests. Following visual assessment of normality (Supplementary Fig. S5), Pearson correlation coefficients ($p < 0.01$) were also calculated to identify linear dependencies between biowaste composition and feeding experiment results.

3. Results and discussion

3.1. Biowaste composition

Nutrient composition varied significantly between the biowastes (Table 3). The results for amino acids are included in Supplementary Table S1. The biowastes showed large variability

Table 3
Mean nutrient composition of individual biowastes as percent of dry mass, moisture content in percent, pH, and caloric content as kcal per 100 g dry biowaste.

Wastes	pH	Moisture content	Protein	Non-fibre carbohydrates			Fibre Total	Cellulose & lignin	Hemicellulose	Lipids	Organic matter	P:NFC ratio	Caloric content
				Total	Glucose	Starch							
Mill by-products	6.2 (0.1)	70.0	14.5 ^d (0.3)	23.2 ^b (0.2)	1.7 ^b (0.0)	21.2 ^b (0.6)	51.7 (0.9)	22.1 (1.0)	29.6 (1.9)	3.0	93.8 ^c (1.3)	1:2	211
Canteen waste	4.3 (0.0)	74.0 (1.2)	32.2 ^b (0.8)	7.5 ^d (0.7)	3.5 ^d (0.4)	4.0 ^d (0.4)	36.2 (1.4)	22.8 (0.6)	13.4 (0.9)	34.9	93.0 ^c (0.7)	4:1	501
Human faeces (1)	6.0 (0.0)	76.7 (0.9)	20.1 ^c (0.9)	1.7 ^e (0.1)	1.0 ^{bc} (0.0)	0.7 ^e (0.1)	27.9 (0.6)	19.5 (0.3)	8.4 (0.6)	20.9	86.4 ^b (0.3)	12:1	288
Poultry slaughterhouse waste	5.7 (0.1)	66.7 (1.2)	37.3 ^c (0.5)	0.3 ^e (0.1)	0.2 ^d (0.1)	0.1 ^c (0.0)	20.8 (1.9)	9.3 (0.9)	11.5 (2.7)	42.9	94.0 ^c (1.3)	152:1	557
Cow manure	7.2 (0.1)	87.0 (0.2)	11.1 ^c (0.4)	1.8 ^e (0.6)	0.7 ^{cd} (0.3)	1.0 ^c (0.4)	58.4 (0.4)	40.9 (1.7)	17.4 (1.2)	4.4	80.7 ^a (0.5)	7:1	96
Vegetable canteen waste	3.8 (0.0)	82.7 (0.1)	12.1 ^c (0.1)	15.5 ^c (0.9)	3.7 ^b (0.3)	11.6 ^c (0.6)	31.5 (1.8)	24.0 (1.5)	7.5 (0.3)	28.9	92.4 ^c (0.5)	1:1	404
Mean	5.5 (1.3)	74.5 (10.0)	21.2 (10.2)	8.3 (9.2)	1.8 (1.5)	6.4 (8.4)	37.7 (14.5)	23.1 (10.2)	14.6 (8.2)	22.5 (16.3)	90.1 (5.4)	29:1	343(177)
Poultry feed (benchmark)	5.7 (0.0)	60.0	19.1 ^c (0.7)	28.5 ^b (0.8)	0.5 ^{cd} (0.2)	27.5 ^a (1.4)	22.0 (1.0)	8.6 (0.0)	13.5 (1.1)	4.8	98.2 ^{ab} (4.0)	1:2	274

In parenthesis: standard deviation for samples where $n \geq 3$ and differences between analyses where $n = 2$.

* results with no shared letter are significantly different from each other.

** P:NFC = ratio of protein to non-fibre carbohydrates (NFC).

*** gross caloric content of protein, NFC, and lipids.

with respect to protein content, which was highest in poultry slaughterhouse waste, canteen waste and human faeces, and lowest in cow manure, vegetable canteen waste and mill by-products. Protein quality may also differ. In contrast to the other wastes, the protein in human faeces and cow manure was likely protein from gut microbial biomass (Rose et al., 2015).

This was the first study in which nitrogen-to-protein conversion factors were determined for human faeces and faecal sludge. Human faeces collected in Zurich and pit latrine sludge collected in Nairobi had conversion factors of 3.9 and 3.8, respectively. These conversion factors are comparable to those for animal manures in the range of 2.8–4.3 (Chen et al., 2017). In comparison, human faeces collected in Nairobi had less non-protein nitrogen, with a conversion factor of 5.2. Potential reasons for this difference could be the differing diets between the residents of Zurich and Nairobi (Rose et al., 2015) or storage conditions (e.g. temperatures) leading to the volatilisation of nitrogen. Overall, these results confirm that multiplying nitrogen results with the generic factor of 6.25 (i.e. the inverse of the mean nitrogen content of protein) can greatly overestimate true protein (i.e. amino acid) content (Mariotti et al., 2008). This is well established but has not been implemented even in recent BSFL research (Lalander et al., 2018; Liu et al., 2018).

Wastes were low in glucose, starch and total NFC. NFC was highest in the mill by-products and vegetable canteen waste. The addition of meat to the vegetable canteen waste increased protein content from below 15 to over 30% DM but concurrently decreased NFC content by half. Cow manure, human faeces, and slaughterhouse waste had almost no NFC. This was expected as animal tissue contains only very small amounts of glycogen and most NFC is digested or fermented in the gut of humans and animals (Riesenfeld et al., 1980). The sum of glucose and starch was much lower than when NFC was calculated as the difference between DM and ash, protein, fibre, and lipids. For example, the calculated value for human faeces was 17% DM compared to 1.7% DM for glucose plus starch (Rose et al., 2015; Spranghers et al., 2017). This indicates that there are either large amounts of non-sugar-non-starch-non-fibre organic matter or that there is an accumulation of analytical error in the gross nutrient measurements, or both. Overall, in the present study, low NFC was the reason why the protein-to-carbohydrate ratios in the waste formulations did not exceed 1:1 and that the mean NFC contents did not exceed 14% DM. The corresponding values described by Barragán-Fonseca et al. (2018b) and Cammack and Tomberlin (2017) were 1:1 to 1:2 and 21–30% DM, respectively.

The content of lipids, fibre and ash also varied among the wastes. Poultry slaughterhouse waste had a high lipid content and low ash and fibre content; the opposite was true for cow manure and mill by-products. The addition of meat to the canteen waste markedly increased the lipid content, while both of the canteen wastes were low in ash. Also, both batches of human faeces were rich in lipids, with values exceeding 20% DM. These results are high considering values ranging from 2 to 21% DM have been reported in the literature. The lipid content of the human faeces and pit latrine sludge samples collected in Nairobi were 9.4 and 16.6% DM, respectively. This suggests that the amount of lipids in faecal sludge can vary depending on management practices (e.g. residence time in the containment and the addition of sawdust) (Gold et al., 2017b), the presence of unabsorbed lipids, endogenous lipid losses (e.g. bile) and microbial processes (Aylward and Wood, 1962; Rose et al., 2015). Overall, the data show that the cow manure, human faeces, and poultry slaughterhouse wastes had low amounts of digestible nutrients and high protein-to-NFC ratios, whereas both the canteen wastes were rich in digestible nutrients and had a high caloric content. However, it is unknown how much of this energy can be harnessed by the fly larvae. Similar to mill by-products, the vegetable canteen waste was balanced or slightly

NFC biased with proteins and NFC ratios of 1:1 and 1:2, respectively. Thus, these wastes were expected to perform best in feeding experiments when offered alone (Barragán-Fonseca et al. 2018b; Cammack and Tomberlin, 2017). For the other biowastes, mixing those with complementary nutrient compositions was expected to be advantageous.

3.2. Treatment performance of individual biowastes

All individual biowastes supported the development of BSFL (Table 4). The mean survival rates were 90–99% and were not significantly different between the biowaste types. They were also comparable to those found in previous research, where survival rates were shown to be above 80% (summarised by Rehman et al., 2017). Lalander et al. (2018) reported survival rates for different biowastes in the range of 81 to 100%, except for wastewater sludge which supported survival rates of only 39 to 81%. These results suggest that the experimental conditions applied in the present study were suitable and confirms that BSFL can develop on a wide variety of biowastes. That said, BSFL treatment performance varied widely between the different biowastes (Fig. 2). Mean performances values were significantly different among most of the biowastes and those that performed best were not always the same for each performance parameter. Waste reduction and protein conversion efficiency were lower for all of the wastes in comparison to the poultry feed, and cow manure had the poorest performance in all of the performance parameters.

Using vegetable canteen waste and mill by-products resulted in the highest waste reduction even though values were still 17 to 20% lower than for the poultry feed. This could be due to the high NFC content of these two wastes, which are easily digested and absorbed into the haemolymph of fly larvae (Bonelli et al., 2019; Pimentel et al., 2018). However, comparison of the waste reduction and larval weight results of mill by-products and human faeces demonstrate that this higher waste reduction did not necessarily result in higher larval weight. The level of waste reduction in the mill by-products exceeded the sum of easily digestible nutrients which are assumed to be reflected by the sum of protein, NFC and lipids (Table 3) based on the morphofunctional features of the BSFL midgut reported by Bonelli et al. (2019). This suggests that some fibre, likely hemicelluloses, were decomposed during

BSFL treatment. Gold et al., 2018b also observed some decomposition of hemicelluloses in BSFL treatment with artificial diets, but this happened to a much smaller extent than that reported by Rehman et al. (2017) with cow manure. Such differences in digestibility have not yet been considered in biowaste formulation and could lead to unexpected performance results when designing formulations based on the glucose and starch content of NFC alone.

Human faeces supported a bioconversion rate that was comparable to the poultry feed (and this was higher for human faeces (1) and lower for human faeces (2)), despite having a much lower waste reduction. This was due to an 85% higher waste conversion efficiency than with the poultry feed. BSFL showed a significantly lower performance using poultry slaughterhouse waste than human faeces. The lowest performance was found for cow manure, which was low in protein, NFC, and lipids. In contrast, the human faeces and poultry slaughterhouse wastes were high in protein and lipids. These results thus suggest that NFC is less important for larval development than high overall nutrient content.

The protein conversion efficiencies were less variable and trends were different in comparison to the other performance parameters. Human faeces (1) and vegetable canteen waste had the highest bioconversion rate but not the highest protein conversion efficiency. This was due to varying larval composition arising from the different wastes and their associated larval weights. Larval protein content was notably higher when fed on mill by-products and canteen waste than on human faeces and vegetable canteen waste (Table 4). Larvae fed with human faeces and vegetable canteen waste likely incorporated more lipids, as indicated by a higher proportion of carbon in organic matter in comparison to the mill by-products and the canteen waste. Larva growing on human faeces contained the most ash.

Considering these findings, the most promising biowaste thus depends on the objective of the BSFL treatment. Mill by-products and vegetable canteen waste performed best with respect to waste treatment whereas human faeces and vegetable canteen waste were more favourable with respect to larval biomass production efficiency. The most protein per unit of biowaste was produced using the mill by-products and the canteen waste. Thus, for facilities targeting insect protein meal production, these wastes would be favourable. Poultry slaughterhouse waste and cow manure resulted in generally poor performance. However, not all wastes

Table 4
Mean performance of BSFL treatment on the different biowastes and formulations.

	Survival rate %	Larval weight mg DM	Waste reduction % DM	Bioconversion rate % DM	Larval biomass composition		
					Protein % DM	Ash % DM	Carbon % OM*
Individual wastes							
Mill by-products	96.2 (1.5)	41.7 (0.9)	56.4 (1.2)	14.9 (0.3)	42.1 (0.4)	7.3	58.0 (0.7)
Canteen waste	92.3 (3.1)	44.2 (5.9)	37.9 (3.8)	15.3 (2.1)	36.1 (0.3)	5.2	62.8 (0.3)
Human faeces (1)	99.1 (0.6)	58.8 (1.7)	39.1 (1.5)	22.7 (0.6)	26.7 (0.4)	13.6	65.8 (0.1)
Human faeces (2)	96.2 (2.5)	50.2 (1.2)	48.6 (0.3)	18.8 (0.8)	27.1 (0.1)	13.1	65.1 (0.6)
Poultry slaughterhouse waste	90.7 (2.9)	39.4 (0.7)	30.7 (4.7)	13.4 (0.5)	31.5 (0.7)	4.1	64.6 (0.4)
Cow manure	89.8 (7.5)	14.3 (0.4)	12.7 (0.9)	3.8 (0.2)	36.2 (0.2)	23.1	56.1 (0.3)
Vegetable canteen waste	97.5 (2.7)	59.1 (2.6)	58.4 (1.4)	22.7 (1.1)	24.5 (0.2)	5.1	65.4 (0.1)
Poultry feed (benchmark)	97.9 (2.1)	55.6 (5.1)	67.7 (6.9)	21.0 (2.4)	36.3 (0.8)	12.2	60.4 (0.7)
Waste formulations							
F 1	99.8 (0.6)	64.2 (1.1)	64.1 (0.6)	31.8 (0.6)	25.2 (0.3)	8.0	65.8 (0.2)
F 2	97.8 (3.7)	39.1 (0.3)	51.1 (0.7)	20.9 (0.9)	33.9 (0.5)	11.4	60.9 (0.4)
F 3 (1)	100.0 (0.0)	29.7 (1.2)	45.3 (1.1)	16.4 (0.7)	38.7 (0.3)	16.1	56.9 (0.3)
F 3 (2)	99.7 (0.6)	29.2 (2.0)	49.2 (1.6)	14.5 (1.1)	39.0 (0.6)	15.9	56.9 (0.6)
F 4	98.0 (1.4)	48.9 (2.4)	58.3 (1.1)	22.9 (1.1)	36.9 (0.3)	8.3	61.7 (0.5)
F 5	97.0 (3.4)	62.8 (1.6)	65.2 (2.0)	30.9 (1.6)	28.6 (0.3)	4.9	65.3 (0.7)
F 6	99.0 (1.0)	39.8 (2.1)	56.6 (0.7)	19.8 (1.1)	38.1 (0.3)	8.1	61.0 (0.2)

In parenthesis: standard deviation for samples where $n \geq 3$.

* OM = organic matter.

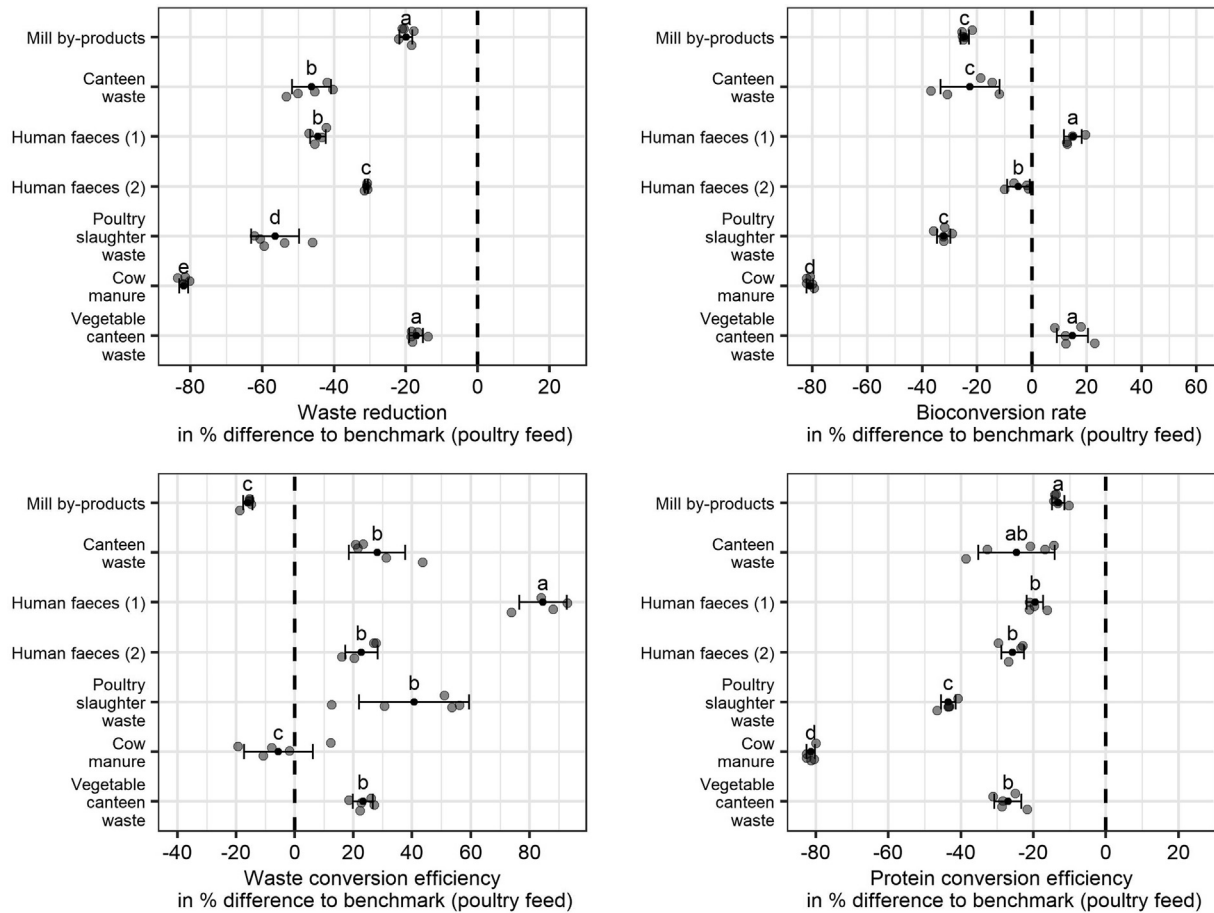


Fig. 2. Effects of the different individual wastes on waste reduction (top, left), bioconversion rate (top, right), waste conversion efficiency (bottom, left) and protein conversion efficiency (bottom, right) in comparison to the benchmark poultry feed (dashed vertical line). Means, standard deviations and results per replicate are displayed. Performance results with no shared letter are significantly different from each other. All results are given in dry mass.

can be employed in BSFL treatment facilities for animal feed production given legal resolutions (Lähteenmäki-Uutela et al., 2017). For example, in the European Union, only mill by-products and pre-consumer wastes (in nutrient composition similar to canteen wastes) can currently be used (European Commission (EC), 2017).

Food, restaurant, and canteen wastes also resulted in the highest—and animal manures the lowest—BSFL treatment performance in previous studies (Lalander et al., 2018; Nyakeri et al., 2019; Oonincx et al., 2015b). Lalander et al. (2018) reported a bioconversion rate of 14% DM for food waste in comparison to 15–23% DM for canteen wastes in this study. The corresponding values for waste reduction were 55% DM in comparison to 38–58% DM. For human faeces, the bioconversion rate was 11% DM as reported by Lalander et al. (2018) compared with 19–23% DM in the present study, and waste reduction data were 48% DM in comparison to 39–49% DM, respectively. In contrast to the present study, Lalander et al. (2018) observed a higher BSFL performance using slaughterhouse waste compared to food waste and human faeces. Values for waste reduction in the literature for cow manure range from 29 to 58% DM (Miranda et al., 2019; Myers et al., 2008; Rehman et al., 2017) and bioconversion rates range from 2 to 6% DM (Miranda et al., 2019; Rehman et al., 2017). This compares with a 13% DM waste reduction and a 4% DM bioconversion rate observed in the present study. These differences confirm that predicting larval performance exclusively based on the type of biowaste is not reliable and can lead to greatly over- or underestimated performance. Such variation is likely to result not only from variable biowaste composition (i.e. nutrient and

microbial numbers and communities) but also differences in experimental setups. To help address this, international standards for BSFL feeding experiments could allow for better comparisons across studies.

3.3. Treatment performance of biowaste formulations

The performance of the BSFL grown on the different waste formulations was significantly different despite targeting a similar protein and NFC content and ratio (Table 4; Fig. 3). Overall, using a formulation significantly increased performance compared to individual wastes. Distributions were different between the waste formulations and individual wastes for survival rate, waste reduction, bioconversion rate and protein conversion efficiency but not for waste conversion efficiency.

Feeding BSFL with the waste formulations resulted in higher survival rates in comparison to the individual wastes, and ranged from 97 to 100%. Despite a 25% lower feeding rate, the median larval weight was 43.5 mg DM for the formulations and 40.1 mg DM for the individual wastes. The median of the survival rate was 99% for the formulations and 95% for the individual biowastes. Individual wastes resulted in the median waste reduction and bioconversion rate being lower, by 45.4 and 25.0%, respectively, compared to poultry feed. In comparison, the median waste reduction was only 18.5% lower—and the bioconversion rate even 8.6% higher—for the formulations compared to the poultry feed. The median protein conversion efficiency was 28.5% lower for the individual biowastes and 8.4% higher for the formulations comparison to the poultry

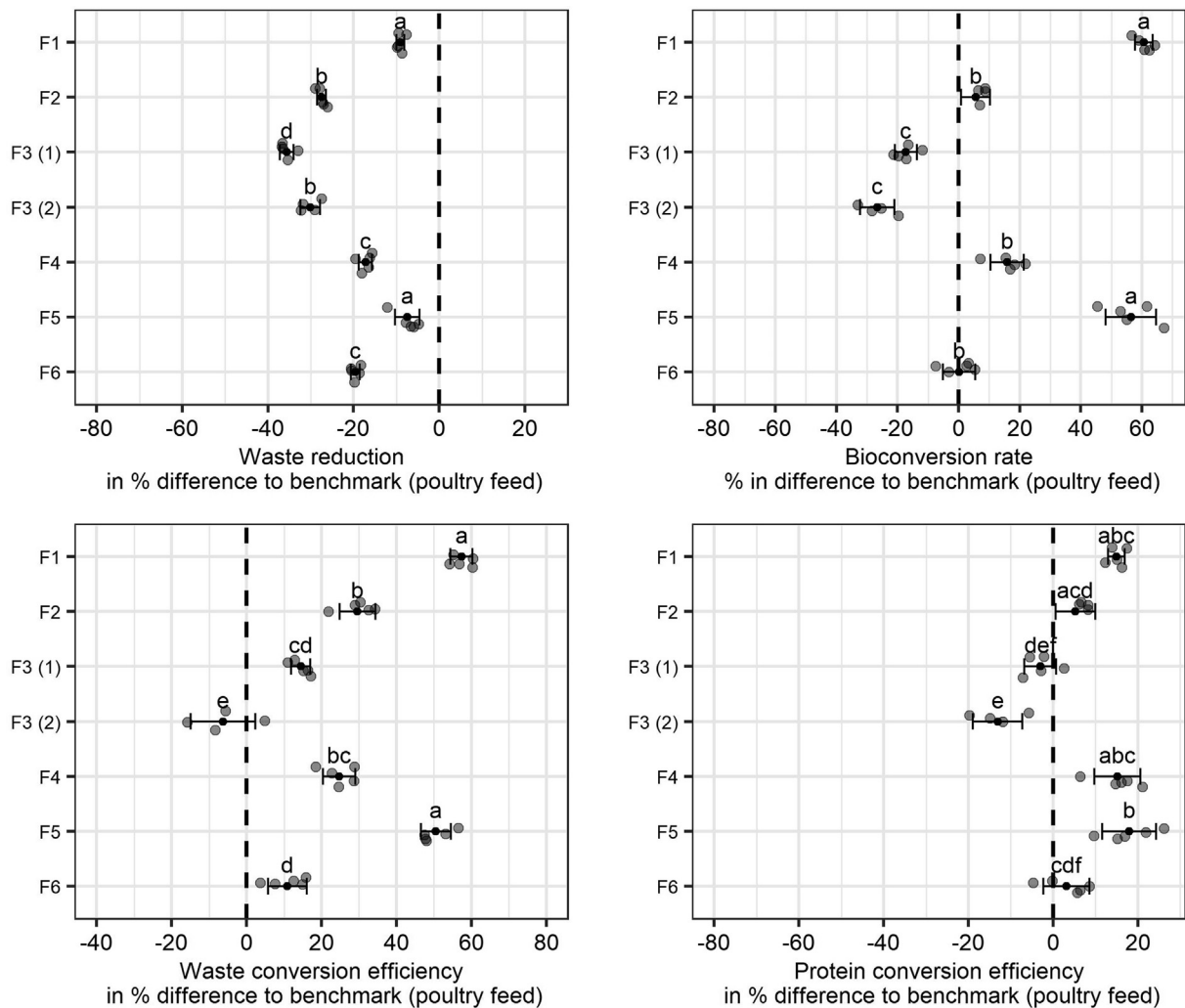


Fig. 3. Effects of the different waste formulations on the waste reduction (top, left), bioconversion rate (top, right), waste conversion efficiency (bottom, left) and protein conversion efficiency (bottom, right) of BSFL in comparison to poultry feed (dashed vertical line). Means, standard deviations and results per replicate are displayed. Performance results with no shared letter are significantly different from each other. All results are given in dry mass.

feed. These results suggest that the performance of BSFL treatment facilities can be increased by designing biowaste mixtures based on similar protein and NFC contents.

By comparing Figs. 2 and 3 it also becomes apparent that the use of formulations decreased the variability in performance. In comparison to the poultry feed, the results for the formulations had a range of 28% for waste reduction, 87% for bioconversion rate, 64% for waste conversion efficiency and 31% for protein conversion efficiency. In comparison, individual biowaste produced a range of 65% for waste reduction, 96% for bioconversion rate, 101% for waste conversion efficiency and 68% for protein conversion efficiency. This suggests that formulating different biowastes based on their initial nutrient composition can improve the reliability of BSFL treatment facilities. Although formulations, on average, contained less NFC, protein and lipids and more fibre than the individual wastes (see Tables 2 and 3), they were more balanced in nutrients without the absence or excess of NFC (as was the case for human faeces, cow manure and poultry slaughterhouse waste), protein (poultry slaughterhouse waste) and fibre (cow manure and mill by-products). It should be stated that all of the formulations included at least 50% mill by-products or canteen waste or both, and these were the wastes that supported high BSFL performance when used individually.

Variability in the performance parameters was, nevertheless, higher than expected in the formulations; bioconversion rates were expected to be similar between the formulations as protein and NFC appear to have the greatest influence on larval development (Barragán-Fonseca et al. 2018a, Barragán-Fonseca et al. 2018b; Cammack and Tomberlin, 2017). However, variable bioconversion rates (with a range of 87%) are not practical for BSFL treatment facilities. Such variability between formulations could be due to variable fibre and lipid contents. In the formulation feeding experiments, for example, lipid correlated positively and fibre negatively with waste reduction ($R^2 = 0.96$, $p < 0.01$ for lipids, $R^2 = -0.97$ and $p < 0.01$ for fibre) and the bioconversion rate ($R^2 = 0.96$, $p < 0.01$ for lipids, $R^2 = -0.95$, $p < 0.01$ for fibre). Formulations 1 and 5 resulted in the greatest waste reduction and bioconversion rate. These formulations were highest in lipids and lowest in fibre (see Tables 2 and 4) due to the high proportion of canteen wastes (see Table 1). In contrast, formulations 2 and 3 had the lowest lipid and highest fibre content due to a high proportion of human faeces and cow manure. This suggests that the variability in performance could be further reduced by keeping content of lipids and fibre within narrower limits. However, maintaining all macronutrients within fixed limits is difficult in practice considering that wastes typically have variable amounts of each macronutrient.

In addition to different lipid and fibre contents between the formulations, biowaste microbial numbers and communities could have been contributing to the variable BSFL treatment performance despite a similar protein and NFC content. This was not part of this study but can be expected considering that microbes can influence biowaste decomposition (De Smet et al., 2018; Gold et al., 2018a) and larval growth and typically differ between biowastes (Bruno et al., 2018; Ryckeboer et al., 2003; Wynants et al., 2019).

Similar to the larvae grown on the individual wastes, larval protein content was variable between the formulations (Table 4). Larvae fed on the formulations with a lower bioconversion rate tended to have a higher protein content. Protein efficiency was not significantly different between formulations 1, 4, and 5, and between formulations 2, 3, and 6, with the latter having a lower protein conversion efficiency, overall.

4. Conclusions

Given reliable biowaste compositional data, the formulation of mixed biowaste offers a promising systematic approach for the more efficient and predictable operation of black soldier fly larvae (BSFL) treatment facilities using a range of biowastes. Formulating biowaste mixtures in such a way that similar protein and non-fibre carbohydrate (NFC) contents are achieved can be expected to increase BSFL treatment performance and to reduce performance variability. Performance variability could be further reduced by keeping lipids and fibre within narrower limits. Future research should investigate whether these bench-scale results are transferable to industry-scale BSFL treatment plants with higher larval densities and feed temperatures. Benefits of biowaste formulations need to be balanced with the additional resources required for biowaste analysis and the needed technologies to produce formulations as part of biowaste pre-treatment (e.g. scales, shredder, dewatering, mixer and tank).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wasman.2019.10.036>.

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Review

Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: Recent progress and future directions elsewhere worldwide



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ABSTRACT

Continuous growth of human population and industrialization has increased the energy demands all over the world and this has resulted in a number of energy related challenges including depletion of fossil fuels, environmental pollution, and shortage of electricity supply. These challenges made it imperative to develop and maximize the abundant renewable energy resources, particularly the biomass via upgrading thermochemical conversion routes such as co-pyrolysis. This review paper presents an overview of previous studies, recent advances, and future directions on co-pyrolysis of biomass and waste plastics for high-grade biofuel production particularly in China and elsewhere worldwide. This paper also discussed the advantages of the co-pyrolysis process, co-pyrolysis product yields, co-pyrolysis mechanisms of biomass with plastics, and synergistic effects between them during co-pyrolysis, as well as the effects of some operating parameters especially the biomass mixing ratio and pyrolysis temperature on co-pyrolysis yields. The result of this critical review showed that co-pyrolysis of biomass with waste plastics is more beneficial than the normal biomass pyrolysis alone, and that it is also a simple, effective, and optional solution to increase the energy security of a nation, achieve effective waste management, and reduce dependency on fossil fuels.

1. Introduction

Rapid depletion of fossil fuels (petroleum, coal, and natural gas) with the risk of energy and environmental challenges has drastically increased the development of alternative, sustainable, and renewable energy worldwide. According to Zhang et al. [1] the only way most countries, like China, can deal with the sharp conflict between rapid economic growth and high CO₂ emissions is by total transition to a low carbon and sustainable energy system. Also, according to Zhao et al. [2], China is facing a number of energy related challenges including the depletion of fossil fuels, environmental pollution, and a shortage of electricity supply owing to her rapid economic growth, large population, and high-speed industrial development with high CO₂ emissions. These challenges make it important to develop and maximize her abundant renewable energy resources such as the biomass, wind, hydropower, geothermal, and solar energy resources. Biomass is the only renewable energy source that can be converted into several forms of fuels—liquid (bio-oil), solid (char), and gas—with promising flexibility

in production and marketing [3]. Biomass has been estimated to contribute somewhere between 15% and 50% of the world's primary energy consumption by the year 2050 [4]. Moreover, biomass as one of the world's largest sustainable energy sources [5], has numerous alternative energy resources existing in diverse forms worldwide and can be used to substitute the conventional fossil fuels due to its availability, innumerable economic and environmental benefits since it is a carbon source with CO₂ neutrality [6,7]. Sources of biomass vary from one country to another with varying rates of accumulation, as a result of several factors which include, among others, geographical conditions and locations, population levels, levels of economic development, agricultural development, forest development, industrial growth, food demand, production and processing technologies, and lifestyle.

According to Yin [8] and Shen et al. [9], biomass is known to be the fourth largest energy system after coal, oil and gas, supplying, presently, approximately 14% of the world annual energy consumption. Therefore, the development and utilization of biomass have attracted worldwide attention [6,10–15]. In China, there are abundant biomass

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resources, and the theoretical value of biomass is about 5 billion tons. The Chinese government also pays much attention to biomass energy utilization, which has been listed as a key scientific research project in four national five-year plans consecutively, most especially, the seaweed biomass. Which due to its strong photosynthetic ability, fast growth, and suitability for large-scale artificial cultivation [16], has become the promising third generation source for biofuel/bioenergy production, and has a high potential to replace petrochemical fuel resources [17].

Generally, either the biochemical or thermochemical conversion methods are normally employed in converting biomass into useful energy. Results of research studies revealed that thermal conversion technologies such as direct combustion, gasification, pyrolysis, and hydrothermal liquefaction have recently gained more attention because they are much faster than the biological processes (e.g., anaerobic digestion, fermentation). Moreover, thermochemical technologies can be applied in production of energy from certain wastes, such as plastics, that cannot be broken down by the activities of microbes [18]. Among the thermal conversion processes, Demirbas [19] demonstrated pyrolysis as the most efficient and promising method which produces energy with high fuel-to-feed ratios. Therefore, pyrolysis has attracted considerable attention as one of the viable and promising ways for extracting energies from biomass, most especially, the pyrolysis oil. Pyrolysis oil (bio-oil) is the liquid product from the pyrolysis process which has potential for use as fuels or feedstock for many commodity chemicals. However, the oxygen content of the pyrolysis oil is high (about 35–60 wt%) [20–23], and has been identified to exist in several forms oxygenated compounds (e.g., acids, alcohols, aldehydes, esters, ketones, phenols, lignin-derived oligomers, etc.), and is mostly found as water [22].

Therefore, the major challenge associated with pyrolysis of biomass alone lies with the production of pyrolysis oil with high oxygen content, which results in a low calorific value, corrosion problems, and instability [24]. As a result, the bio-oil needs to be upgraded to overcome

these challenges. According to literature reports of previous studies, different upgrading methods for oils (such as hydrogenation, hydrodeoxygenation (HDO), catalytic pyrolysis, catalytic cracking, steam reforming, molecular distillation, supercritical fluids, esterification, and emulsification), have been employed to eliminate the high oxygen content of the pyrolysis oil. Currently, two main pathways for upgrading the bio-oil exist: high-pressure hydrogenation processing and catalytic cracking [23–28]; and more recently, the co-pyrolysis of biomass with hydrogen-rich feedstock of higher fuel qualities (such as synthetic polymers) [29,30]. Fig. 1 presents an overview of the various techniques for upgrading pyrolysis oil; while Table 1 gives a comparison of co-pyrolysis technology with other upgrading techniques for pyrolysis oil in terms of operating conditions, reaction mechanism/process description, and technical feasibility. Co-pyrolysis is a simple and safe production process for high quality fuels since it does not bring in high-pressure hydrogenation; hence the hydrogen transfer may also be involved in the co-pyrolysis under ambient pressure conditions [31]. Thus, the co-pyrolysis process of biomass and plastics has been reported as an effective upgrading method that will not only increase the quantity of the oil produced but also improve its quality in terms of high calorific value [6], because the synthetic plastics are typically organic polymers derived mainly from petroleum products with high carbon and hydrogen contents, having little or no oxygen, and also offer a comparable high heating value (HHV) to conventional fossil fuels (diesel and gasoline). According to Zhou et al. [29], plastics with high hydrogen contents of about 14 mass % (such as polyethylene, polypropylene, and polystyrene), could donate hydrogen during co-pyrolysis with biomass which results in an increase and improvement in yield and quality of the oil produced respectively. Plastics are particularly attractive synthetic polymers, because they have a low recycling rate and most of them are non-biodegradable. Moreover, waste plastics have constituted not only serious environmental problems but also a huge waste of fossil fuel resources considering their high-value chemicals and high energy density even though they have contributed

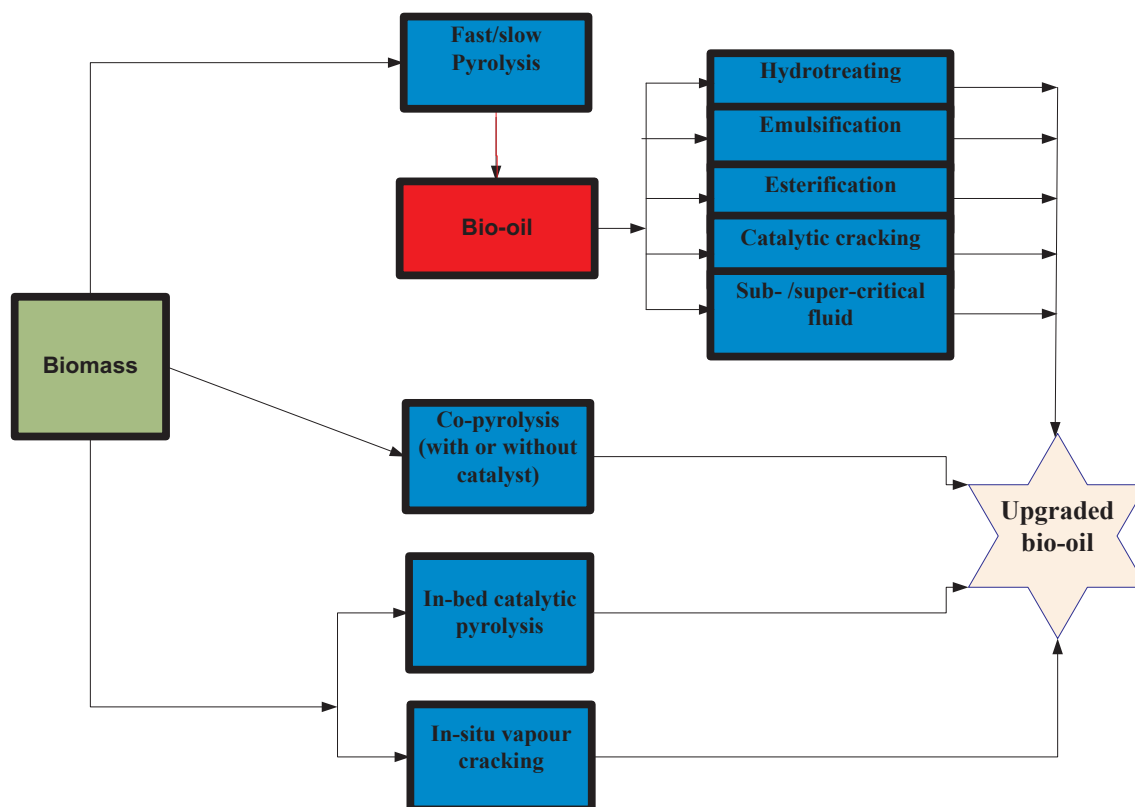


Fig. 1. Pyrolysis oil upgrading techniques.

Table 1
Comparison of co-pyrolysis with other upgrading techniques for pyrolysis oil.

Upgrading methods	Operating conditions	Process description	Technical feasibility	
			Pros	Cons
Hydro-cracking/hydrogenolysis/ catalytic cracking	Severe conditions (> 350 °C, 0.69–13.8 MPa), it requires H ₂ /CO or H ₂ donor solvents, catalyst (e.g., Ni/Al ₂ O ₃ -TiO ₂)	It involves both hydrogenation and cracking; it is also a destructive process (with low molecular products production)	It gives room for large quantities of light products	High cost, it needs complicated equipment, catalyst deactivation, reactor clogging
Co-pyrolysis (with or without catalysts)	Moderate temperature (400–600 °C); two or more feedstock materials at optimal mixing ratio, absence of oxygen; moderate pressure and high heating rate; inert gas (e.g., N ₂ , Argon, etc. if applicable based on the reactor type); and short vapor product residence time	It involves three basic steps (samples preparation, co-pyrolysis, and condensation), two or more feedstock materials, moderate operating conditions, absence of O ₂	Simple, safe, and effective approach for production of a high grade pyrolysis oils due to the synergistic effects between the constituent feedstocks.	Drying process of feedstock prior to co-pyrolysis is time and energy consuming. However, the heat required for feedstock drying could be recovered by internal heat sources by process integration, especially during industrial applications.
Emulsification	Mild conditions, needs surfactant (e.g., CANMET)	Combines with diesel directly. Bio-oil is miscible with diesel fuels with the aid of surfactants	Simple and less corrosive	Requires high energy for production
Hydrotreating/hydrofining	Requires mild conditions (of about 150 °C to a severe condition of about 400 °C, low pressure); It needs CO, H ₂ and also catalysts such as HZSM-5, CoMo, HDS, NiMo	Hydrogenation without simultaneous cracking (eliminating N, O, and S as NH ₃ , H ₂ O, and H ₂ S)	Cheaper route; it is already a profitable commercialized technology	It involved high coking (8–25%) and poor quality of fuels are obtained
Sub-/super-critical fluid	Mild conditions, organic solvents needed such as alcohol, acetone, ethyl acetate, glycerol	Promotes the reaction by its unique transport properties: gas-like diffusivity and liquid-like density.	Higher oil yield, better fuel quality (lower oxygen content and lower viscosity)	Solvent is expensive
Solvent addition (direct addition of solvent or esterification of the oil with alcohol and acid catalysts)	Mild conditions, polar solvents like water, methanol, ethanol, and furfural are required	It can reduce the oil viscosity by physical dilution, molecular dilution, changing the oil microstructure; and chemical reactions like esterification and acetalization	Simple and the most practical approach with low cost of solvents	Mechanisms of the solvent addition involved are not quite understood

immensely to our daily activities. Thus, various recycling methods (mechanical, landfill, incineration or energy recovery, and chemical methods such as pyrolysis, hydrothermal treatment, catalytic pyrolysis, and more recently co-pyrolysis of biomass, with or without catalysts) have been applied in order to solve these problems and produce high-grade fuel oils or valuable chemicals [32]. Some comprehensive review articles have reported, in detail, the use of different upgrading techniques in improving the oil quality [17,33]. Also, more recently, Lopez et al. [34] reviewed the main thermochemical routes for the valorization of only the waste polyolefinic plastics to produce fuels and chemicals. They pointed out that pyrolysis has received greater attention among other different valorization strategies; however, most of the studies are of preliminary nature carried out in laboratory scale batch reactors. They also emphasized that the degree of development of pyrolysis technologies should be improved to facilitate their industrial implementation. Likewise, Zhang et al. [35] presented a comprehensive review of another aspect of pyrolysis technology of polymers, however, with lignocellulosic biomass. They focused, mainly on the catalytic fast pyrolysis aspect of lignocellulosic biomass and polymer pyrolysis technology with much emphasis on the chemistry of catalytic co-pyrolysis. However, a holistic, more detailed and comprehensive review articles on the current advances and recent findings as well as the future directions in research and development of co-pyrolysis of waste plastics and biomass of different types, including the algae, besides the second generation biofuels resources, for high grade liquid fuel production are either reported in bits, completely omitted or missing [6]. This article thus, holistically, focuses on co-pyrolysis of waste plastics and different types of biomass as an upgrading thermochemical technology for high quality biofuel production with emphasis on the overview of current advances, recent findings, previous studies and future directions of research and development on co-pyrolysis of different types of biomass and plastics, particularly in China, and also elsewhere worldwide. Also, several fundamental aspects of co-pyrolysis, the co-pyrolysis product yields and the characteristics of bio-oils produced, the advantages and drawbacks of the co-pyrolysis process, co-pyrolysis mechanism of biomass and plastics, and synergistic effects between a biomass and a plastic during co-pyrolysis are reviewed. Finally, the effects of some operating parameters, most especially, the biomass mixing ratio and pyrolysis temperature on biomass–plastic co-pyrolysis product yields as

well as the role of catalysts in co-pyrolysis are summarized. The result of this piece of work revealed that co-pyrolysis technology, most especially of biomass and waste plastics, using the appropriate catalyst, is a promising technology, a simple, effective, and optional solution to increase the energy security of a nation, achieve effective waste management, and reduce over-dependency on fossil fuels, while keeping the environment and ecosystem safe.

2. Relevance and drawbacks of co-pyrolysis process

A lot of studies have focused on co-pyrolysis techniques as a result of their simplicity, effectiveness, and efficiency in operations for production of valuable pyrolysis liquid fuels; and with a less coke formation [36–38]. These techniques are more economical than the other conventional upgrading methods for pyrolysis oil as they do not require any solvent, catalyst, or any amount of hydrogen, which can cost even more than the oil itself. Co-pyrolysis can be operated in the absence of hydrogen pressure. The technique does not only offer simplicity in design and operations, but also it is capable of producing bio-oils of high quality and quantity (up to about 75 wt% at moderate temperature condition (of 500 °C) and short hot vapor residence time (of 1 s); with the yields of other products being optimized by simple adjustment of the parameters of the operating conditions) [20,39]. Therefore, this technique can play a pivotal role in development of the biomass energy industry. Moreover, many research studies (Table 2) have shown that co-pyrolysis of biomass results in higher bio-oil quality and quantity than those from pyrolysis of individual biomass alone [34,40,41]; most especially, co-pyrolysis of biomass with plastics has successfully improved the oil quantity and quality without causing any adverse effects on the system process or encountering any form of challenge like other forms of traditional upgrading methods for pyrolysis oils. Kositkanawuth et al. [18] also pointed out that co-pyrolysis of algal biomass and polystyrene can improve the quality of bio-oil. Unlike the catalytic cracking and HDO, co-pyrolysis has been demonstrated as a promising technology for future applications in the industry as a result of its economic cost ratios and efficient performance. The major factor which has led to the inevitable success of this technique mainly lies with the synergistic effect due to the interactive reaction mechanisms of the co-feeding materials during the process [42]. However, several factors

Table 2
Summary of the results on co-pyrolysis of biomass with plastics (at 1:1 mixing ratio).

Biomass	Type of plastics	Pyrolysis devices & conditions	Liquid yield/wt %		Extra yield/wt %	Calorific value (MJ/kg)		Ref.
			Biomass alone	Mixture		Biomass alone	Mixture	
Palm shell	PS	A stainless steel tubular reactor; 500 °C; 45 min; N ₂ gas at 2 L/min	46.13	61.63	15.50	15.50	38.01	[48]
Pine residue	Plastic waste	A stainless autoclave with furnace; 400 °C; 30 min; 1.0 MPa	32.00	53.00	21.00	20.00	45.00	[49]
Karanja seeds Niger seeds	PS	A stainless steel reactor; 1.0 MPa; 550 °C	32.90	60.11	27.21	37.65	42.18	[50]
			33.39	61.31	27.92	32.15	41.42	
Cotton straw	PP	A fixed-bed reactor; 380–480 °C	20.00	35.80	15.8	15.50	46.90	[51]
Pine cone	LDPE	A glass reactor under atmospheric pressure; 500 °C; 10 °C/min	47.50	63.90	16.4	Nr	46.33	[52]
	PP		47.50	64.10	16.60	Nr	45.58	
	PS		47.50	69.70	22.20	Nr	46.43	
Wood chip	PP (block)	A fixed bed reactor; 500 °C	39.30	63.10	23.80	19.90	45.00	[53]
Sunflower stalk	LDPE	A dropdown tubular reactor; 600 °C; 10 min; 100 cm ³ /min of argon flow	29.94	57.17	27.23	Nr	nr	[41]
Cedar wood	38.83		64.08	25.25	Nr	nr		
Fallopia Japonica stem	30.43		58.96	28.53	Nr	nr		
Cellulose	PS	A vertical Pyrex reactor; argon flow rate of 5 dm ³ /h; 500 °C; 5 °C/min	45.50	58.80	13.30	Nr	nr	[54]
Potato skin	HDPE	A stainless steel retort; 500 °C; 400 cm ³ /min; 30 min	23.00	39.00	16.00	32.00	45.61	[55]
Pinewood sawdust	PS	A vertical Pyrex reactor; 450 °C; 5 °C/min	46.00	67.00	21.00	Nr	nr	[56]

HDPE = high-density PE; LDPE = low-density PE; PE = polyethylene; PP = polypropylene, PS = polystyrene, nr = not reported.

which influence the synergistic effects between the component mixed feedstocks during co-pyrolysis include, among others, the type and contact of feedstock, the feedstock blending ratio, temperature and heating rates, pyrolysis duration, removal or equilibrium of volatiles formed, the function of hydrogen donors, and the addition of suitable catalyst for the recently emerged catalytic co-pyrolysis technology. According to Panda et al. [43], co-pyrolysis of woody biomass with plastic produces a higher oil yield with a higher calorific value than those of the woody biomass alone as a result of the hydrocarbon polymers consisting of paraffins, *iso*-paraffins, olefins, naphthenes, and aromatics. Also, the co-pyrolysis process produced a non-condensable gas with a high calorific value than that from the pyrolysis of the wood biomass alone. Kuppens et al. [44] also demonstrated, through the study of the economic consequences of the synergistic effects of flash co-pyrolysis, that the use of co-pyrolysis techniques is more profitable than normal pyrolysis of biomass alone and has potential for quick commercial development. Biomass co-pyrolysis thus becomes relevant as the pyrolysis-oil from biomass cannot completely mix with oil from waste plastics or tires by simple and direct mixing/blending because of the polar nature of the biomass pyrolysis oil, which is in an unstable mixture form that is capable of breaking (phase separation) after a short period of time. Thus, the idea of direct blending of oils from normal pyrolysis of biomass with the oils from plastics (or tires) pyrolysis seems uneconomical as this process may increase the operation costs since more energy is required. However, co-pyrolysis technique has been demonstrated to be more reliable in producing homogenous and stable pyrolysis oil than the direct blending oil method as the interaction of the radicals during the co-pyrolysis reaction can promote the formation of a stable pyrolysis oil that avoids phase separation [45]. Another major benefit of co-pyrolysis method is that it acts as a promising and efficient waste management technology that is capable of significantly reducing the volume of waste as more waste is consumed as feedstock, reducing the landfill needed, while saving costs for waste treatment, and solving a number of environmental problems as the disposal of wastes in landfills is undesirable [46]. Co-pyrolysis could therefore serve as an effective and efficient alternative waste management method for waste reduction and energy security enhancement for the future [6]. Thus, co-pyrolysis of biomass and plastics will not only reduce the volume of wastes generated but will also allow the recovery of vital chemicals and replacement of fossil fuels [30,47]. However, proper understanding of the reaction mechanisms is also very vital in order to improve the overall process design, planning, and operation; as the reaction mechanisms between the biomass and plastics are complex and need in-depth investigation [48].

However, despite of its numerous advantages, the co-pyrolysis process of biomass and waste plastics has a number of disadvantages which are evident drawbacks of the process. One of the disadvantages presented is the liquid product extracted after the pyrolysis process, which is also referred to as bio-oil [57]. Inarguably, the co-pyrolysis liquids are still not as stable as the conventional diesel or other fossil fuels due to a number of factors and as a result it needs to be further upgraded before it is used as an automotive fuel. This persisting challenge is traced to the existence of high water content, high oxygen content, high sulphur content, high heteroatom content, numerous complex compounds and high yield of PAH (polycyclic aromatic hydrocarbons) in the oil together with poor ignition and constant corrosiveness. Hence, due to the ineffectiveness of the bio-oil, which is the main product of the co-pyrolysis process, there exist certainly some drawbacks for the process [58]. However, the co-pyrolysis of biomass with plastics as a hydrogen-rich co-reactant as well as the use of suitable amount of catalysts during pyrolysis process has, inarguably, improved the oil yield and/or upgraded the quality of the bio-oil produced to a greater extent, besides the improve of the overall efficiency/performance of the process. Also, another disadvantage of the co-pyrolysis of biomass with waste plastics is that the thermal decomposition of the waste plastics, inarguably, produces a lot of toxic gases, most

especially, the decomposition of PVC plastic facilitates the formation and release of chlorinated hydrocarbons such as furan and dioxins that may be hazardous to the human health. Thus, due to the high chlorine content of PVC plastic ((about 57 wt%), the co-pyrolysis of waste PVC plastic with biomass is, inarguably, very harmful to health as it also produces a lot of toxic products such as chlorinated aromatics and hydrochloric acid, which is also corrosive. The waste PVC plastic is therefore not suitable to be utilized, directly, for co-pyrolysis or catalytic co-pyrolysis, without being properly treated via dechlorination process using appropriate absorbents such as Fe_3O_4 , Fe_2O_3 and FeOOH , to either totally remove or reduce drastically to minimum the chlorine content [59,60]. Moreover, polystyrene is also a toxic plastics, for example, when the it is burnt, a small amount of it can cause blindness, symptoms of inhalation and to some extent vomiting to human beings and thus can bring about complications especially to young children. The burning of such toxic waste plastics should therefore not be done in the presence of human beings and those who burn the plastics should, therefore, wear facial masks to avoid inhaling the fumes from the plastic that is burning. Another disadvantage is that biomass energy is not entirely clean. This is because it produces gases such as the methane gases which are harmful to the earth's ozone layer. Destruction of the ozone layer causes the sun's rays to directly scorch on the earth and thus can easily damage plants and the skin of human beings. Also, one of the challenges limiting the development of biomass pyrolysis into a large industrial continuous scale project is mainly because many people are not aware that it exists. A large number of people are not aware of the benefits of biomass and as a result of this; even those with animals do not conserve the wastes from the animals which can be used to produce energy. Thus a lot of creation of awareness to the people needs to be made so that they can know of the importance of biomass and thus get to understand the importance of having a large scale development of biomass pyrolysis. Moreover, the production costs and lack of markets for the co-pyrolysis products also pose as a huge challenge to co-pyrolysis technology development. Thus, these challenges tend to limit the zeal to drive the technology of biomass and waste plastics co-pyrolysis to the desired commercial scales in spite of all the numerous efforts that have been invested to improve the technology. Thus, if the co-pyrolysis technology is to become a viable renewable energy source, then favourable policies and financial supports are needed to drive it to commercial scales.

3. Mechanism of biomass-plastic co-pyrolysis process

The most commonly proposed mechanism of co-pyrolysis of biomass with plastics like other co-feeding elements is the mechanism of radical interactions in the process reactions which contributes immensely to the synergistic effects claimed to be experienced during the co-pyrolysis process studies by many researchers while but only a few researchers argued that in many cases these synergies are unclear or scarcely found [35,48,61]. However, the synergistic effect usually depicts the interaction of two or more elements which when combined produced a total effect that is greater than the sum of the effects or contributions from the individual co-feeding elements which results either in an improvement of the quality and quantity of the resultant products or leads to the worsening of any property of the resultant mixture or its output products. Zhang et al. [35] and many other researchers also recognized the existence of this synergistic effect between the biomass and polymers during the co-pyrolysis process as the main factor for the improvement in the oil quantity and quality. It was noteworthy that the extent of the contact between the co-feeding elements (such as the biomass and plastics), the compositions of the individual co-feeding elements and their blending ratio, besides the pyrolysis temperature and reaction time, are the key factors to achieving the synergistic effect. Thus, because the extent of the contact between the co-feeding elements is a major parameter to achieving the positive synergistic effects, the co-pyrolysis process is thus, effectively,

more likely to be performed in a fixed-bed and auger reactors rather than in a fluidized-bed reactor [6,35]. However, the auger reactor was proven to be more effective for high-grade liquid yield with the better characteristics (in terms of the total acid number, density, pH value, calorific value, and oxygen content) than the fixed-bed reactor by implementing the co pyrolysis of lignocellulosic biomass with waste tires under the same condition, and also, the effect of the blending ratios of the co-feeding elements (i.e., biomass to plastics ratio) on liquid yield was observed to be more severe than other effective parameters such as the pyrolysis temperature and reaction time [6,57]. It is also worth noting that the thermal decomposition mechanisms of the normal pyrolysis of individual biomass and plastics are relatively different however the chemistry and steps of co-pyrolysis and normal pyrolysis are almost similar as co-pyrolysis is also basically operated in a closed reactor system and in the absence of oxygen at 400–600 °C [6,35,57]. Generally, the inert gases (such as nitrogen, argon, helium, etc.) are commonly employed during the co-pyrolysis process step to get rid of the oxygen in the pyrolytic systems, and to also facilitate the sweeping of the pyrolytic volatiles to the condensers for fast cooling, thus avoiding secondary reactions to maximize the liquid yield [57].

Fundamentally, co-pyrolysis involves the thermal degradation of a mixture of two or more materials as feedstocks, producing synergistic effects between them which results in high quality and quantity of yields. Thus the proper understanding of the co-pyrolysis mechanism offers simplicity and effectiveness for production of high-grade pyrolysis oil. Therefore, for the purpose of oil production, co-pyrolysis involves fundamentally three basic steps or process mechanisms: sample preparation/pretreatment, co-pyrolysis, and condensation stages. On that note, co-pyrolysis process requires that the feedstock materials be properly prepared and pretreated after harvest or procurement from the suppliers, mainly by drying (commonly by oven method at 105 °C for 24 h) and grinding into small particles (usually less than 2–3 mm to achieve higher biomass heating rates) so as to make the conversion process more efficient and stable. Bridgwater [57] suggested that the maximum moisture content in dried feedstock material prior to pyrolysis should be about 10% since high moisture in the feed results in the oil product having a high water content. Several other pretreatment methods (such as sorting, dewatering, etc.) apart from dehydration and size reduction exist for proper and efficient thermal degradation to be achieved. Although the drying process of wet biomass most especially at the laboratory scales operations, majorly employs external heat supply sources. However, for industrial applications, the heat demand for feedstock drying can be recovered by internal heat sources through process integration. According to Veses et al. [62] and Venderbosch and Prins [63], many researchers have suggested that the by-products (char or gas) of the process can be combusted to provide the necessary heat for endothermic pyrolysis and other intermediate processes, such as biomass drying. Thus, the feedstock materials should be properly prepared prior to co-pyrolysis phase for effective production of high quality and quantity bio-oils.

However, the mechanism of thermal degradation of biomass alone differs, slightly, from the co-pyrolysis of its blends with other feedstock materials due mainly to the differences in their compositions [64–67]. Thus, biomass and plastic have different decomposition mechanisms during the thermal pyrolysis process. According to Demirbas [68] and Onal et al. [13], a series of exothermic and endothermic reaction mechanisms characterized the pyrolysis of biomass while the thermal pyrolysis of plastic occurs by radical mechanisms (involving initiation, propagation/secondary radicals' formation, and termination via radicals' disproportionation or recombination). The secondary radicals formation are typical free radicals formation induced in the co-pyrolysis of biomass with plastics which involves depolymerization, hydrogen transfer reactions, monomers formation, intermolecular hydrogen transfer (i.e., generation of paraffin and dienes), and isomerization via vinyl groups. Besides, Jakab et al. [69] observed that biomass has a lower thermal stability state than plastics, and this can affect their

radical degradation mechanism by promoting the degradation of synthetic macromolecules. It is also worth noting that the co-pyrolysis mechanism of biomass and plastics under low heating rate conditions, most especially for those co-pyrolysis studies performed in TGA instruments, is completely different from that under fast heating rate conditions as in the case of the industrial reactors and Py-GC/MS devices in which the thermal degradation of all the biomass and plastics components takes place concurrently. However, for co-pyrolysis studies performed under the low heating rate conditions, the thermal degradation peaks are normally observed due to the presence of several pyrolysis steps at different temperatures.

The last but not the least basic step of the pyrolysis process mechanism is condensation which involves the rapid cooling of the pyrolysis vapors generated during the process. This is another important step in the production of pyrolysis oil and without this step, only the char and gas products can be obtained from the co-pyrolysis process of the biomass and plastics. The vapors generated during the process usually pass through the condensation units and change their physical state from the gaseous phase into the liquid phase.

Unlike the pyrolysis process mechanisms described above, the pyrolysis reaction mechanisms of biomass degradation involve only two process reaction mechanisms: primary and secondary processes. Generally, biomass mainly consists of three components: cellulose (30–60%), hemicellulose (polysaccharides) (20–35%), and lignin (15–30%), together with some resins and minerals (Fig. 2). Pyrolysis of biomass as well as its co-pyrolysis is very complex due to the diversity, heterogeneity, and limited thermal stability of some of the components involved. The pyrolysis product yields are almost similar to the products expected from the individual pyrolysis of the three main components, despite the synergistic effects [70,71]. Thus, the study of the thermal decomposition of the individual components may form the basis of the expected reaction pathways and determine the primary and secondary reactions for the entire biomass pyrolysis, hence the co-pyrolysis mechanisms of the co-feeding materials. Thermal decomposition of biomass during pyrolysis consists of complex reaction network of hundreds of species and reactions, which include, among others, the depolymerization of natural polysaccharides and aromatic polymers, reactions of unstable intermediates, and the formation of products through mechanisms such as glycosidic bond cleavage, C–C bond cleavage, hydrolysis, unzipping, dehydration, fragmentation, rearrangement, char formation reactions, ring-opening/closing, retro Diels–Alder, retro aldol, enol–keto tautomerization, isomerization, and decarbonylation [72–74]. According to Zhou et al. [29], the state-of-the-art reviews [57,75–82] have covered different aspects of biomass pyrolysis ranging from the fundamental bench-scale level to the applied reactor and process development level examining pyrolysis parameters, product quality and properties, kinetics and mechanisms, multi-scale modeling, techno-economic analysis, and fundamental challenges. All of these aspects of biomass pyrolysis, including the reaction and process mechanisms, are almost similar to those of co-pyrolysis process, probably; except for the cases of the synergistic reaction mechanisms due to the interactions between the constituents of the mixture, the type and compositions of the feedstocks, as well as the blending ratios of the co-feeding materials of the mixture.

However, biomass pyrolysis reactions are characterized by the integration of the activation energy (E_a), the pre-exponential factor (i.e., frequency factor), A , and the conversion function, $f(\alpha)$. The term, $f(\alpha)$, is the reaction model used which depends on the controlling mechanisms. The integration of A , E_a , and $f(\alpha)$ is usually known as the kinetic triplet [83,84]. Many researchers have observed that an increase in the apparent activation results in an increase in the pre-exponential factor; and vis-à-vis a decrease. According to Chornet and Roy [85], a kinetic compensation effect (KCE) exists during the pyrolysis of different biomass materials with a definite linear correlation between the variables, A and E_a ; and, any change in the experimental conditions that causes E_a to change will also result in a complementary compensating response in

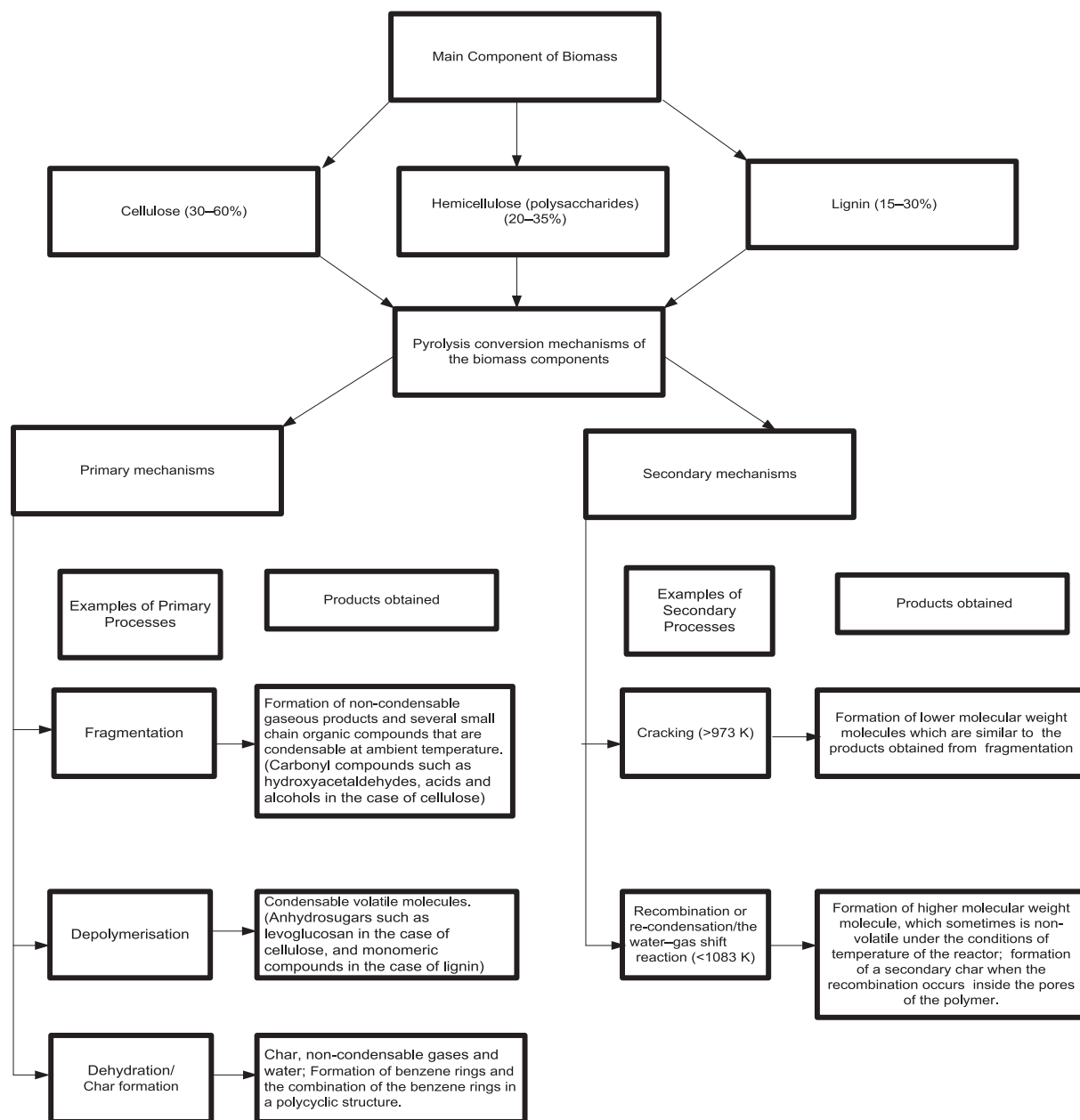


Fig. 2. Main components of biomass and their thermal degradation products.

A. Thus, the determination of the kinetic parameters (like the activation energies, pre-exponential factors, and the order of reaction for all the pseudo-components) is of fundamental importance to provide data for developing the detailed kinetic schemes. Suriapparao et al. [86] determined, through series of extensive TGA experiments, the apparent activation energies of thermal decomposition using various methods like the First Kissinger method and isoconversional Kissinger–Akahira–Sunose (KAS) method. Even though cellulose and polypropylene (PP) decomposed, during the co-pyrolysis process, in distinct temperature regimes, they observed that the activation energy of the decomposition of cellulose (158 ± 3 kJ/mol) was not affected by the presence of PP (20–80 wt%), while the presence of cellulose significantly decreased the activation energy of PP decomposition (206–120 kJ/mol on addition of 20–80 wt% of cellulose). The kinetics of the biomass decomposition could be thus routinely predicated on a single reaction [87,88], and can be expressed under isothermal conditions by the following canonical equation:

$$\frac{d\alpha}{dt} = k(T)f(\alpha) = A \exp\left(-\frac{E}{RT}\right)f(\alpha) \quad (1)$$

where t is the time, α represents the degree of conversion, or extent of reaction, $\frac{d\alpha}{dt}$ is the rate of the isothermal process (i.e. the isothermal reaction rate), and $f(\alpha)$ is the conversion function that depicts the reaction model used and depends on the controlling mechanisms. The extent of reaction, α , can be defined either as the mass fraction of biomass substrate that has decomposed or as the mass fraction of volatiles evolved, as shown below:

$$\alpha = \frac{w_0 - w}{w_0 - w_f} = \frac{v}{V_f} \quad (2)$$

where w is the mass of substrate present at any time t , w_0 is the initial substrate mass, w_f is the final mass of solids (i.e., residue and un-reacted substrate) remaining after the reaction, v is the mass of volatiles present at any time t , and V_f is the total mass of volatiles evolved during the reaction. The non-isothermal rate expressions (i.e. the reaction rates) as a function of temperature at a linear heating rate, β , can be expressed

through an ostensibly superficial transformation [83,89] of Eq. (1):

$$\frac{d\alpha}{dT} = \frac{d\alpha}{dt} \frac{dt}{dT} \quad (3)$$

where $\frac{dt}{dT}$ is the inverse of the heating rate, $\frac{1}{\beta} \frac{d\alpha}{dt}$ denotes the isothermal reaction rate, and $\frac{d\alpha}{dT}$ is the non-isothermal reaction rate. Thus, an expression of the rate law for non-isothermal conditions can be obtained by substituting Eq. (3) into Eq. (1):

$$\frac{d\alpha}{dT} = \frac{k(T)}{\beta} f(\alpha) = \frac{A}{\beta} \exp\left(-\frac{E}{RT}\right) f(\alpha) \quad (4)$$

Therefore, in order to identify and appreciate the interaction of the components of a mixture during co-pyrolysis process, the calculated interacting and non-interacting components decomposition curves, have been drawn by many researchers [90–92] using the canonical equation expressed above, which involves a proportional relationship between the activation energy and the frequency factor, and have been compared with the experimental results. The calculated non-interacting component decomposition curve is usually generated based on the assumption that each component undergoes the decomposition as if it exists as a pure component in the mixture and the simple additivity of the constituent components in the mixture is assumed to obtain the conversion of the mixture [91]. The non-interacting model is thus completely predictive in nature. The degradation rate of the mixture using this model is expressed as shown in Eq. (5):

$$\left. \frac{d\alpha_i}{dt} \right|_{mix} = x_1 \left. \frac{d\alpha_i}{dt} \right|_1 + x_2 \left. \frac{d\alpha_i}{dt} \right|_2 \quad (5)$$

where $\left. \frac{d\alpha_i}{dt} \right|_{mix}$ = rate of degradation of the mixture, x_1 = weight fraction of the component 1 in the mixture, x_2 = weight fraction of the component 2 in the mixture, $\left. \frac{d\alpha_i}{dt} \right|_1$ = rate of degradation of component 1, $\left. \frac{d\alpha_i}{dt} \right|_2$ = rate of degradation of component 2, α_i is the degree of conversion, or extent of reactions, i . However, such model cannot predict the kinetic behavior of the mixture of co-feeding materials, if the degradation of each component in the mixture is not completely independent. Thus, the predictions of the non-interacting models deviate significantly from experimental observations, and hence to overcome these limitations, an interacting approach has been adopted by many researchers for modeling and scale-up of pyrolysis reactors; thus, in this type of interacting model, a quadratic mixing rule type expression is used for expressing the thermal degradation kinetics of the mixture of two co-feeding materials of different components. Consequently, the thermal degradation kinetics of a binary mixture is expressed as follows:

$$\left. \frac{d\alpha_i}{dt} \right|_{mix} = x_1^2 \left. \frac{d\alpha_i}{dt} \right|_1 + x_2^2 \left. \frac{d\alpha_i}{dt} \right|_2 + 2x_1x_2 \left. \frac{d\alpha_i}{dt} \right|_{12} \quad (6)$$

where

$$\left. \frac{d\alpha_i}{dt} \right|_{12} \{T\} = \beta_{12} \{T\} x_1 + \gamma_{12} \{T\} \quad (7)$$

In the above Eq. (7), the temperature term in the parenthesis shows the functionality. The parameters β_{12} and γ_{12} for a mixture at a given temperature are obtained from the linear regression of the calculated values of $\left. \frac{d\alpha_i}{dt} \right|_{12}$ from Eq. (5), at the same temperature, for different mixture compositions. These parameters can then be used to correlate the binary mixture degradation kinetics.

4. Main compositions of biomass and different plastic types, co-pyrolysis technologies, reactor types mainly used, process conditions/parameters and the role of catalysts in biomass-plastic co-pyrolysis

4.1. Main compositions of biomass and different plastics types commonly used for co-pyrolysis and the co-pyrolysis products obtained

Basically, the main components of biomass, most especially, the lignocellulosic biomass are cellulose (30–60%), hemicellulose (polysaccharides) (20–35%), and lignin (15–30%), together with some resins and minerals [6,35,93,94] while other forms of biomass such as the algae, may not contain lignin. However, the algal biomass is generally categorized based on the two main groups of algae, namely; the macroalgae (i.e., the seaweeds), which contain mainly fatty compounds, soluble polysaccharides and proteins [95], and the microalgae which also consists of three main biochemical compositions, namely; lipids, carbohydrates and proteins, and the nature of the compositions of the algae is the major factor for the viability of its utilization in fuel production [11]. Moreover, it has been comprehensively reviewed and reported in the literature that biomass consists of certain percentages of characteristic compositions determined via the proximate analysis technique by various researchers, and these compositions include, among others, the ash content, volatile matter, fixed carbon and moisture contents, besides the biochemical compositions analysis results previously highlighted [6,48,95,96]. Similarly, elemental analysis results unveiled that biomass is also made of certain percentages of elements such as carbon, hydrogen, oxygen, nitrogen, and sulphur (however in minute quantity). However, this aspect has also been comprehensively reviewed and reported in the literature by many authors and researchers.

It is worth noting that in analyzing the interactions between biomass and plastic during the co-pyrolysis process, the types of plastics commonly used include, among others, the polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene-terephthalate (PET). The polyethylene (PE) is the most common type of plastic. The primary characteristic of polyethylene is that it consists of polymers of ethylene having the chemical formulae $(C_2H_4)_n$. Also, the polyethylene has either a low density of LDPE that ranges between 910 and 940 kg/m³ or a high density of HDPE. Inarguably, the melting point of polyethylene is 105–115 °C. Consequently, the pyrolysis product of PE includes; 69.82% liquid, 28.84% gas, and 1.34% of the solid residue [97]. Polypropylene (PP) is a thermoplastic consisting of propylene and monomers, and one of its characteristics is that it can easily crystallize [98]. It also has a very soft surface, hence, reduction of friction. It is chemically resistant, for instance; it does not simply react when in contact with either an acid or a base. PP is also highly resistant to electricity, and lastly, despite being hard, PP is also considered elastic, it is equally regarded as being a tough material as it cannot easily break [98]. Consequently, the pyrolysis product distribution for the polypropylene is about 59.70% of Liquid, 31.90% gaseous, and 8.40% of solid residue. Due to the hydrocarbon component, the polypropylene has a higher yield of paraffin whereas the polyethylene gives a higher yield of olefins and naphthenes. Also, the kinetic energy of the polypropylene is about 250–300 °C [99]. Polyethylene terephthalate (PET) is one of the most common thermoplastic polymers and is used in clothing fibers. The basic building block for PET is ethylene glycol and terephthalic acid. It is worth noting that it is the most recycled plastic globally. Similarly, Polyethylene terephthalate may exist in the form of the amorphous and semi-crystalline polymer. Also, the thermochemistry of the PET is 1.0 kJ (kg K). Upon undergoing pyrolysis, the C=O bondage is subjected to thermal degradation to produce terephthalic and benzoic acid and ultimately leads to the production of carbon (II) dioxide [100]. Polystyrene (PS) is an aromatic polymer that is made from the monomer styrene that can either be in solid or foamed form. Inarguably, despite naturally being colourless, it can be coloured

using various colourants. Equally, polystyrene is slow to degradation and as a result posed a great challenge to environmental conservatives, flame retarded and high impact resistant. Lastly, the melting point for the PS is 240 °C (464 °F; 513 K) [101].

Moreover, the proximate analysis results of different plastic types disclosed that plastic consists mainly of volatile matters, for example, PP (95.08–100.00%), PS (97.85–99.80%), PE (98.87–99.80%), PVC (92.14–98.57%) and PET (88.61–91.75%), followed by fixed carbon contents but with low ash contents and very little or no moisture (Table 5). The presence of high volatile matters and absence of moisture in its composition make plastic an effective co-feeding material for improving the quality of biomass fuels during co-pyrolysis. Similarly, the ultimate or elemental analysis of different waste plastic materials indicated that plastic is composed, mainly, of carbon and hydrogen; however, it contains low oxygen, low nitrogen and traces of sulphur (Table 6). The high contents of carbon and hydrogen in plastics make it a good source of liquid hydrocarbons, and hence when pyrolyzed with biomass can improve, not only the yield, but also the quality of the bio-oil produced, via the synergistic interactions that occur during the co-pyrolysis process (Table 2).

The pyrolysis product of biomass consists of a solid residue (bio-char), a liquid fraction (bio-oil), and gaseous component. Consequently, the kinetic energy of biomass occurs based on the specific process undertaken at the given period. Generally, during pyrolysis, the biomass decomposes under temperatures of between 673 K and 873 K and during the thermal process, there are three distinct products materials, namely; liquids that are about 50%, 30–80% of gaseous residue, and 20–35% of solid residue; and notably, some of the gases present include; CO₂, H₂, NH₄ and CO, depending on the biochemical compositions of the biomass type [102]. Similarly, the products of co-pyrolysis of biomass and different waste plastics are the liquid fraction (bio-oil), the solid residue (bio-char/charcoal) and the gaseous fractions, but of greater quality and quantity than those of the normal pyrolysis of biomass alone, and have been used as raw materials in the industries for manufacturing of various valuable products such as chemicals, fuels (for transportation, heating and lightening purposes), fertilizers or soil amendment materials, besides the generation of electricity and heat energy used for various applications. Notably, the bio-oil which is the liquid and the main products of the process can be used as fuel [103] while the bio-char (the solid by-product) is advantageous to the agricultural industries is ultimately quite economical for manufacturing of fertilizers that are crucial in the agricultural sector [102].

4.2. Biomass and waste plastics co-pyrolysis technologies/processes

Generally, pyrolysis technologies have been categorized by many researchers as slow, intermediate, fast and flash pyrolysis [93,94], but since the most commonly used systems are the slow and fast pyrolysis process, even in the case of biomass and waste plastics co-pyrolysis, and as a result, this paper focuses mainly on these two technologies. It is also worth noting that the main product of the slow pyrolysis process is the bio-char because the process occurs at moderate temperature, low heating rate conditions and longer residence time. On the other hand, pyrolysis oil (bio-oil) is the major product of fast pyrolysis and is characterized by a rapid heating rate and short residence time. Thus, fast pyrolysis process normally produces a higher quantity and quality of pyrolysis oil than slow pyrolysis [93,94,104]. According to Roy and Dias [94], slow pyrolysis may provide greater environmental benefits than the fast pyrolysis because it produces more bio-char which can be applied to soil to improve its quality and to sequester carbon; however, fast pyrolysis has a better economic return because of its production of higher value products. Moreover, both the slow and fast pyrolysis processes/technologies of biomass are not entirely different from those of the co-pyrolysis of its blend with various hydrogen-rich co-feeding elements such as the waste plastics or other synthetic polymers. Thus, on that note, basically, the pyrolysis of different biomasses as well as

their blends with other materials which are carried out in the TGA devices are normally slow pyrolysis with several process stages, including dehydration, component decomposition, depolymerization, devolatilization, and slow decomposition of carbonaceous solid residues, however, depending on the type and compositions of the biomass, and this typical pyrolysis process takes place normally under low heating rate conditions. On the other hand, the pyrolysis carried out in the industrial reactors and Py-GC/MS devices are fast pyrolysis and normally take place under fast heating rate conditions. Generally, there are three main stages of thermal decomposition for seaweed biomass, and this is slightly related to those of the lignocellulosic biomass but yet different. These thermal degradation stages include dehydration, devolatilization and slow decomposition of carbonaceous solid residues [105–109]. For example, Sanchez-Silva et al. [110] performed the pyrolysis of three lignocellulosic biomasses (fir wood, eucalyptus and pine bark) and a marine biomass (*Nannochloropsis gaditana microalgae*) via TGA-MS, and observed that the thermal degradation of the lignocellulosic biomasses took place in four stages corresponding to water removal (dehydration process) and the decomposition of the main components (cellulose, hemicelluloses and lignin) with slight differences in their degradation rates due to the differences in the volatile matter and cellulose contents of the lignocellulosic species while that of the microalgae occurred in three stages due to its main components. Likewise, Peng et al. [111] investigated the pyrolysis characteristics of two microalgae species (*Spirulina platensis (SP)* and *Chlorella protothecoides (CP)*) at different heating rates (15, 40, 60 and 80 °C/min), up to a pyrolysis temperature of 800 °C and identified three different major stages (dehydration, devolatilization and solid decomposition) of the pyrolysis process. Their results further revealed that SP and CP devolatilized mainly at 190–560 °C and 150–540 °C respectively. Similarly, Marcilla et al. [112] studied the pyrolysis process of the microalgae *Nannochloropsis species* at a heating rate of 35 °C/min and also identified the three main stages in the decomposition process: the dehydration stage (that occurs within 25–180 °C), the devolatilization stage (180–540 °C) and the residue slow decomposition stage (540–800 °C), with the main step of the decomposition as the devolatilization stage which involves at least three overlapped steps at 290, 340 and 460 °C, respectively. However, Wang et al. [113] investigated the pyrolysis of seaweed (*Enteromorpha clathrata*), rice husk, and pyrolysis of the blends of *Enteromorpha clathrata* and rice husk at different mass ratios using thermogravimetric–infrared–mass spectrometry analysis. The results of their study indicated that the pyrolysis of seaweed and rice husk can be classified into four stages: evaporation, depolymerization, devolatilization, and carbonization.

4.3. Main reactor types used during biomass-plastic co-pyrolysis and the process conditions /parameters

It is worth noting that both the slow and fast pyrolysis technologies are carried out in a pyrolyzer. A typically pyrolyzer generally consists of a reactor, cyclone and condenser. Therefore, the feedstock materials such as the biomass, plastics or their blends are usually fed into the reactor and converted into various products via several thermochemical reactions. The cyclone is employed to separate the solid products from the liquid fractions and gases while the condenser rapidly quenches the vapor products, thus separating the bio-oil from the non-condensable gases [97]. Recently, in most cases, catalysts are also employed, either directly or indirectly, together with the biomass feedstock materials or their blends to improve the conversion efficiency and the quality of pyrolysis products in the pyrolyzers during the cases of catalytic pyrolysis, catalytic co-pyrolysis of biomass and catalytic upgrading processes of the products into more valuable products, respectively [62,114,115].

Basically, the type of pyrolysis reactor employed in any pyrolysis operation or system/unit is wholly dependent on the pyrolysis process and conditions. Thus, the most common reactors employed for slow

Table 3
Summary of previous studies and recent advances on co-pyrolysis of biomass and plastics in China.

Biomass	Plastic	Pyrolysis devices & conditions	Result	Ref.
Pine wood sawdust	HDPE, LDPE, PP	TGA instrument; 20 °C/min; 25–650 °C; 30 mL/min N ₂ flow.	A significant synergistic effect existed at about 530–650 °C which resulted in about 6–12% weight loss.	[29]
Pine sawdust	PE, PP, PS	A fluidized-bed reactor; 400–650 °C; 250 mL/min N ₂ flow.	Positive synergistic effects between the mixed feedstocks were observed. A maximum carbon yield of petrochemicals (71%) was obtained at 600 °C at polyethylene to pine sawdust ratio of 4:1.	[155]
Poplar wood	HDPE	Py-GC/MS in an integrated system pyrolyzer; 475, 550, 625 °C; 20 °C/min.	The pyrolytic product distribution of HDPE changed apparently in the presence of the poplar wood during pyrolysis resulting in increased yield of light oil (paraffins).	[156]
Fir sawdust	WEEE	A vertical drop fixed-bed reactor; 250–600 °C; 20 min; 400 mL/min.	Oil yield of 62.3%, which was significantly higher than those of either component alone (i.e., 53.1% for WEEE and 46.3% for biomass) was obtained.	[157]
Bamboo waste	PS	TGA instrument; 25–800 °C.	Synergistic effect which resulted in a reduction in overall energy usage up to 6.2%, depending on the ratio of PS in the mixed feed was observed.	[148]
Cellulose, lignin, and pine wood, plastics	LDPE, PP, PS	A pyroprobe 5200 analytical pyrolyzer; 450–750 °C; 20 °C/min; 60 s	Synergistic effect exists, resulting in higher petrochemical (aromatics and olefins) yields and lower solid (coke/char) yields than those of their individual yields.	[146]
<i>Pubescens</i>	LDPE	A fixed bed reactor; 470–450 °C; 50 mL/min N ₂ flow.	Significant synergistic effects were observed resulting in the yield of aromatic hydrocarbons and coke reduction	[158]
Pine wood sawdust	PVC, LDPE, HDPE, PP	TGA instrument; 25–600 °C; 100 mL/min N ₂ flow; heating rate of 5–40 K/min.	A significant synergetic effect existed at the high-temperature region of the co-pyrolysis process.	[149]
Bamboo, empty fruit bunch, sawdust	PS, HDPE	TGA instrument; 25–800 °C; 50 mL/min N ₂ flow.	Existence of synergistic effects during the co-pyrolysis between the plastic and biomass fractions of the blends was observed.	[64]
Cotton straw	PP	A fixed-bed reactor; 380–480 °C.	Results showed that there was a synergy in the co-pyrolysis process of the cotton straw and PP at the temperature range of 380–480 °C	[51]
Black-liquor lignin	PE, PP, PS	A fluidized bed; N ₂ at 250 mL/min flow rate; 25–650 °C; 20 min	Results showed that the catalytic co-pyrolysis improved the petrochemical yields (aromatic and olefin) and the xylene selectivity.	[143]
<i>Dundaliella teretifolia</i>	PP	TGA instrument; N ₂ at 50 mL/min; 25–800 °C & heating rates of 5, 10, 20 & 40 °C/min.	The TGA results showed that the existence of significant synergistic interaction between the microalgae and PP achieved maximum hydrocarbon conversions when the mass ratio of PP and <i>D. teretifolia</i> is 6:4, and lowered the activation energy.	[150]
Potato	HDPE	A horizontal quartz tubular reactor; argon at 0.42 L min ⁻¹ ; 25–900 °C.	Synergistic effect existed but became more significant during the secondary co-pyrolysis process than the primary process, which improved the bio-oil quality.	[151]
Waste newspaper biomass	HDPE	A quartz tubular furnace; N ₂ at 20 mL/min; 25–500 °C; 10 °C/min.	Synergistic effect occurred (at 400–500 °C) resulting in a significant increase in oil phase compared to the theoretical results.	[36]
Lignin	LDPE, PC, PS	A micro pyrolyzer coupled with GC/MS (i.e., Py-GC/MS) and TGA at 25 to 900 °C.	Synergistic effect existed which promoted the formation of monomer aromatic hydrocarbons during the co-pyrolysis of lignin with PS; while the production of several aromatic compounds assigned to lignin pyrolysis was suppressed by the addition of PC or LDPE.	[139]
Paulownia wood	PP, PVC, PET	TGA instrument; 50–1000 °C; 60 mL/min N ₂ flow; heating rates of 10, 20 & 40 °C/min.	A significant synergistic effect existed between the plastic and the Paulownia wood during the co-pyrolysis process with more volatiles release than the predicated values.	[152]
Waste vegetable oil	HDPE	A titanium retort of Autoclave heated by an electric furnace; N ₂ flow rate of 100 mL/min; 25–900 °C; 10 °C/min; 40 min.	The results revealed that a maximum hydrocarbon fuel yield of 63.1 wt% was obtained at 430 °C, and that oxygenates were rarely detected in the hydrocarbon fuel due the synergistic effects of the catalytic co-pyrolysis.	[153]
Ligno-cellulosic biomass (rice straw)	LDPE	TGA instrument; 25–600 °C; 30 °C/min, N ₂ flow rate of 20 mL/min.	Results showed that rice husk & LDPE co-pyrolysis was more complicated than that of the individual components and there was a positive synergistic interaction between rice husk and LDPE which results in the reduction of the activation energy of the reaction.	[126]

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Table 3 (continued)

Biomass	Plastic	Pyrolysis devices & conditions	Result	Ref.
Organic food waste (soybean protein)	Plastic waste (PVC)	A horizontal quartz tubular reactor (i.e., A fixed bed reactor); N ₂ flow rate of 100 mL/min; 400, 500 and 600 °C; 10 min; 10 °C/min	The results indicated that the synergistic interaction accelerated the reaction during co-pyrolysis by lowering the activation energies by 2–13% for the decomposition of mixture compared with linear calculation while the maximum reaction rates were 12–16% higher than calculation. However, the interaction also resulted in the reduction of the yield of tar by 2–69% and promoted the yield of char by 13–39% compared with linear calculation.	[159]
Bamboo	PP	A microwave oven at 1000 W and 2450 MHz.	A maximum yield of bio-oil (of 61.62 wt%) was obtained at 250 °C. Also, the oxygenate proportion compounds decreased with increasing catalyst content.	[125]

pyrolysis include, among others, the drum, rotatory kilns, and screw/ auger while for the fast pyrolysis, the reactors that can be applied include the fluidized bed, fixed bed, auger, vacuum, entrained flow, rotating cones, ablative reactors, etc. [116,117]. However, the auger reactors can be used in both slow and fast pyrolysis [117]. According to Vamvuka [118], Marshall [117], and Roy and Dias [94], it has become obvious that the fluidized beds and rotating cone configurations are more cost effective and easier to be scaled-up; however, both auger and fluidized bed configurations are more commercially important technologies for agricultural applications since they can successfully manipulate and control the rates of the feedstock in the pyrolyzer; and thus both configurations are commonly used for effective bio-oil production. Marshall [117], also stated that the screw feeder is a typical reactor with a feed system design and high torque, which can thus effectively and efficiently handle a variety of difficult feedstock materials such as the herbaceous biomass, like the corn stover that tends to bind together and hence affects its flowability in the pyrolyzing system. Therefore, it requires a feed system design with a greater torque. It is also worth noting that the pyrolysis product yields, distributions and properties are almost entirely dependent on the pyrolysis reactors design/configurations, the operating pyrolysis conditions (e.g., temperature, pressure, heating rate, residence time, etc.), the feedstock properties/compositions and special parameters like the feedstock blending ratio in the case of co-pyrolysis, either with or without catalysts, and also the pyrolysis environment (including the presence of inert gases or carbon dioxide, or even the various materials of reactor beds) [95,119,120] (see also Tables 2–4). Besides, according to Crombie and Mašek [121] and Yoder et al. [122], each pyrolysis technology has a distinct application and target. Thus, if a higher yield of bio-char is required, then the slow or intermediate pyrolysis technology is preferable, but if maximizing the bio-oil is the target, then the fast/flash pyrolysis is employed. Thus the production of high-grade quality and quantity of such valuable pyrolysis products (bio-oils and bio-char) can be achieved by varying the operational parameters/conditions. However, in the case of biomass and waste plastic co-pyrolysis, the most effective of those parameters include, among others, the pyrolysis temperature, heating rate and the feed blending ratio; and these parameters not only affects the bio-oil and bio-char yields, but grossly influence the gas yields. Thus, during the pyrolysis of either the single biomass sample alone or its blend with plastics or other co-feeding elements, it has been evidenced that the production of bio-char or charcoal during the slow pyrolysis commonly occurs at a lower heating rate (most especially within the range of 0.1–0.8 °C/s) with a longer residence time (of either 5–30 min or even 25–35 h) and at a moderate temperature range of 573–823 K, however, the bio-char yield normally decreases, in most cases, with the increasing pyrolysis temperature since at higher temperatures, the biomass are combusted as cellulose and hemicellulose are also destroyed [19,117,123,124]. Roy and Dias [94] traced the trends of the effects of these effective parameters on the product yields and distributions during slow pyrolysis, and noticed that the yields of bio-oil and bio-char depend on the feedstock properties and operating temperatures, however, there no clear trend on the effect of heating rate on yields.

4.4. The role of catalysts in biomass-plastic co-pyrolysis

Catalysts have been found to play a number of important roles in the conversion of biomass–plastic mixtures to valuable aromatics and reduction of coke formation during catalytic co-pyrolysis [125–132]. Notably, the primary catalyst used in this process is the zeolite. Catalytic co-pyrolysis has been observed by many researchers to enhance the carbon yield of the petrochemicals (particularly the monocyclic aromatic hydrocarbons), and also lowers the formation of coke owing to the addition of suitable zeolite catalyst in the right proportion during the process [101,125,126,132]. Likewise, the addition of appropriate catalysts has been also found to enhance the efficiency of the

Table 4
Summary of recent progress and previous studies on co-pyrolysis of biomass and plastics elsewhere worldwide (from 2002 to 2018).

Biomass	Plastic	Pyrolysis devices & conditions	Result	Ref.
Beech wood, pine wood, cellulose, lignin	Medium density PE, PP	A stainless steel rotating autoclave; 360–450 °C.	A higher light liquid yield was observed with a maximum yield occurring at 400 °C which indicated a synergistic effect	[160]
Olive residue	HDPE	TGA instrument; heating rates of 2, 10, 20 and 50 K/min; 300–975 K.	A synergistic effect occurred which resulted in a 7–11% difference in the experimental and theoretical weight loss at 450–630 °C	[175]
Timber	LDPE, PP, and PS	A stainless steel tubular Curie-point pyrolyzer/reactor; 700, 800, 900 °C; 30 °C/min; N ₂ at 0.33–0.53 mL/s; 3 min.	There was an interaction between the biomass and plastic mixtures resulting in higher oil yield with lower char product was obtained	[176]
Olive residue	LDPE, PP, and PS	TGA instrument; 27–1000 °C; N ₂ as the carrier gas; heating rates of 2, 10, 20 and 50 K/min.	Significant interaction/synergistic effect occurred at 400–500 °C, between the olive residue and plastic during the co-pyrolysis process	[177]
Pine wood sawdust	PS and PP	A vertical Pyrex reactor; 450 °C; 5 °C/min.	Addition of the polymers resulted in the production of more oils with lower oxygenated compounds than that from the individual polymer	[56]
Hazelnut shell	Ultra-high-molecular weight PE	A tubular reactor with electric furnace; 425–650 °C; 15 min.	Results revealed a higher yield of liquid and gas products at 515 °C	[178]
Pine biomass	PP, PE, PS	An autoclave system; 400 °C; 15 min; 40 MPa.	Synergistic effect resulted in higher liquid yield	[179]
Willow (target biomass)	Biopolymers (PLA, corn starch, PHB, Biopearls, Eastar, Solanyl and potato starch)	A semi-continuous home-built pyrolysis reactor; 723 K.	Improved pyrolysis characteristics with specific benefits at a mixing ratio of 1:1 and temperature of 723 K were obtained. Flash co-pyrolysis of willow and PHB was the most performing option with a maximum condensable yield of 64.24 wt % and HHV of 20.2 MJ/kg	[180]
Pine	Mixture of PE, PP, and PS (plastic wastes)	A stainless autoclave with furnace; 350–450 °C; 30 min; 1.0 MPa.	Higher liquid yields of high heating values were obtained due to the addition of the plastic mixture which improved the overall efficiency of the slow pyrolysis of pine	[49]
Hazelnut shell	PE oxide	A tubular reactor with electric furnace; 425–650 °C; 15 min.	Interaction effect increased oil yield but not gas yield	[181]
Pine cone	PE, PP, and PS	A glass reactor under atmospheric pressure; 500 °C; 10 °C/min.	Higher oil yield with lower char product was obtained	[52]
Oil shale	HDPE, LDPE, PP	A stainless steel autoclave under nitrogen atmosphere; 400–600 °C; 2–20 °C/min.	The results indicated the existence of interactions between the constituents during the co-pyrolysis which enhanced the chemical reactivity and produced a higher conversion than that from individual oil shale, with a maximum oil yield of 54.8 wt% obtained from the oil shale-PP mixture at 525 °C and 10 °C min ⁻¹	[182]
Beech wood sawdust and paper	PE	A stainless steel capsule with electric heater; 500, 750, 800 °C	No remarkable effects of interaction on product yields for wood-PE mixtures at both 0.1 °C/s and 1 °C/s, and for paper-PE mixtures at 1 °C/s probably due to the presence of large amounts of inert materials, mainly metal oxides	[165]
Palm shell	PS	A stainless steel tubular reactor; 2 L/min of N ₂ flow; 400, 500, 600 °C.	Synergistic effect between the palm shell and PS resulted in a maximum liquid yield of 68 wt% at 600 °C, with a high heating value of 40.34 MJ/kg	[48]
Cotton stalk, hazelnut shell, sunflower residue, and <i>Euphorbia rigida</i>	PVC, PET	TGA instrument; 10 °C/min; N ₂ flow rate of 100 cm ³ /min; 25–800 °C.	The co-pyrolysis results in significant changes in both the thermal decomposition and kinetic behaviors of the biomass and plastic mixtures	[183]
Swine solids	Spent plastic mulch films	A stainless steel batch reactor; 25–500 °C; Argon as carrier gas.	Synergistic effects exist between the co-feeds during co-pyrolysis and the heating value (HHV) of the produced gas was found to be much higher than that of the natural gas	[167]
Switch grass, cellulose, xylan, and lignin	PET, PP, HDPE, LDPE, PS	A micro pyrolyzer coupled with GC/MS (i.e., Py-GC/MS); 650 °C	Addition of the polymers enhanced the conversion of the mixture, resulting in increase in the total aromatic yields and changes in the selectivity for the production of individual aromatic compounds	[132]
Alder wood (hardwood) and pine wood (softwood).	PP	A steel retort; N ₂ at 3 dm ³ /h; 600 °C	Addition of plastics to biomass led to synergistic effects, as determined by variations in the amounts of products obtained from the co-pyrolysis of biomass and polypropylene relative to those obtained from the pyrolysis of pure biomass or polypropylene	[128]
Wood (beech and pine); lignin and two types of cellulose: Avicel and Whatman	PVC	Py-GC/MS (at 600 °C for 20 s in a quartz tube with helium gas) and TG/MS (at 25–900 °C; 20 °C min ⁻¹).		[184]

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Table 4 (continued)

Biomass	Plastic	Pyrolysis devices & conditions	Result	Ref.
Karanja and Niger seeds	Wastes PS	A stainless steel reactor; atmospheric pressure; 500–600 °C.	The addition of PVC to the biomass sample resulted to formation of lower amount of several reactive compounds with a significant amount of chloromethane in the pyrolysate of wood and lignin samples mixed with PVC Results confirmed that co-pyrolysis of the non-edible seeds and waste polystyrene not only enhanced the conversion of seeds to useful products but also significantly affected the oil fuel properties (viscosity, calorific value, cold flow properties), and altered the composition of the oil with a positive influence Co-pyrolysis of rice husk blended with plastic wastes led to the production of high quality bio-oils	[50]
Rice husk	PE	A batch reactor; 430 °C; 0.2–1 MPa; 5–6 °C/min; 10 min.		[154]
Red oak	HDPE	A lab-scale, continuous fluidized bed reactor; 525–675 °C.	Synergistic interaction between the red oak and HDPE mixture during co-pyrolysis resulted in higher heating value (36.6 MJ/kg) of the pyrolysis-oil produced, increased the production of furan, acids, and water, inhibited char formation and improved the HHV of the resulting char	[185]

conversion process by lowering the activation energy and temperature/heat of the reactions during catalytic co-pyrolysis of biomass and plastics [114,118,129,130,132]. However, it has been noticed that the life time of the zeolite-based catalysts can be significantly affected by the presence of heteroatoms during the catalytic co-pyrolysis process. Thus, the development of more appropriate catalyst that has more suitable acid sites and acidity for target products via certain reaction pathways, and of quality life time is required to mitigate the problems associated with catalytic co-pyrolysis. Nevertheless, catalytic co-pyrolysis is discerned to be a very promising technology, most especially, for reduction of over-dependency and consumption of fossil fuels, mitigation of global warming effects, improvement of waste management systems as well as enhancement of energy security. In addition, highly valuable by-products, gas and char, are also obtained via the process. It is also, inarguably, worth noting that the catalytic co-pyrolysis of biomass with waste plastics for production of valuable aromatics is a much more promising technology than the catalytic pyrolysis of biomass alone [125–132]. Several research results have proven that the use of the catalyst, HZSM-5, is the most effective technique in the pyrolysis of biomass and plastics by transforming the waste products into aromatics [132]. However, the use of the catalyst, HZSM-5, in the process of catalytic thermal decomposition of the synthetic polymer-biomass mixture shows different characteristics when exposed to fast and slow heating. Under slow heating; the thermal decomposition of the biomass-plastic waste mixture into valuable products significantly reduces when the catalyst (HZSM-5) is applied due to acid catalyzed reactions on the zeolite surface [132]. By increasing the amount of the catalyst to about 10%, the process of the catalytic decomposition increases to a given extent indicating that the process increases as the catalyst is applied [130]. This will lead to almost half of the decomposition as compared to a catalyst-free process. At the same temperature, when the amount of HZSM-5 is increased in a 1:1 ratio, the level of decomposition of biomass plastic mixture increases significantly leading to the formation of 10% char. This shows that a small amount of the catalyst has a negligible effect on the decomposition of the biomass-plastic waste, however, when the ratio of the catalyst and biomass is 1:1, the level of decomposition increases significantly at low temperatures to form char [130]. For instance, when 10% of HZSM-5 is applied in the biomass-plastics co-pyrolysis to decompose 60% of the biomass-plastic mixture, the process of decomposition is hindered, and very little decomposition takes place. However, when the catalyst ratio is increased by 50%, the catalytic thermal decomposition of synthetic polymer-biomass mixtures is evident as it completely decomposes the whole polymer. This is because the cellulose and lignin contained in the polymer mixture start to decompose after the catalytic pyrolysis of PE and PP at a temperature of about 230 °C. At 330 °C temperature, the intensity of the catalytic degradation products drops abruptly while the remaining PE and PP decompose at a higher temperature of about 470 °C. The presence of lignin completely hinders the process of catalyst activity in the decomposition process leading to most thermal decomposition occurring at normal temperature without the catalyst. The blocking of catalyst activities by lignin can be interpreted by the number of aromatic products produced where low amounts of aromatic products indicate an incomplete thermal decomposition on the biomass-plastic mixture due to deactivated acidic zeolite sites and delayed reactions from the catalyst in the decomposition process of the biomass products [128]. This is generally because the thermal decomposition of lignin begins at very low temperatures. The presence of the catalyst, HZSM-5, increases the thermal decomposition of biomass-plastic products and the total amount of aromatic products produced which increases with increase in temperature up to the optimal level temperature of 550 °C. At this temperature, complete thermal decomposition of the biomass products is observed. Thus, HZSM-5 catalyst in the process of catalytic decomposition significantly decreases the amount of heat need for the decomposition of hydrocarbon polymers but does not modify the thermal decomposition of PET. Research indicates that a

small amount of cellulose only hinders the process of biomass-plastic decomposition while increasing cellulose in ratios more than the catalyst completely blocks the catalytic activities of HZSM-5 on biomass-plastics decomposition under low temperatures.

5. Overview of recent advances and studies on co-pyrolysis of biomass and plastics

5.1. Overview of recent advances and previous studies on biomass-plastics co-pyrolysis in China

China, as a large agricultural country, is rich in biomass resources. The principal biomass resources in China include residues from agriculture and forest industries (with the annual available amounts of 440 and 350 million tons of coal equivalents (tce) respectively), animal manure from medium and large-scale livestock farms and municipal solid wastes (of annual available amounts of 28 and 12 million tce, respectively) [133]. Thus, China has a huge development potential for biomass energy [134]. As a result of the abundant biomass resources, China's biomass power generation industry develops rapidly [135]. Since the total amount of potential renewable energy sources in China is substantial, it is therefore essential and meaningful to properly integrate renewable energy into future energy systems in China through different methods of renewable energy generation, including the thermo-chemical and biological technologies for biofuel/bioenergy production.

However, China is currently experiencing the ever-increasing twin challenges of energy supply and demand as a result of high-speed economic growth and modern development which attract tremendous energy consumption. According to the National Bureau of Statistics of China [136], the total energy production in China, between 1978 and 2014, increased from 627.7 million tce to 3.6 billion tce with an annual increase rate of 4.83% while the energy consumption increased with the annual rate of 5.58% in the same period, reaching 4.26 billion tce in 2014, jumping by 7.45 times. As a result, by the end of 2014, China has accounted for 23% of global energy consumption and 61% of net energy consumption growth. Thus, Chinese government faces a growing pressure to address the energy shortage and environmental deterioration, mainly resulting from an over-dependence on fossil fuels, majorly coal. According to Chai and Zhang [137], coal presently contributes about 70% of China's primary supply, and will continue to play a vital role in powering China's economic development. However, the coal-based energy production and consumption system face many considerable challenges/problems, including shortages of resources, low energy efficiency, high emissions and environmental damage, and lack of effective management systems [138].

The increasing challenges of energy of China coupled with environmental pollution problems as a result of excessive CO₂ emissions, have promoted a great research effort on a search for not only appropriate technologies for production of alternative, sustainable, and renewable energy, but also environmentally friendly waste management technologies for an improved and efficient handling of generated wastes, while converting them to valuable resources such as energy/fuels and valuable chemicals. As a result, a wide variety of strategies for thermochemical conversion of the nuisance biomass and municipal solid wastes, most especially, waste plastics have been explored in the last decades. Pyrolysis has, undoubtedly, been pointed out as the most studied thermochemical process and has recently metamorphosed into co-pyrolysis for production of high-grade fuels, capable of replacing the depleting fossil fuels or reducing the over-dependency on them. As a result, co-pyrolysis of biomass with polymer wastes has gained increasing attention and interest in recent years worldwide as it is capable of producing high quality and quantity oil. However, most of the co-pyrolysis studies have been carried out in thermobalances, micro-reactors and fixed bed or autoclave batch reactors, and therefore they are of a preliminary nature and the information obtained cannot be directly extrapolated to industrial reactors conditions

[13,43,47,62,65,113,132,139–142]. The studies performed in continuous reactors are scarce and limited to laboratory scale units [143]. The most widely studied feedstock for co-feeding with biomass are plastics and tires [13,65,141,144]. However, recent research studies and development in the co-pyrolysis field, both in China and elsewhere in the world, revealed that significant attention has been paid to the recently emerging catalytic co-pyrolysis of biomass and plastics, with more emphasis on the investigation of the reaction mechanisms of biomass and plastics, applications, and investigation of various types of catalytic co-pyrolysis reactors such as the Py-GC/MS and microwave assisted catalytic co-pyrolysis technology, and understanding of the functions and effects of the different catalysts (e.g., ZSM-5 zeolite and mesoporous materials) that are being used in co-pyrolysis of biomass. Thus, a large number of works have been reported on catalytic co-pyrolysis of biomass and plastics [141,145,146]. For example, Zhou et al. [29] employed the single first order reaction kinetics for Chinese pine wood sawdust, high density polyethylene (HDPE), and low density polyethylene (LDPE), two thermal events for polypropylene and three events for blends of wood sawdust and plastics. A significant synergistic effect was observed between the biomass and plastic during the co-pyrolysis process. Li et al. [146] investigated the catalytic fast pyrolysis (CFP) of a series of biomass (cellulose, lignin, and pine wood), plastics (LDPE, PP, and PS), and their mixtures with ZSM-5 zeolite. The results showed that co-feeding of cellulose with LDPE (4:1), and that of pine wood with LDPE mixtures (2:1), have a synergistic effect, and produced higher petrochemical (aromatics and olefins) yields and lower solid (coke/char) yields than those of their individual yields determined by linear addition of their CFP corresponding yields. Li et al. [65] analyzed the performance of different acid catalysts in the co-pyrolysis of biomass and LDPE in a Pyroprobe reactor. In a preliminary study dealing with the co-pyrolysis of cellulose and LDPE on a HZSM-5 zeolite, interesting synergies were observed involving the yield of aromatic hydrocarbons and coke reduction. In a later study, they approached HZSM-5 modification with P and Ni/P for the co-pyrolysis of LDPE and biomass in the same experimental unit. The main improvement by incorporating P and Ni was an increase in the yield of light olefins and aromatics and a reduction in that of alkenes and coke. Similarly, Ga incorporation to the HZSM-5 zeolite improved the co-pyrolysis performance by improving the yield of single ring aromatics and light olefins. Qian et al. [147] studied the co-pyrolysis of lignite and relatively small amounts of polyethylene (PE) (below 10 wt% in a fixed bed batch reactor. The plastic co-feeding showed a positive effect on lignite pyrolysis, promoting tar and gas formation and reducing the char yield, with these changes being more pronounced than theoretically predicted from the results obtained in the individual pyrolysis of lignite and PE. This synergetic effect was related to the stabilization of lignite depolymerization primary products, which avoids their deposition on the solid residue. Oyedun et al. [148] studied the possible synergistic effects on the overall energy used during co-pyrolysis process of polystyrene (PS) and bamboo waste using two different modeling approaches, at China. The mass loss and volatile generation profiles revealed that considerable interactions existed between the two co-feeding materials (feedstocks), and that both modeling methods gave an appreciable synergistic effect of reduction in the overall energy when PS and bamboo are co-pyrolyzed. Oyedun et al. [64] also investigated the thermal behavior of plastics (PS and HDPE) and their blends with biomass (bamboo, empty fruit bunch and sawdust) using a thermogravimetric analyzer subjected to a heating rate of 10 K/min from room temperature to 1073 K under a nitrogen flow rate of 50 mL/min. The results revealed the existence of chemical interactions or synergistic effects between the plastic and biomass fractions of the blends during co-pyrolysis. The results of the kinetics of the blends revealed that an increase in the percentage of plastic in the blends led to a decrease in the apparent activation energy of the first decomposition stage process reaction, however, it results in a subsequent increase in the activation energy of the second decomposition stage reaction. Han et al. [149] studied the co-pyrolysis behaviors of plastics (polyvinyl chloride (PVC), LDPE, HDPE, PP) and biomass (pine wood sawdust) blends using a thermogravimetric (TG) analysis from room

temperature to 873 K with a heating rate of 5–40 K min⁻¹ in an inert atmosphere. The results showed that a considerable synergetic effect existed during the high-temperature region of the process. Hua et al. [51] investigated the co-pyrolysis behavior of a mixture (PP and cotton straw) under an inert atmosphere by a TGA. Afterwards, the crude bio-oil was used as feedstock for hydrodeoxygenation over Ni-Mo/Al₂O₃, and the upgraded oil was analyzed by GC-MS. It was observed that the doping of PP with cotton straw improved the bio-oil yield, which revealed the existence of a synergy between the cotton straw and PP at the temperature range of 380–480 °C during the co-pyrolysis process. Also, the deoxygenation rate of the model compounds decreased over Ni-Mo/Al₂O₃ in the following order: alcohol > aldehyde > acetic acid > ethyl acetate. The upgraded oil mainly consisted of C11 alkane. Zhang et al. [143] conducted catalytic co-pyrolysis of black-liquor lignin and waste plastics (PE; PP; PS) in a fluidized bed, and studied the effects of temperature, plastic to lignin ratio, catalyst, and plastic types on product distributions. The results revealed that both aromatic and olefin yields increased with increasing PE proportion. Petrochemical yield of co-pyrolysis of PE and lignin assumed the order: LOSA-1 > spent FCC > Gamma-Al₂O₃ > sand while the yield (43.9%) with LOSA-1 is more than two times of that without catalyst. The effect of feedstock for co-pyrolysis with lignin follows the trend: polystyrene > polyethylene > polypropylene. Catalytic co-pyrolysis of black-liquor lignin with PS produced the maximum aromatic yield (55.3%), while co-pyrolysis with PE produced the maximum olefin yield (13%). Wu et al. [150] investigated the co-pyrolysis kinetics of *Dunaliella tertiolecta* and polypropylene (PP) via TGA, and analyzed the gas-phase components and volatiles transition using TG-FTIR and TG-MS. The TGA results showed that the existence of significant synergistic interaction between the microalgae and PP achieved maximum hydrocarbon conversions when the mass ratio of PP and *D. tertiolecta* is 6:4, and lowered the activation energy. Xiong et al. [151] investigated the interactions between HDPE and potato during their primary and secondary co-pyrolysis processes by a thermogravimetric analyzer (TGA) and a tubular furnace. The result revealed that synergistic effect was much more significant during the secondary co-pyrolysis of potato and HDPE blends than the primary process, and the bio-oil quality was improved by enhancing the hydrogen content and reducing the oxygen content of the pyrolysis oil. Also, the results of tubular furnace experiments showed that the interaction that occurred in the gas phase not only favored the formation of gaseous products, but also improved the bio-oil quality by significantly reducing the oxygen-to-carbon ratios (O/C) of the pyrolysis oil.

More recently, Chen et al. [36] investigated the synergistic effects during the co-pyrolysis process of waste newspaper biomass with HDPE using thermogravimetric analysis (TGA) coupled with infrared spectroscopy (TG-FTIR), physical properties analysis, elemental analysis, Fourier transform infrared spectroscopy (FTIR), and gas chromatography/mass spectrometry (GC/MS) in order to enhance the oil yield and its fuel properties. The results showed that a positive synergistic effect occurred at 400–500 °C resulting in a significant increase in oil phase by 31.59% as compared to theoretical data. Also, a dramatic decrease in viscosity and total acid number by 75.96% and 216.04% respectively in comparison to theoretical data were observed. Chen et al. [152] also studied the thermal behavior of Paulownia wood (PAW), model plastics (PP, PVC, and polyethylene terephthalate (PET)) and their mixtures during pyrolysis process through thermogravimetric analyzer. They also applied scanning electron microscopy technology (SEM) and fractal theory to evaluate the surface morphology of pyrolysis chars. The results revealed the existence of synergistic effect between PP and PAW during the co-pyrolysis process with more volatiles release than predicated value, and the maximum volatile yield was achieved with 25% PAW blending ratio. However, higher char yields were observed compared with the predicted values during the co-pyrolysis process of PAW blends with PVC or PET, and a significant decrease in the mean activation energy was observed during the co-pyrolysis process of the PAW blending with plastics. While Wang et al. [153] performed the catalytic co-pyrolysis of waste vegetable oil and

HDPE for hydrocarbon fuel production using a ZrO₂-based polycrystalline ceramic foam catalyst and examined the effects of pyrolysis temperature, catalyst dosage, and HDPE to waste vegetable oil ratio on the product distribution and hydrocarbon fuel composition. The results showed that a maximum hydrocarbon fuel yield of 63.1% was obtained at 430 °C, and that oxygenates were rarely detected in the hydrocarbon fuel due the synergistic effects of the catalytic co-pyrolysis. Also, the hydrocarbon fuel yield increased when the catalyst was used; and the fuel composition was simplified and the fuel quality improved. Table 3 presents a summary of the studies on co-pyrolysis of biomass with plastics for high quality biofuel production in China. Likewise, Table 4 presents a comprehensive summary of the recent progress and previous studies on co-pyrolysis of biomass and plastics elsewhere worldwide. From both tables, it can be seen that several studies have been carried out on co-pyrolysis of biomass and waste plastics, and recent research advances focused mainly on catalytic co-pyrolysis. The results in these tables, inarguably, revealed that a lot of recent and previous research works have been performed on biomass and plastic co-pyrolysis to either investigate the pyrolysis characteristics, thermal behavior of the blend, extent of synergistic interactions during co-pyrolysis, the role of catalyst in co-pyrolysis of biomass with different types of waste plastics or examine /analyze the product yields, distributions and quality of its products. Thus, from those two tables, it can also be observed that the pyrolysis studies were performed mainly either under low or fast heating rate conditions using different reactors (including the fluidized bed reactors, fixed bed or quartz tubular reactors, pyroprobe pyrolyzers, micro pyrolyzers, microwave oven, autoclave with electric furnace, TGA and PY-GC/MS devices, etc.). It is also worth noting that different operating pyrolysis conditions were applied during each pyrolysis process in the reactors/pyrolysis devices, however, depending on the type of reactor/device used and its design/configurations as well as the desired results/targeted goal. For example, when alder wood was pyrolyzed with Polypropylene (PP) in a steel retort reactor at a nitrogen gas flow rate of 3 dm³/h; and temperature of 600 °C, the results indicated that the addition of the plastic to the biomass led to synergistic effects which results in an obvious difference in the oil yield from the co-pyrolysis of biomass with PP and that obtained from pyrolysis of pure biomass [128]. Likewise, when the cotton straw is mixed with PP in a fixed bed reactor at the temperature of about 380–480 °C, the results showed that there was also a positive synergy which improved the yield and quality of bio-oil obtained [51]. Similarly, the co-pyrolysis of rice husks with polyethylene plastic waste that was performed in a 1-l batch reactor at a temperature of 430 °C and pressure of 0.2 MPa for 10 min, led to the production of high-quality bio-oil [154]. On the other hand, the results of the TGA pyrolysis process performed under the temperature of 25–600 °C and a heating rate of 30 °C/min showed that rice husk & LDPE co-pyrolysis was more complicated than that of the individual components, but there was also a positive synergistic interaction between rice husk and LDPE which results in the reduction of the activation energy of the reaction [126]. Moreover, when different types of biomass (switch grass, cellulose, xylan and lignin) were pyrolyzed with various forms of waste plastics (PET, PP, HDPE, LDPE, PS) using the H-ZSM-5 catalyst in a micro pyrolyzer coupled with GC/MS (i.e., Py-GC/MS) and at a temperature of 650 °C, it was also observed that the addition of catalyst and synthetic polymer to biomass enhanced the conversion of the mixtures resulting in an increase in the total aromatic yield obtained [132]. Therefore, these results show that the type of reactor used, the pyrolysis conditions, compositions of co-feeding elements, and catalysts used influenced the performance of the entire process of co-pyrolysis and also determine the product yields, distributions and quality.

5.2. Overview of recent progress and previous studies on biomass-plastics co-pyrolysis elsewhere in the world

Like China, effective research and development on biofuel

production and upgrading via co-pyrolysis process and other conversion technologies are also in progress in different parts of the world as the search for alternative energy resources to replace fossil fuels lingers, however, the feedstock material for the production of biofuels varies from one country to another owing to a number of factors as identified at the initial section of this paper. For example, Sharypov et al. [160–162] and Marin et al. [163] studied in detail the thermal degradation of mixtures of polyolefins (PE and PP), biomass and biomass components (cellulose and lignin) in both thermogravimetric analyzer and autoclave reactor. The results obtained revealed a different kinetic behavior of biomass and polyolefins in the mixture, with the former being degraded at lower temperatures than the latter, and an increase in biomass content in the feed favoring the formation of water and gases, while an increase in plastic content enhances the heavy liquid fraction. Jakab et al. [164] investigated the thermal decomposition of polypropylene (PP) with wood flour, lignin, cellulose, and charcoal using the thermogravimetric method and observed the existence of two effects: the shift to a lower temperature of the thermal decomposition of polypropylene and the promotion of monomer and dimer. Paradelo et al. [49] investigated the co-pyrolysis of biomass (pine) and plastic wastes (a mixture of PE, PP, and PS). The results showed that the addition of plastic mixture improves the overall efficiency of the slow pyrolysis of pine by achieving higher liquid yields with heating values similar to that of the heating fuel oil and less solid products than in the classic slow pyrolysis carbonization of biomass. Similarly, the gas products had energetic contents superior to that of producer gas, and the solid fractions showed heating values higher than some coals. Grieco and Baldi [165] studied the interaction effects on the product yields during the pyrolysis of plastics (polyethylene) with beech wood sawdust and paper, respectively. However, the results of the study showed no remarkable effects of interaction on product yields for wood–PE mixtures at both 0.1 °C/s and 1 °C/s and for paper–PE mixtures at 1 °C/s probably due to the presence of large amounts of inert materials, mainly metal oxides, that can promote decomposition reactions of aliphatic hydrocarbons with formation of char. Brebu et al. [52] studied the co-pyrolysis of pine wood with different polyolefins (PE and PP) in a batch fixed bed reactor at 500 °C. The liquid products obtained consisted of two immiscible fractions, i.e., aqueous and oil fractions. The plastic co-feeding increased the oil fraction yield and decreased the aqueous one. Interestingly, the liquid yields were higher than the theoretical ones predicted from the pyrolysis of individual materials, which provides evidence of the synergetic effect occurring in the co-pyrolysis of biomass and polyolefins. The biomass (potato skin) and HDPE co-pyrolysis studied by Onal et al. [55] in a batch fixed bed reactor at 500 °C also revealed the existence of synergetic effects affecting the liquid yield. This effect was more pronounced for a biomass/plastic ratio of 0.5, with the liquid yield reaching a value of around 48%. The main interest of the co-pyrolysis strategy is, apart from liquid yield increase, the upgrading of its properties. Thus, the carbon and hydrogen content of the liquid were significantly increased, and both heating value and stability were also improved. Zanella et al. [47] studied the co-pyrolysis of different mixtures of coffee waste and PP in a fixed bed batch reactor between 360 and 420 °C. When the heating rate in the runs performed was low, two pyrolysis stages were observed, which is explained by the lower degradation temperatures for biomass. Conversion is limited at low temperatures, below 40% at 360 °C, mainly due to the mild PP cracking, whereas it reached values above 90% at the highest temperature studied. An increase in PP content in the feed shifts liquid product composition to heavier products. Dewangan et al. [166] analyzed the co-pyrolysis of sugarcane bagasse and LDPE in a fixed bed batch reactor in the 475–525 °C range. Oil production was 52.7% at 500 °C, with plastic co-feeding greatly improving oil properties due to the reduction of water and oxygenate content, thereby leading to heating values of up to 40 MJ kg⁻¹. Interestingly, the lower content of oxygenates, especially phenols and acids, also improved oil stability, and therefore eased its handling. Bhattacharya et al. [142]

studied the continuous co-pyrolysis of pine wood and plastics (PE and PP) in an auger (screw kiln) reactor between 475 and 525 °C. These authors did not observe any significant interaction between plastic and biomass devolatilization products. Thus, the main interest of the co-pyrolysis strategy was related to the improvement of the liquid product properties corresponding to the bio-oil, especially heating value and water content. Ro et al. [167] performed co-pyrolysis of swine manure with agricultural plastic waste to investigate the energetics of the co-pyrolyzing swine solids with spent plastic mulch films (SPM) and the characteristics of its gas, liquid, and solid byproducts. Synergetic effects existed between the co-feeding materials during co-pyrolysis and the heating value (HHV) of the produced gas was observed to be much higher than that of the natural gas. The results demonstrated the potential of using pyrolysis technology to manage two prominent agricultural waste streams (SPM and swine solids) while producing value-added biochar and a power source that could be used for local farm operations. Dorado et al. [132] performed the catalytic fast co-pyrolysis of mixtures of biomass (switchgrass, cellulose, xylan, and lignin) and plastic (PET, PP, HDPE, LDPE, PS) at 650 °C in the presence of H-ZSM-5, and evaluated the desired mixtures as well as the product distributions using a micro-pyrolyzer coupled with GC/MS (py-GC/MS). The results revealed that conversion enhancement occurred for the mixture, with the aliphatic polymers (PE and PP) and PET generally providing the biggest increase in total aromatic yields. This study does not only produce high quality fuels from biomass via co-pyrolysis of both feedstocks but will also help to address the problems associated with disposal of agricultural plastics. Sajdak and Muzyka [128] also investigated the effects of using polypropylene in the co-pyrolysis of two types of biomass (alder wood (hardwood) and pine wood (softwood)). The results show that addition of polymers (polypropylene) to biomass led to synergetic effects, as determined by variations in the amounts of products obtained from the co-pyrolysis of biomass and polypropylene relative to those obtained from the pyrolysis of pure biomass or polypropylene. Shadangi and Mohanty [50] studied the co-pyrolysis of Karanja and Niger seeds with waste polystyrene to enhance the quality of pyrolytic oil. This study confirmed that co-pyrolysis of the non-edible seeds and waste polystyrene not only enhanced the conversion of seeds to useful products but also significantly affected the co-pyrolytic oil fuel properties (viscosity, calorific value, cold flow properties), and altered the composition of the pyrolytic oil with a positive influence. Pinto et al. [154] co-pyrolyzed rice husk with polyethylene (PE) bags that are used for rice packaging and transporting seeds as well as fertilizers used for rice culture, in a batch reactor; and the produced bio-oils and solids were further subjected to different upgrading techniques (such as hydrogenation, pyrolysis followed by hydrogenation and hydrogenation of pyrolysis liquids) with gaseous hydrogen, considering technical, economical, and environmental aspects. The results showed that co-pyrolysis of rice husk blended with plastic wastes led to the production of high quality bio-oils. It was also observed that hydrogenation led to higher quality bio-oil conversions than other investigated upgrading techniques, as both gas and total liquid yields increased. Dorado et al. [48] catalytically co-pyrolyzed cellulose and plastics in the presence of HZSM-5 at 650 °C. The distribution of various ¹³C_x, ¹²C_y products was used to suggest the active mechanisms that resulted in the formation of the observed products. The result showed that the addition of co-reactants (PET, PP, HDPE, LDPE, and PS) can enhance yield and possibly increase catalyst lifetimes by reducing coke formation during catalytic pyrolysis over HZSM-5, and also offers a method for productive disposal of waste agricultural plastics.

More recently, Zhang et al. [168] investigated the thermal decomposition behaviors and kinetics of biomass (cellulose/Douglas fir sawdust) and plastics (LDPE) in a non-catalytic and catalytic co-pyrolysis over ZSM-5 catalyst using a thermogravimetric analyzer (TGA). A positive synergetic interaction existed between the biomass and plastics which resulted in increase in the quality of the bio-oil produced, and a decrease in the formation of the solid residues, suggesting that the

catalytic co-pyrolysis is a promising technique that could significantly reduce the energy input. Chattopadhyay et al. [169] performed catalytic co-pyrolysis of biomass (paper) and plastics (HDPE, PP, PET) in a fixed-bed reactor in presence of cobalt based alumina, ceria, and ceria-alumina catalysts to analyze the product distribution and selectivity towards hydrogen. The results showed that the synergistic effect between the biomass and plastics led to an increase in the liquid products, and at the same time, gaseous and solid products have followed the inverse trend. Dewangan et al. [166] carried out pyrolysis of sugarcane bagasse (SCB), LDPE, and their mixtures of different ratios in a semi-batch reactor with varying temperatures ranging from 350 to 600 °C at a heating rate of 20 °C/min in order to investigate the effect of plastic on the pyrolysis products during co-pyrolysis with biomass. The results of GC–MS and FTIR analysis also confirmed the interaction between SCB and LDPE during co-pyrolysis, which resulted in a decreasing amount of oxygenated compounds, phenol and acidic compounds, making the co-pyrolysis process more favorable for the production of high calorific value fuel. Yang et al. [41] performed co-pyrolysis of LDPE with three kinds of biomass (cedar wood, sunflower stalk, and *Fallopia japonica* stem) in a dropdown tube reactor, and investigated the synergistic effect by comparing the experimental relative yields and characteristics of oil with the calculated ones based on the results from the pyrolysis of the individual components in the mixture. The result showed that synergistic effect was positive for the production of aliphatic compounds. Kumagai et al. [170] investigated the interactions between beech wood (BW) and PE during co-pyrolysis of both their individual components and mixtures from ambient temperature to 650 °C at a heating rate of 10 °C min⁻¹ using a thermogravimetric analyzer and a tube reactor. The result revealed that the addition of PE enhanced the production of levoglucosan (LG) and methoxyphenols with unsaturated alkyl side chains from beech wood, resulting in higher yields than expected due to the interactions between BW and PE, which mainly involve hydrogen exchange to stabilize the radical species, leading to a significant decrease in the production of CO, CO₂, C2 - C3 compounds and five-membered ring compounds (which are LG decomposition products) than expected. While Kim et al. [171] carried out catalytic co-pyrolysis of torrefied yellow poplar (TYP) and HDPE using microporous HZSM-5 and mesoporous Al-MCM-41 catalysts, and evaluated the effects of biomass torrefaction, co-feeding of plastic wastes, their combination, and the catalytic upgrading mode (in situ vs. ex situ) on the aromatic formation efficiency during the catalytic pyrolysis. It was observed that the experimental yields of aromatic hydrocarbons from the catalytic co-pyrolysis of TYP and HDPE were higher than their theoretical yields, highlighting the synergistic aromatic formation by the interaction of TYP and HDPE. Sebestyén et al. [172] carried out thermal decomposition of model waste mixtures of plastics and biomass, and studied the influence of temperature and catalyst (HZSM-5 zeolite) ratio as well as the hindering effect of cellulose and lignin on the catalytic decomposition of plastic waste at both low and high heating rate by thermogravimetry/mass spectrometry (TG/MS) and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS), respectively. It was observed that co-pyrolysis of the waste plastic mixtures with biomass produces synergistic effect which affects positively the product yields. Fan et al. [173] examined the effects of pyrolysis temperature, lignin to LDPE ratio, MgO to HZSM-5 ratio, and feedstock to catalyst ratio on the product yields and chemical profiles by fast microwave-assisted catalytic co-pyrolysis of lignin and LDPE with HZSM-5 and MgO catalysts. The result showed that synergistic effect between lignin and LDPE, and the proportion of aromatics increased with increasing LDPE content. While Sajdak [174] evaluated the co-pyrolysis of lignin-rich materials (alder wood biomass, straw biomass, and furniture waste) with two types of plastic waste blends (blend 1 consists of 30% m/m SBR, 40% m/m PET, and 30% m/m PP; and blend 2 consists of 40% m/m PET, 30% m/m PP, and 30% m/m ABS) under the same conditions, and the products of the pyrolysis were analyzed. The pyrolysis experiments and analysis of variance showed

that the combination of biomass with plastic materials had a positive effect on the liquid and gas yields. A summary of the research studies on biomass co-pyrolysis particularly with plastics, performed elsewhere in the world, other than China, is presented in Table 4.

6. Synergistic effect between biomass and plastics in co-pyrolysis

According to Onal et al. [13], synergy exists when two or more different agents interact together to produce an effect greater than that determined from the individual agents. Synergistic effect is the major factor responsible for all improvements in oil quality and the increase in quantity of oil produced, and these effects were achieved through radical interactions between biomass and plastics during the co-pyrolysis process. A significant increase in the pyrolysis oil yield and improvement in oil quality indicate the occurrence of synergistic effects during the process, and this effect could be positive or negative synergy depending on a number of factors such as the type and contact of component blending feedstock materials, pyrolysis duration, pyrolysis temperature and heating rate, removal or equilibrium of volatiles formed, and addition of solvents, catalysts, and hydrogen-donors [42]. The types of blending feedstock and feed ratios are the major factors that greatly affect the complicatedly varying synergistic effects [186]. Many researchers claimed that during co-pyrolysis, the synergistic effect between co-feeding feedstocks exists when the differences between the experimental and calculated values are positive [37,61] while some contend that the knowledge of synergistic effects still remains poor. Zhou et al. [29] emphasized that the mechanisms of synergistic effect between biomass and plastic during co-pyrolysis is not quite clear, and Onal et al. [13] described the synergistic effect during co-pyrolysis process as complex because of the various chemical species involved. The mechanism of hydrogen donation is one of the mechanisms of the synergistic effects between biomass and plastic during co-pyrolysis. A detailed report on the synergetic effect and reaction mechanisms during co-pyrolysis of plastics and biomass has been provided by Abnisa and Daud [6].

6.1. Increased bio-oil yield

The co-pyrolysis process of biomass and plastics (Table 2) has the tendency to increase the oil yield due to the nature of the biomass and the co-feed blending ratios. The amount of liquid product of co-pyrolysis process can be predicted (as being low or high) when the compositions of the biomass and that of the blending co-feed have been determined usually by proximate analysis method of characterization, which identifies the four major compositions of a biomass: volatile matter, fixed carbon, moisture content, and ash content. Volatile matter and ash contents are the main factors that have a severe effect on liquid yield production during pyrolysis. Many researchers reported that the increase in volatiles generation favors the production of a large amount of pyrolysis oil and results in high reactivity, however, high ash content (alkali metals) contributes to a decrease in oil yield, resulting in production of more char [187–189]. The results of proximate analysis of lignocellulosic biomass revealed that their compositions include cellulose, hemicellulose, and lignin as primary components. Cellulose and hemicelluloses play an important role in generating volatile matter during pyrolysis but cellulose is more volatile than hemicelluloses [190], which results in an increase in oil yield. Lignin is made up of aromatic rings with various branches and could decompose over a wide range of low to very high temperatures with a very low mass loss rate. Wood-based biomass, with higher lignin contents might have a relatively higher char yield. The effects of lignocellulosic compounds on the production of volatile matter have been widely studied by many researchers [190,191]. However, proximate analysis of plastics depends grossly on their types. Table 5 shows that all plastic types have high characteristic volatile matter, and thus have great potential to produce high liquid yields through pyrolysis.

Table 5
Proximate analysis of plastics.

Type of plastic	Moisture (wt %)	Fixed carbon (wt %)	Volatile (wt %)	Ash (wt %)	Refs.
PP	0.00–0.30	0.00–1.22	95.08–100.00	0.00–9.00	[12,182,192–196]
PS	0.00–0.30	0.12–0.24	97.85–99.80	0.00–1.99	[48,139,193,196,197]
PE	0.00–0.30	0.04–0.20	98.87–99.80	0.00–0.99	[154,192,198]
PVC	0.00–0.80	0.03–7.86	92.14–98.57	0.00–1.40	[152,196,197,199]
PET	0.00–0.46	7.77–11.39	88.61–91.75	0.00–0.02	[152,194,200,201]

PET = Polyethylene terephthalate; HDPE = High-density polyethylene; PVC = Polyvinyl chloride; LDPE = Low-density polyethylene; PP = Polypropylene; PS = Polystyrene; PE = Polyethylene.

Also, in order to improve the product yield during co-pyrolysis of biomass with plastics, Chen et al. [194] performed fast co-pyrolysis of waste newspaper (WP) with HDPE via py-GC/MS to enhance the yields of hydrocarbons and alcohols, and hence the oil yield. They observed that fast co-pyrolysis of waste newspaper (WP) with HDPE produces hydrocarbons as its major products and alcohols as main interaction pyrolysates. Anhydro-sugars, aldehydes, ketones, furans, acids esters, and ethers were also observed in its derived products, and the experimental yield of the hydrocarbons and alcohols were obviously higher as compared to theoretical data, indicating that WP and HDPE derived compounds may be involved in the interaction during co-pyrolysis resulting in the formation of more hydrocarbons and alcohols due to the deoxygenation caused by HDPE and the dehydration reaction by the β -scission of a tertiary carbon radical in any of the first to fifth position in the WP structure generating hydroxyl radicals and favoring the formation of alcohols. The authors also illustrated that the hydrocarbons with activated radical sites from random scission of the original polymer chains in HDPE structure were involved in interactions with the hydroxyl fragments from the initial cellulose degradation in waste newspaper (WP) structure resulting in the formation of interaction alcohols with long chain (Fig. 3).

6.2. Improved bio-oil quality

Many researchers have recognized that the improvement in oil quality during pyrolysis of biomass and plastics is due to the synergistic effects that exist between them, and this is usually reflected in the oil fuel properties such as high heating value (HHV) Table 2. Research results from various studies on co-pyrolysis have shown that high proportion of plastics in biomass pyrolysis contribute more in

increasing the heating value of pyrolysis oil obtained by reducing the high oxygen content of the oil. This tendency can be explained by the increased hydrocarbon contents of the oil. The contents of C and H, and the H/C ratio of the oil can significantly control the calorific value [49]. From Table 6, it can be seen that plastic, as a petrochemical product, has a huge amount of carbon and hydrogen content and this can improve the bio-oil from biomass quality during co-pyrolysis process.

6.3. Effect of biomass–plastic co-pyrolysis on byproducts (char and gas) production

Onal et al. [55] noted that the main reason for blending polymers, most especially plastics and tires, with waste biomass is to improve the bio-oil products, and to evaluate the polymers' effect of hydrogen donation. However, co-pyrolysis of biomass with waste plastics also produces improved char and gas (by-products), which are of great importance. The char is majorly a carbon-rich matrix that contains almost all the inorganic compounds in the raw wastes and a significant amount of the condensed by-products generated during pyrolysis and dispersed throughout the solid porous structure [205]. According to Bernardo et al. [206] the char obtained from the pyrolysis of PE, PP, and PS with pine biomass contained some liquid-phase residues and metals, such as Mg, Ca, K, and Fe, which were removed in order to improve its physicochemical properties. On the other hand, the composition of the co-pyrolysis gas product depends greatly on that of the feedstock used. Generally, the gas product of wood pyrolysis is made up of CO, CO₂, H₂, CH₄, C₂H₄, C₃H₆, and minor amounts of other hydrocarbons [207]; however, the gas composition in plastics pyrolysis was found to be different depending on the type of plastics. Williams and Williams [208] studied the pyrolysis of HDPE, LDPE, PP, PS, PVC, and PET and

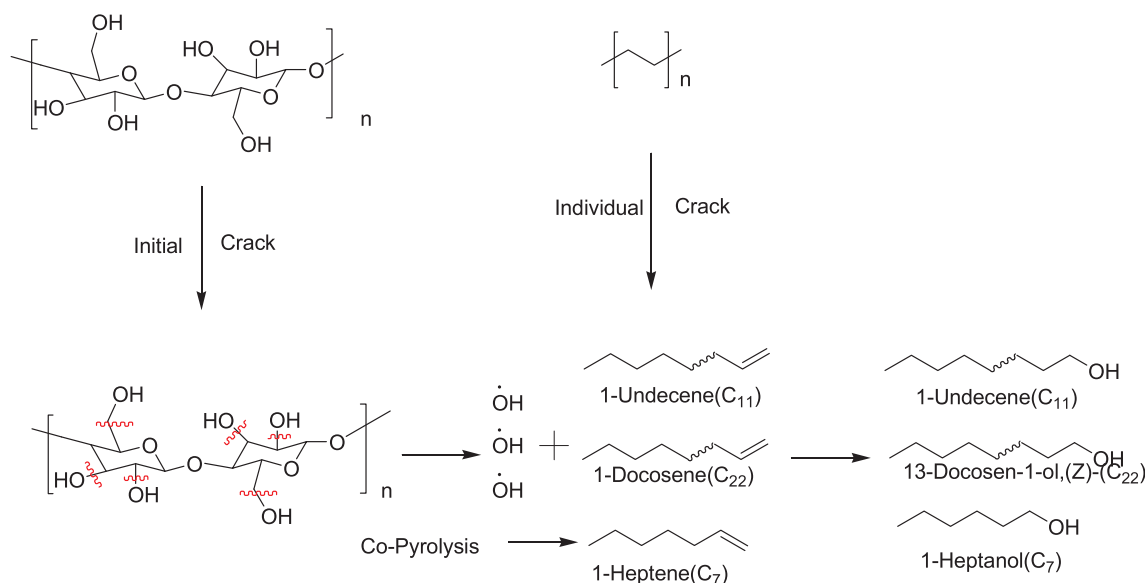


Fig. 3. Possible interaction scheme for the production of alcohols with linear long chain [194].

Table 6
Elemental compositions and HHVs of various plastics compared with those of diesel and gasoline.

Type of plastic	C (%)	H (%)	O (%)	N (%)	S (%)	HHV (MJ/kg)	Refs.
PE	80.50–85.40	14.30–15.50	0.03–3.90	0.00–0.30	0.00–0.30	46.10	[193,202,203]
PP	85.1–86.50	12.90–14.40	0.00–0.20	0.00	0.00–0.5	37.60–46.40	[182,193,196,203]
PS	86.40–92.70	7.40–8.50	0.00–1.30	0.00–6.10	0.00–0.10	39.00–42.10	[193,196,198,203]
Diesel ^a	86.58	13.41	0.01	0.0005	0.0005	45.96	[204]
Gasoline ^a	82.68	15.13	2.09	0.0016	0.0006	45.80	

^a Summer gasoline and diesel in Republic of Korea.

observed that the major composition of the gas product from the individual plastics were H₂, CH₄, C₂H₆, C₂H₄, C₃H₈, C₃H₆, C₄H₁₀, and C₄H₈; and for the PET plastic, CO, and CO₂. The presence of hydrogen chloride was only observed to be high for the pyrolysis of PVC.

Moreover, Bridgwater [57] noted that the byproduct of char from the pyrolysis of biomass contains up to 12 wt% on a dry-feed basis, together with a gas of about 13 wt% with a lower calorific value than the natural gas or pyrolysis plastic gas. However, co-pyrolysis of biomass with plastics may increase the calorific value. According to Widiyannita et al. [209], the heating value of char from the co-pyrolysis of wastes (mixture of biodegradable and non-biodegradable) is approximately 34 MJ/kg, which is comparable with that of a typical coal. Moreover, Paradela et al. [49] reported that the solid products from the co-pyrolysis of a mixture of biomass and waste plastic had higher heating values than those of certain coals, and can be combusted to provide energy for the pyrolysis process, processed into activated carbon or used for other purposes. They also observed that the increase in the biomass percentage led to an overall decrease in the effective liquid yield, and an increase in both the solid residue and gas fraction, but the reverse trend is true with the addition of plastics. Brebu et al. [52] also reported that the char from the pyrolysis of pine cone alone had a lower calorific value, due to its high oxygen content, than that from co-pyrolysis. They also observed that the elemental composition of chars from the mixture of the synthetic polymers with pine cone and cellulose may be due to the presence of lignin in pine cone. Furthermore, they found that very low sulphur content was present in the chars, thus making them suitable for use for incineration and as fuels in co-combustion with coal or other wastes. Chattopadhyay et al. [169] co-pyrolyzed a mixture of plastics and paper biomass at 800 °C and at different blending ratios. It was observed that the pyrolysis of pure paper biomass alone yielded 53% gas, 15% oil, and 32% char but the pyrolysis of a mixture of paper biomass and plastics made it possible to obtain about 51.5% gas, 21% oil, and 27.5% char. The results revealed the existence of synergistic effects between the biomass and plastics

during co-pyrolysis, resulting in the increase in liquid products with more plastic content in the feedstock, while gaseous and solid products followed the inverse trend. However, on addition of more paper biomass content than plastics (3:1) in the mixture as in a representative municipal solid waste sample, the pyrolysis of such a mixture gave about 55% gas, 17% liquid, and 30% solid residues. Also Grieco and Baldi [166] co-pyrolyzed a mixture of polyethylene and biomass (paper and beech wood sawdust pellets) to study the interactions between them. The results revealed that the amount of char and gas increased by increasing the biomass materials while that of the oil decreased, but the addition of more plastic followed a reverse trend.

7. Summary of the effect of major operating parameters on co-pyrolysis product yields

Co-pyrolysis process like the normal pyrolysis process is influenced by several factors which, among others, include the type/compositions of biomass, temperature, heating rate, reaction time, type of reactor used and particle size of feed [210]. However, unlike the normal pyrolysis, co-pyrolysis has a special parameter, known as the blending ratio of feedstock. According to many researchers, this vital parameter has a considerable effect on the co-pyrolysis product yields, especially in terms of its quantity. Sharypov et al. [160] investigated the co-pyrolysis of wood biomass and a synthetic polymer mixture and noted that the feed blending ratio is the most vital parameter for production of liquid fuels. Similar findings were also made by Abnisa and Daud [48], who studied the co-pyrolysis of palm shell and polystyrene waste mixtures for the synthesis of liquid fuel. Chen et al. [152] also demonstrated via py-GC/MS that the compositions and mass feed ratios of the components (waste newspaper (WP) and HDPE) in the mixture do not only affect the product yields and distributions (Table 7) but also the properties of the various oils produced from the fast co-pyrolysis process at different mass feed ratios (Table 8). The results of the co-pyrolysis of wood biomass (beech wood) and synthetic polymers (atactic

Table 7
Effects of temperature (at 50:50) and mass feed ratio (at 500 °C) on the experimental and theoretical product yields from fast co-pyrolysis of newspaper (WP) and HDPE (in % yield) [194].

	Effect of temperature on product yields (at 50:50 feed ratio)								Effect of feed ratio (WP:HDPE) on product yields (at 500 °C)					
	500 °C		600 °C		700 °C		800 °C		75:25		50:50		25:75	
	Exp	Theo	Exp	Theo	Exp	Theo	Exp	Theo	Exp	Theo	Exp	Theo	Exp	Theo
<i>Product yield (%)</i> :														
Alcohols	18	1	19	3	23	9	2	7	10	2	18	1.0	6	0.5
ALH	58	46.5	68	47	62	52	54	46	32	22	58	46	78	70
ARH	–	–	–	2	3	18	14	28	–	–	–	–	–	–
Acids/ester	–	2	–	–	–	–	–	–	1	–	2	–	–	–
Furans	1	4	2	1.5	2.5	1	–	1	4.0	8	1.5	5	1.5	3
Aldehydes/ketones	2	19	4	33	7	14	20.5	3	18	28	3	20	2	10
Anhydro-sugars	4	14	6	9	3	2	–	2	14	20	4	14	3	8
Phenols	1	2.5	–	–	–	1	12	6	2	6	1	4	1	2
Ethers	0.5	1	–	–	–	–	–	–	0.5	3	0.5	2	0.5	1
Others	2.5	2.5	–	1	–	3	3.5	2.5	8	5	3.0	3.0	2.5	2
Char	13	9	3	6	1	4	0.5	1	16	10	14	10	12	10

ALH = Aliphatic hydrocarbons, ARH = Aromatic hydrocarbons, Exp = Experimental values, Theo = Theoretical values.

Table 8

Comparison of typical properties of oils from different mass feed ratios from WP and HDPE fast co-pyrolysis with the commercial diesel no. 0 [194].

Sample	Oils from different mass feed ratios of WP:HDPE					
	100:0	0:100	75:25	50:50	25:75	Diesel
<i>Elemental analysis</i>						
C	38.1–44.2	85.2–86.4	60.1–65.9	71.5–75.8	83.5–85.4	84.0–87.0
H	5.8–7.2	14.6–15.2	8.1–9.9	9.2–11.8	10.7–14.1	11.0–15.0
O ^a	49.3–56.8	0.0	26.6–32.6	14.9–20.6	2.4–5.4	0.0
N	0.2–0.4	0.0	0.1–0.2	0.1–0.2	0.1–0.3	0.01–0.3
Calorific value (MJ/kg)	14.2–16.8	43.2–45.4	21.2–24.8	28.2–34.4	34.8–39.8	42.0–46.0
<i>Physical properties</i>						
Water content (wt %)	45.2–52.6	0.0	27.8–31.2	12.1–17.8	0.5–1.4	0.0–0.02
Total acid number (mg KOH/g)	61.8–82.3	0.5–0.8	31.3–48.3	17.8–24.5	6.5–14.8	0.0–0.5
pH	2.3–2.8	7.3–7.5	2.8–3.1	3.6–4.0	4.6–4.9	5.0–6.0
Density (g/cm ³)	1.36–1.48	1.08–1.14	1.21–1.31	1.14–1.20	1.12–1.24	0.82–0.85
Viscosity (cPs 40 °C)	45.21–70.62	2.96–5.46	21.61–40.89	10.28–18.83	6.23–12.19	2.0–4.5

^a Calculated by difference; WP = waste newspaper; HDPE = High density polyethylene.**Table 9**

Influence of beech wood/aPP ratio on the composition of gaseous products (at 400 °C and reaction pressure of 3.0 MPa) [160].

Reaction temperature, °C	Yields of gaseous products, mass %							
	CO	CO ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	C ₃ H ₆	C ₃ H ₈	∑ C ₄ ^a
0:100	1.0	1.2	8.0	1.0	11.9	74.3	1.3	1.3
20:80	18.1	31.6	26.7	0.6	7.4	6.9	6.3	2.4
50:50	17.8	43.8	25.8	0.1	3.7	2.0	4.7	2.1
80:20	14.8	51.2	27.2	0.7	2.1	1.2	2.1	0.7
100:0	16.8	50.4	28.7	0.0	2.5	0.4	1.2	0.0

aPP = Atactic-polypropylene.

^a Sum of the C₄ hydrocarbons.

polypropylene) under inert atmosphere in autoclave conditions by Sharypov et al. [160] also showed that the feed ratio has a great influence on the product yields (Table 9). Many research results on co-pyrolysis of biomass with plastics have also proven that temperature is another vital operating parameter, and that it can be varied within the range of 400–600 °C to maximize the production of oil during the co-pyrolysis process. However, according to Velghe et al. [211] and many other researchers, the optimum temperature required to produce the maximum oil yield is dependent on the characteristics of feedstock. Sharypov et al. [160] also demonstrated the influence of temperature on the yields of gaseous products from co-pyrolysis of Beech wood and aPP (atactic polypropylene) mixture (at 1:1 mass % and reaction pressure of 3.0 MPa). They reported that an increase in reaction temperature favors the release of gaseous compounds (Table 10). Paradela et al. [103] also reported that the increase in reaction temperature seems to decrease the liquid yields, and favors the release of gaseous compounds, probably because the rise in reaction temperature favored cracking reactions, converting longer and heavier molecules into smaller molecules. Moreover, the type of reactor used also has a large role to play in the co-pyrolysis process. Bridgwater et al. [21] outlined the important characteristics of effective and efficient pyrolysis reactors to include, among others, very high heating rates, moderate temperatures, and short vapor product residence times, most especially, for liquids. Several comprehensive reviews have extensively discussed in detail the various types of pyrolysis reactors for production of liquid and other useful products during pyrolysis [57,59]. Also, the use of carrier gases (nitrogen, argon, helium, hydrogen, ethylene, propylene, etc.) in the pyrolysis/co-pyrolysis process has been proven by different researchers [212–215] to have a significant effect on liquid yield. Therefore, proper setting of the inert gas flow rate is a necessity for maximizing the oil yield during pyrolysis or co-pyrolysis process. However, it has been observed that a very high flow rate of inert gas

Table 10

Influence of temperature on the yields of gaseous products from co-pyrolysis of beech wood and aPP mixture (1:1 mass % and reaction pressure of 3.0 MPa) [160].

Reaction temperature °C	Yields of gaseous products, mass %							
	CO	CO ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	C ₃ H ₆	C ₃ H ₈	∑ C ₄ ^a
360	1.43	5.62	0.74	0.00	0.21	0.05	0.17	0.12
400	1.54	5.41	1.37	0.01	0.31	0.25	0.58	0.36
430	2.38	4.29	7.18	0.06	1.79	0.25	1.21	0.52
450	2.43	4.52	9.13	0.07	2.92	0.31	1.62	0.61

aPP = Atactic-polypropylene.

^a Sum of the C₄ hydrocarbons.

actually lowers the total oil yield. Obviously, the use of inert gas is dependent on the type of reactor used. According to Vamvuka [216], the fluid bed reactor, circulating fluid bed reactor, and entrained flow reactor need a high flow rate of inert gas but in the vacuum and ablative reactors, the use of inert gas is not compulsory. For ablative reactors, according to Bridgwater and Peacocke [217], nitrogen purging and the use of any inert gases is not required, but is included in the laboratory tests for control purposes to ensure safety in the feeder and residence time control in the reactor.

8. Future directions in biomass–plastics co-pyrolysis

The current research on biomass co-pyrolysis and oil production is focused on the development of advanced pyrolysis technology (e.g., catalytic co-pyrolysis). Co-pyrolysis is the common pyrolysis of two or more fuels, which takes the advantage of the pyrolysis synergistic coupling effect of fuels, to improve oil production and quality. Thus, the emergence of the use of suitable catalysts in co-processing of mixed pyrolysis feedstocks is one of the most recent areas of interest that have attracted a considerable attention in biomass–plastics co-pyrolysis for high quality bio-oil production. Thus catalytic co-pyrolysis of biomass and plastics has recently gained wide popularity, and as a result have paved way for enormous and important future investigations for many interested researchers [132,143–146] both in China and elsewhere worldwide, most especially, in the aspects of understanding of the complex reaction mechanisms and kinetics as well as the synergistic effects that exist between biomass and plastics during co-pyrolysis in order to improve the process mechanisms, system process design, planning, operation and efficiency. The catalytic co-pyrolysis technology employs two or more feedstock materials and an acidic catalyst for production of high quality bio-oils. According to Zhang et al. [143], the addition of an acidic catalyst during pyrolysis deoxygenates the bio-oil and enhances the yield and selectivity of hydrocarbon products

through catalytic cracking and refineries. Thangalazhy-Gopakumar et al. [218] stated that, besides improving the degradation mechanisms of biomass, the application of a suitable catalyst also adjusts the product's spectrum closer to the long chain hydrocarbons and/or aromatic range.

Dorado et al. [48] reported that the co-feeding of hydrogen-deficient biomass and its derivatives with hydrogen-rich feedstocks (such as plastics, tires) is a practical solution to improve the overall H/C_{eff} of the feedstocks. Chen et al. [219] was the first to introduce a parameter called H/C_{eff} for measuring the relative content of hydrogen of different feedstocks. Valle et al. [220] discovered that the H/C_{eff} ratio of biomass and biomass-derived feedstock is only between 0 and 0.3, thus biomass is indeed a hydrogen-deficient feedstock. However, a feedstock with high H/C_{eff} ratio can function as a hydrogen-source for biomass conversion. According to Chen et al. [219], feedstocks with H/C_{eff} ratio of less than 1 are difficult and uneconomical to be converted to hydrocarbons over a ZSM-5 zeolite because of rapid catalyst deactivation caused by coke deposition. Moreover, the H/C_{eff} ratio of the feedstock is significantly correlated with hydrocarbon content.

However, Lin et al. [221] highlighted the two major technical challenges that hinder the commercialization of co-pyrolysis oil. Firstly, they pointed out that the high amounts of 'heavy' hydrocarbons in the bio-oil instead of light ones originated from the decomposition of polyolefins, and could restrict the immediate application. Therefore, in light of this problem, a high temperature process (of over 700 °C) is needed to produce light paraffins and olefins. Secondly, the bio-oils from co-pyrolysis contain excessive oxygenated compounds—such as acid, ketones, aldehydes, furans, phenols, and anhydrosugars—due to the thermal degradation of the biomass. Therefore, further upgrading process must be carried out to integrate the bio-oil as liquid fuel for many applications and as feedstock for production of hydrocarbons, which may be readily integrated into existing petroleum refineries or future bio-refineries [36,48].

Currently, research publications mainly focused on the co-processing of plastics with terrestrial biomass and their component origins [85], however, the co-processing of plastics with microalgae and their component origins have been scarcely reported in the literature. Pei et al. [222] and Duan et al. [223] studied the co-processing of microalgae with high density PE and waste rubber tire, respectively. Positive synergistic effects were observed during the co-pyrolysis process. However, investigations on the reaction dynamics, which are very important for the effective design and operation of thermochemical conversion units, are not included in these studies. Tang et al. [159] also studied the co-pyrolysis characteristic of microalgae and municipal solid waste (consisting mainly of plastics) under different atmospheric conditions using TGA. They found that the addition of microalgae could promote the pyrolysis of municipal solid wastes. However, detailed interaction information of the microalgae and plastics was not discussed, which needs further research.

Presently, no investigations have been conducted on both the co-pyrolysis and catalytic co-pyrolysis of residual seaweed biomass (macroalgae) and plastic wastes, both in China and elsewhere worldwide regardless of the abundance of residual seaweed biomass, most especially in China. The non-existence of this piece of relevant information in the literature has attracted the interest of the authors of this review article to focus their further investigations in that direction with the aim to understand the reaction mechanisms and the synergistic effects between seaweed biomass and waste plastics during co-pyrolysis and catalytic co-pyrolysis, respectively. According to Wang et al. [113] and Kositkanawuth et al. [18], the algal biomass, like other aquatic biomass is a promising renewable energy resource due to its high growth rate, high oil content and lack of competition with lands for food crops. The algae (i.e. both the macroalgae and microalgae) could be converted to liquid fuels through pyrolysis. However, the main challenge facing the biofuel production from the microalgae is the high costs of harvesting due to its low biomass concentration and small cell size. Residual

seaweeds (macroalgae) pyrolysis reduces the challenges associated with the seaweed waste disposal in the coastal areas. Also, seaweed pyrolysis has been demonstrated to yield a high amount of oil compared to that of the woody biomass, with similar heating values; and several potential advantages like the low temperature requirement, less energy input requirement owing to the exothermic reactions and few phenolic compounds that require deoxygenation for upgrading the oil. However, the high oxygen content of the bio-oil results in a low calorific value compared with the fossil fuels. Therefore, co-pyrolysis of the residual seaweed biomass with synthetic polymers can improve both the oil quantity and quality.

9. Conclusion

This review has been focused on the overview of recent advances, studies and future directions on co-pyrolysis techniques of biomass and plastics for biofuel production in China and elsewhere worldwide. Various studies from the literature, both past and current, have been used to support the analysis and discussion in this paper. Co-pyrolysis technology has been recognized by several researchers to improve, significantly, the quantity and quality of pyrolysis oil without necessarily the addition of catalysts, solvents, or free hydrogen pressure. It has also been considered as a simple, economical, and effective method for producing high grade biofuels from co-processing of wastes. Moreover, the availability of waste plastics, as the additive materials for co-pyrolysis, could play an important role in the sustainability of this technique for production of high quality biofuels as the conventional fuels (fossil fuels) are fast depleting and non-renewable in nature. China is one of the largest producers of plastics worldwide. Therefore, with no doubt, China will generate a huge amount of plastic wastes annually. China also has the potential of generating abundant municipal solid wastes and residual biomass as a result of her rapid economic development and growing population. The interaction of plastic and organic wastes during co-pyrolysis is an interesting issue, as it may increase the efficiency of waste plastics recycling process, if properly manipulated, while adding values to organic wastes that otherwise have to be sent to landfills. Thus, co-pyrolysis technology has the economic advantage of reducing significantly the volume of waste as more waste is consumed as feedstock to reduce the amount of landfills required, save the costs for waste treatment, and solve a number of environmental problems associated with wastes disposal in landfills. Co-pyrolysis could therefore serve as an optional solution or alternative waste management method for the future that will have a significant impact on waste reduction, and could enhance the energy security of the nation; and thus reduce the dependency on fossil fuels.

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Current solid waste management strategies and energy recovery in developing countries - State of art review

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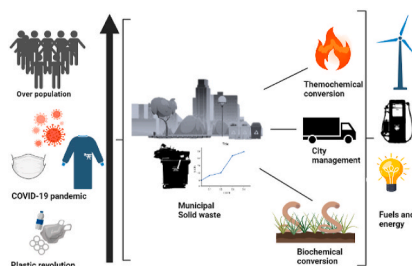
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HIGHLIGHTS

- Current MSWM strategies and energy recovery in developing countries were reviewed.
- This review analyzed several problems and shortcomings in MSW management in developing countries.
- Open dumping is the biggest challenges during and after the COVID-19 outbreak in developing countries.
- Technologies for energy recovery from MSW, and challenges of WTE techniques were discussed.
- WTE limits emissions land consumption and ensure cleaner environment.

GRAPHICAL ABSTRACT



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ABSTRACT

Solid waste generation has rapidly increased due to the worldwide population, urbanization, and industrialization. Solid waste management (SWM) is a significant challenge for a society that arises local issues with global consequences. Thus, solid waste management strategies to recycle waste products are promising practices that positively impact sustainable goals. Several developed countries possess excellent solid waste management strategies to recycle waste products. Developing countries face many challenges, such as municipal solid waste (MSW) sorting and handling due to high population density and economic instability. This mismanagement could further expedite harmful environmental and socioeconomic concerns. This review discusses the current solid waste management and energy recovery production in developing countries; with statistics, this review provides a comprehensive revision on energy recovery technologies such as the thermochemical and biochemical conversion of waste with economic considerations.

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Furthermore, the paper discusses the challenges of SWM in developing countries, including several immediate actions and future policy recommendations for improving the current status of SWM via harnessing technology. This review has the potential of helping municipalities, government authorities, researchers, and stakeholders working on MSW management to make effective decisions for improved SWM for achieving sustainable development.

Abbreviations

4R's	reuse, reduce, recycle and recover	MSWM	municipal solid waste management
BOD	biological oxygen demand	MT	metric tons
C&D	Construction and demolition	NGO's	non-governmental organizations
C/N	Carbon/Nitrogen	NOX	nitrogen oxides
CH ₄	methane	NSWP	National Solid Waste Policy
COD	chemical oxygen demand	O	Others
G	Glass	OC	Other composition
GC	Glass composition	Org	Organic
Gross Domestic Product	GDP	P	Paper
GHGs	greenhouse gas	PC	Paper composition
GIS	geographic information system	PI	Plastic
HIC	High-income countries	PIC	Plastic composition
H ₂ S	hydrogen sulfide	PPE	personal protection equipment
IEC	information, education, and communication	PSW	plastic solid waste
IoT	Internet of things	PtC	Putrescible composition
LIC	Low-income countries	RDF	refuse-derived fuel
LPG	Liquefied petroleum gas	SOx	sulfur oxides
M	Metal	SW	Solid waste
MC	Metal composition	TC	Textile composition
MNRE	Ministry of New and Renewable Energies	WHO	World Health Organization
		WTE	waste-to-energy

1. Introduction

As the world's population continues to grow, solid waste production increases simultaneously, with the prediction to reach 3.40 billion metric tonnes (MT) per year by 2050 (Kaza et al., 2018). In low-income countries (LIC), the total waste generated is expected to grow by more than three folds by 2050. Currently, the generation of solid waste from Asia accounts for one-third of the total waste share, including India (0.50–0.9) kg/capita/day and China (0.44–4.3) kg/capita/day (Kaza et al., 2018). In high-income countries (HIC), 51% of waste materials are converted to recycled products, whereas LIC recycled only 16% of waste. Furthermore, LIC open dump about 93% of waste, whereas HIC only accounts for 2% of waste, which indicates improper solid waste management (SWM) practices, leading to severe risks to human health, the environment, and livelihoods in LIC regions. Local municipalities and government agencies of LIC face many challenges in implementing innovative SWM programs.

Historically, the lack of SWM caused cities to be exposed to fatal health crises under pandemics such as storms, earthquakes, floods, pandemics, etc (Songsore, 2017). Recently, COVID-19 pandemic exposure that impacts more than 190 million people around the world (World Health Organization, 2021). Several government agencies prompted at all levels to minimize the spread of COVID-19 across their nations, taking many regulatory actions such as meticulous cleanliness, social distance, closing down schools and workplaces, travel restrictions, and self-insulation, amongst others. Moreover, different recommendations have been released by the World Health Organization (WHO) and the different national disease monitoring centers (Penteado and Castro, 2021; A. V. Shah et al., 2021). In addition, emergency measures and reaction operations affect the generation, management, and disposal of waste (Songsore, 2017). Frontline physicians (e.g., physicians, nurses,

and carers), as well as those dealing with COVID-19 patients, were advised to wear *personal protection equipment* (PPE) such as facemasks, medical gloves, trays, and towels (Kumar and Agrawal, 2020; Patwa et al., 2020; Saxena et al., 2021; Iyer et al., 2021; Das et al., 2021a; Tripathi et al., 2020; Ragazzi et al., 2020). Furthermore, residents should wear facemasks in public regions (World Health Organization, 2021).

These WHO guidelines had provoked the manufacture and use of billions of PPE every day due to COVID-19 pandemics (Kumar and Agrawal, 2020; Srivastav and Kumar, 2021). As urbanization and economic growth increased, PPE constitutes one of the most contemporary by-products that over-increased at the corresponding period (Alshehrei and Ameen, 2021; Khatri et al., 2021; Oghenejoboh et al., 2021; Sebastian and Louis, 2021).

The global population is now expanding at around 1.05% a year and is predicted to exceed 10 billion in 2057 (Islam and Bhat, 2019; Kumar et al., 2021; Singh and Singh, 2019). So, the population increment plays an essential part in producing a significant amount of MSW, which poses a substantial challenge to environmental sustainability (Ho et al., 2021; Tayeh et al., 2021; Zamri et al., 2021). On the other hand, the globe produces around 2.01 billion tons of MSW each year, of which 33% are not adequately handled. These findings show that methods to deal with the growth pace of MSW generation globally are urgently needed. According to International Monetary Fund (IMF), developed and developing countries are categorized based on Gross Domestic Product (GDP) per capita. A direct link between GDP and solid waste generation rate is shown in Fig. 1. Typically, the waste generation rate of developed and developing countries varies from 1.00 to 2.50 kg/c/d and 0.50–1.00 kg/c/d respectively (Thitame et al., 2010).

The continuous increase in the amount and complexity of urban and industrial waste has been recognized as one of the present and future concerns in society. Mismanagement also presents threats to community

well-being and produces various social and economic problems, along with significant environmental repercussions (Malini R. Capoor and Parida, 2021; Mpofu et al., 2021; H. B. Sharma et al., 2020a; Winterstetter et al., 2021, Santi et al., 2021, Ferronato et al., 2017). Deposit dependency and poor waste disposal have continuously affected individuals with financial, health, and safety issues (Dai et al., 2020; Ismail and Hanafiah, 2020; Saedi et al., 2020). On the other hand, environment-friendly processing of MSW has been acknowledged as vital to lower socioeconomic and environmental impacts and thereby to stabilize the 3-aspects of sustainability (i.e., economic viability, environmental protection, and social equity) (Nsenga Kumwimba et al., 2020; Owusu-Twum and Sharara, 2020; S. Sharma et al., 2020b; Walling and Vaneeckhaute, 2020). The answer to these problems is to minimize waste, recycle, sanitary and closing open waste disposal sites, improve waste gas recovery, compost, and energy recovery (Ayub and Khan, 2014). Amongst all these, waste-to-energy (WTE) is a sustainable approach limiting emissions and land consumption; it is considered the most promising strategy for tackling waste production (Nguyen et al., 2021; Nosare and Wahid, 2019; Siddiqi et al., 2020; Yan et al., 2020, Malinauskaitė et al., 2017). Recovery of resources offers a viable way to minimize the consumption of raw materials, limit greenhouse gas (GHGs) emissions and minimize the bulk disposed of waste (Siyal et al., 2020). All feasible recycling alternatives for waste reduction in sands include recycling, composting, and generating power from waste (Mahinroosta and Senevirathna, 2020).

The characteristics and content of solid waste produced in rural areas vary from waste produced in metropolitan areas. The 2011 census shows that 68% of India's total people are living in a rural environment. According to the National Institute for Rural Development and Panchayati Raj, Union Ministry for Rural Development, Government of India, the total waste generated in rural areas is 0.3–0.4 million MT a day (Jiang et al., 2019; Odoh et al., 2019; Roidt and Avellán, 2019). Table 1 shows solid waste composition for different countries. Cleanliness, sanitary and open defecation accessible in villages are essential to improve the quality of life in rural settings (Bianchini et al., 2019; Islam and Bhat, 2019; Singh and Singh, 2019).

Solid waste management and selecting appropriate technologies are essential to identify the features and the composition of rural solid waste because it contains higher organic content (> 50%) (Mankad et al., 2019; Sindhu et al., 2019; Zimmer and Bragança, 2019). Previous work established that composting is the most prominent technology to transform waste into agricultural manure (dos Santos and Maranhão, 2018; Kabir et al., 2018; Mankad et al., 2019; O'Brien et al., 2018;

Sindhu et al., 2019; Zimmer and Bragança, 2019).

Composting is the decomposition of organic waste using soil microorganisms that are naturally accessible to produce compost (Potysz et al., 2018; Wu et al., 2018; Zomorodian et al., 2018). Initial degradation of organic material occurs when earthworms and soil insects such as springtails, ants, mites, beetles and convert them into smaller particles. Secondly, the action of microorganisms begins after the physical disintegration, and organic material is decomposed by manure (Bădescu et al., 2018; Kumar et al., 2018; Rodríguez-Perez et al., 2018). In developing countries, different composting techniques can be applied in rural regions, such as vermicomposting, windrow composting, co-composting, in-vessel composting, aerobic and anaerobic composting, and anaerobic (biological) biodigesters (Kumar et al., 2018; Rocamora et al., 2020; Yuvaraj et al., 2021). Different aspects affecting the composting process and design may be relevant in selecting composting technologies. Moisture content, aeration, frequency of turning and temperature, C/N ratio, and compost material particle dimensions might affect compost (Gruchlik et al., 2018; Julinová et al., 2018; Mo et al., 2018).

This review highlights many elements of MSW production and management in developing countries. This covers a review of MSW features, energy recovery requirements, and the transfer of value-added products from MSW. It also gives updates on technical developments in terms of energy generation via MSW recovery and challenges in transforming MSW byproducts using various technologies. It also provides the latest current information on MSW energy generation. Overall, this review will be comprehension insight into the recovery of essential products and energy recovery via technological approach and facilitating a sustainable solution for transforming MSW to end products.

2. Production and management of MSW

As mentioned above, the global annual production of MSW is about 2.01 billion tons with no ecologically appropriate handling of at least 33% (Trends in Solid Waste Management, 2021; Saxena et al., 2021). For instance, the management of solid waste and its hierarchy in India indicates little intent towards SWM strategies except in urban areas that have noticed a significant increase in population and waste generation (Kumar and Agrawal, 2020). Although similar issues have occurred in other developing countries like Africa (Liyala, 2011), Asia (Zurbrügg, 2003), Czech Republic (Slavik and Pavel, 2013), China (Chen et al., 2021), Latin America and the Caribbean (Hettiarachchi et al., 2018), and Mexico (Salazar-Adams, 2021). However, the situation of SWM has

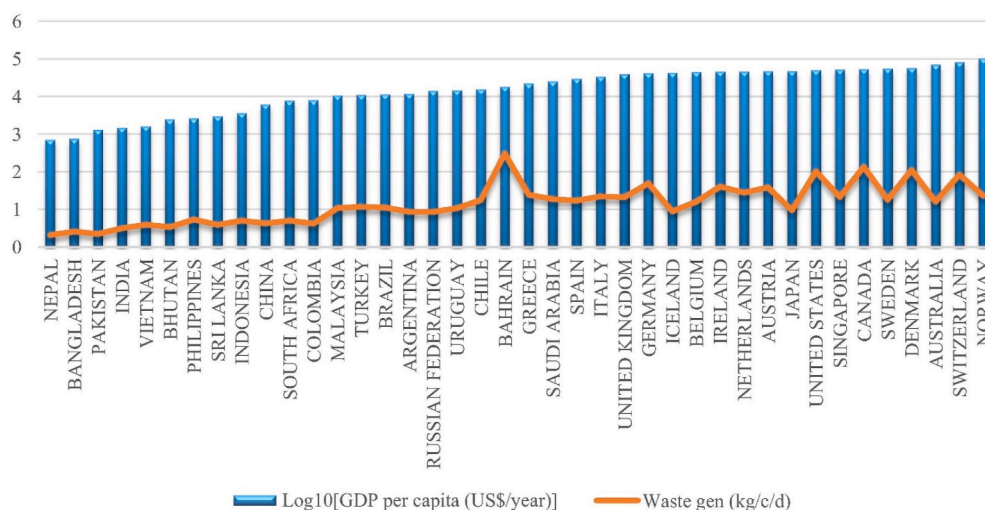


Fig. 1. Comparative representation of Waste generation rate and GDP of 40 countries (developed and developing countries) (Waste Atlas, 2016; Kumar and Samadder, 2017).

Table 1
Solid waste composition around the world.

No.	Country	SW _{PtC}	SW _{PIC}	SW _{MC}	SW _{GC}	SW _{TC}	SW _{PC}	SW _{OC}	References
1	Africa	57	9	13	4	4	13	–	Hoornweg and Bhada-Tata (2012)
2	China	43.54	8.78	1.28	2.54	2.75	7.7	32	Lu and Xu (2021)
3	Czech Republic	11.7	9.7	2.6	4.9	2.3	9.7	44	Golwala et al. (2021)
4	East Asia and Pacific	62	10	13	3	2	10	–	Hoornweg and Bhada-Tata (2012)
5	Eastern and Central Asia	47	14	8	7	5	19	–	Hoornweg and Bhada-Tata (2012)
6	Ghana	63.7	36.3	–	–	–	–	–	Saxena et al. (2021)
7	Iran	41.0	10.1	8.0	8.2	4.5	7.2	21.1	(Das et al., 2021a; A. V. Shah et al., 2021)
8	Latin America and Caribbean	54	16	12	4	2	12	–	Hoornweg and Bhada-Tata (2012)
9	Middle East and North Africa (MENA)	61	14	9	3	3	10	–	Hoornweg and Bhada-Tata (2012)
10	Organization for Economic Co-operation and Development (OECD)	27	32	11	7	6	17	–	Hoornweg and Bhada-Tata (2012)
11	Persian Gulf	42.49	8.24	6.08	5.77	4.84	8.77	23.5	(A. V. Shah et al., 2021)
12	South Asia	50	4	7	1	1	37	–	Hoornweg and Bhada-Tata (2012)
13	South China	52	11.5	0.7	2.3	2.6	1	30	Srivastav and Kumar (2021)

SW: Solid waste; PtC: Putrescible composition; PIC: Plastic composition; MC: Metal composition; GC: Glass composition; TC: Textile composition; PC: Paper composition; OC: Other composition.

changed steadily (Srivastav and Kumar, 2021). On average, approximately 143,449 MT of MSW is generated daily, only 111,000 MT collected, and around 35,602 MT are treated (S. Kumar and Samadder, 2017). However, a lot more has to be done to develop good techniques of SWM. The problem was exacerbated due to increased waste products with the expansion in population and urban development (Das et al., 2021b).

For successful treatment and management of MSW, it is necessary to take care of the collection, storage, and transfer (Boateng et al., 2016). In Ghana, MSW collection in urban area are generally controlled by local municipal authorities or by private sector for a fee while the rural MSW diverted to open dumping sites (Song et al., 2016; Tassie and Endalew, 2020). Since solid waste continues to grow, the vast variety of constituent waste materials present in solid waste need contemporary waste management techniques. For instance, in India, solid waste emerging from urban areas comes from several sources, such as municipal (67.8%), commercial (23.5%), whereas rural solid waste constitutes 92.4%. Besides, urban solid waste comprises 50% putrescible and 50% non-putrescible waste. On the other hand, rural waste has a greater amount of putrescible waste (63.5%) and a comparatively lower amount of non-putrescible waste (36%) (Patwa et al., 2020).

On the other hand, a study found open dumping is practiced by 78% of the rural as well as the urban population of Ghana (Boateng et al., 2016). In China, there is an estimated 1 kg/capita/day of solid waste production, which is compared relatively low to solid waste generated in metropolitan regions (Patwa et al., 2020). In India, the waste production in 2001 was 0.24 kg/capita/day, which in 2018 climbs to 0.85 kg/capita/day shows that waste generation grows with time and relies on people's shift in lifestyles income variation, and resources availability (Kumar and Agrawal, 2020). Table 2 shows the % by mass solid waste composition in some growing cities of India.

In another investigation, the solid waste composition in the 24 villages of Shaharmahal and Bakhtiari regions (from 64 chosen

households) of Iran, with a population of 82,562 inhabitants having 0.513 kg/capita/day of solid waste products that include cow dung and kitchen waste (57%), agriculture waste (32%) and human excreta 8% (Patwa et al., 2020). The maximum rate for solid wastes generation is @0.84 kg/h and least @0.65 kg/h/day. The most significant and lowest solid waste density was reported at 432 kg/m³ and 407 kg/m³, respectively (Patwa et al., 2020). Seasonally waste, putrescible waste production has been estimated to be about 33.6% in the fall and 42.0% in the winter, 38.1% in spring, and 43.4% in the summer (Kumar and Agrawal, 2020). The authors of the study (Pervez et al., 2021) characterize the weighed MSW as follows: organic fraction (82.73%) followed by the plastic waste (6.78%), the combined paper and cardboard (6.78%), and then other wastes (2.51%) in total for Jammu city, India.

2.1. Characteristics of MSW

Global waste generation is estimated at 27 billion tons per year by 2050. Asia now generates 1/3 of overall waste, with substantial Chinese (0–0.49) kg/capita/day and India (0.50–0.9) kg/capita/day contribution (Malini R. Capoor and Parida, 2021; Patwa et al., 2020; H. B. Sharma et al., 2020). If this is not the case, waste generation from (334–661) MT/day for the Indian continent is anticipated to continue compared with China East Asia-Pacific (468–714) MT/day every year (2016–2050) (Dastjerdi et al., 2021; Santagata et al., 2021; Yaqoob et al., 2021). The typical per capita waste generation is between 150 g and 300 g, according to current figures. The overall expected worldwide increase in municipal waste, including construction and demolition (C&D) and industrial waste, is 7–10 billion tons/year (Davidson et al., 2021; Kurniawan et al., 2021). The present situation and future projections compared to various parts of the globe have also been outlined by the World Bank. The average waste generation per person per day in 2016, ranging from (0,09–0,60) kg to (0,16–0,79) kg to lower-medium revenue and (0,1–1,2), correspondingly to (0,1–2,2) kg for

Table 2
Solid waste composition in developing cities of India.

No.City		% by mass					References	
		SW _{Org}	SW _{PI}	SW _P	SW _M	SW _G		SW _O
1	Solapur	68	11	14			7	Sharma et al. (2020)
2	Rewa	69	8	6	4	1	11	Patwa et al. (2020)
3	Shyampur	79	01	4	1	1	14	Kumar and Agrawal (2020)
4	Sajanpur	79	01	3	0	1	14	Kumar and Agrawal (2020)
5	Kongri	64	0.5	14	1	1	15	da Silva et al. (2020)
6	Bhogpur	76	0.6	2	00	6	13	Das et al. (2021a)
7	Dummanpur	72	0.7	12	0	5	13	(A. V. Shah et al., 2021)

SW: Solid waste; Org: Organic; PI: Plastic; P: Paper; M: Metal; G: Glass; O: Others.

upper-medium revenue groups; these trends in regional waste generation worldwide have been projected to quadruple by 2050 between 2016 and 2020, as estimated (Bădescu et al., 2018).

MSW can vary in quantity, content, and type, depending on their geography, season and economic situation, culture. MSW includes domestic waste, commercial waste, industrial waste, C&D waste, agricultural waste, and urban waste. The Indian MSW has distinctive characteristics and structure, in contrast to other developing nations. 70–75% of MSW produced in India is organic waste. The chemical composition of the Indian MSW is made up on the other hand of nitrogen of $0.64 \pm 0.8\%$, $0.67 \pm 0.15\%$, potassium of $0.68 \pm 0.15\%$, and a ratio between 26 and 5% of Carbon/Nitrogen (C/N) ratio. An average range of 25:1 to 35:1 of the C/N ratio was reported in most countries (Bachert et al., 2008). As per the manual on the Ministry of Housing and Urban Affairs, Government of India, the optimum C/N ratio should be 30:1 (CPHEEO, 2016). If the C/N ratio is lower than 25:1 leads to the formation of a foul smell, whereas a higher C/N ratio (> 30:1) improves the compost quality (CPHEEO, 2016). Overall, comprehensive knowledge of the volume and composition of waste generated is greatly influenced the SWM procedures and provides an overview of how much energy from following MSW may be recovered (Amato and Beolchini, 2018; Rathna et al., 2018; Rodriguez-Perez et al., 2018). Table 3 depicts the varying C/N ratio and its effect on composting process.

Around 143,449 MT of MSW is produced every day in India. Strictly (0.24–0.85) from 2001 to 2018, the city-wise production of waste showed considerable variations in per capita per day production provided in its 2018 annual report (Gautam et al., 2019; Islam and Bhat, 2019; Singh and Singh, 2019). This is expected to rise soon at a fast pace. With the geographical circumstances, climate, social and economic situation of the population, the typology of waste in urban areas varies.

Mostly, MSW is produced in overpopulated cities (Nsenga Kumwimba et al., 2020; Owusu-Twum and Sharara, 2020; S. Sharma et al., 2020). Differences in waste contribute to community issues that demonstrate that the same technique does not apply to all areas (Breitenmoser et al., 2019; Mahinroosta and Senevirathna, 2020; Siyal et al., 2020). The explanation is that municipalities cannot cope and look to be behind except in fewer circumstances. A more significant portion of the solid waste production in India is covered by metropolitan cities such as Bangalore, Chennai, Delhi, Hyderabad, Kolkata, and Mumbai. A heterogeneous sort of solid waste forms a very dense population in these areas every single day, accounting for 70%–80% of the total waste produced in India every day (MNRE, 2018; Islam and Bhat, 2019; Kaliyavaradhan et al., 2019; Zimmer and Bragança, 2019). According to the Ministry of New and Renewable Energy's (MNRE) 2018 reports, congested states like Gujarat, Karnataka, Maharashtra, Tamilnadu, Uttar

Table 3
Optimum Carbon/Nitrogen (C/N ratio) and its effect for composting and their effects.

No.	SW composition for composting	C/N ratio	Effect on process	References
1	Domestic waste, including Kitchen left-out	>25	Good degradation, high thermophilic retention time	Das et al. (2021a)
2	Manure	<14	Ample NH ₄ -N generation and low degradation of organic carbon.	Srivastav and Kumar (2021)
3	Food waste	<20	Low CH ₄ generation, high NH ₃ generation	Pujara et al. (2019)
4	Vegetable waste	24–36	Below 24 will release ammonia and forfeiture nitrogen, at 36 reduce degradation.	Rodríguez-Perez et al. (2018)
5	Meal supply industry	23	Degradation of protein in waste	Patwa et al. (2020)
6	Cornstalk	20	Less GHG's emission	Sharma et al. (2020)

Pradesh, and West Bengal generates a significant volume of solid waste in the region (Patwa et al., 2020).

It is important to note that the MSW production in 2018 amounted to 68.2 million tons, with the door-to-door collection system collecting 62.79 million tons (Kumar and Agrawal, 2020; Patwa et al., 2020). In 2010, a *National Solid Waste Policy* (NSWP) was introduced to regulate SWM in India. This strategy provides an obligatory waste management hierarchy that includes waste disposal, collection, processing (reduce/reuse), recycling, and waste conversion. Moreover, the policy has considered several instruments, such as the principles of extended producers' responsibility and the product life cycle, which include the implementation of municipal solid waste management (MSWM) plans which require federal funds to be provided for the financing of waste management projects by municipalities, social inclusion of waste collectors and economic emancipation, valorization of waste materials. Moreover, selective collection and recycling represent a minor portion of the total MSW generated (Kumar and Agrawal, 2020, 2020, 2020; Patwa et al., 2020).

Although selective collection advancements have been made in the previous years, just 17% of the population today has this collection available. Some 800,000 ragpickers who operate independently or as members of official organizations or cooperatives recycle almost 90% of the recovered MSW collects (Kumar and Agrawal, 2020, 2020, 2020). However, recyclable materials in per capita countries are collected at 14.4 kg per inhabitant/year, or 1.7 million tons annually. These amounts, however, form a large portion of rejects and are recovered successfully by materials, at about 1.05 million tons per year. An investment of R\$ 2.8 billion was provided for 802 recycling cooperatives and 858 recycling businesses (from November 2015 to November 2017) and the construction of 2802 drop-off locations resulting in 26.8% higher recycling rates. As far as organic waste is concerned, while the biodegradable part of the 62,78 million tons collected in 2018 accounts for over 50% of the total MSW, only a small quantity of 124,000 tons was composted at 70 plants around the nation (CEMPRE, 2019).

Due to the poor recycling rates and organic materials, waste disposal is still the primary option (Brazil, 2019; World Bank, 2018). Furthermore, 40% of MSW is still disposed of inappropriately at dumps in almost 3000 municipalities, despite the NSWP objective for eliminating all dumps by 2014. The present state of MSWM in Brazil shows that the NSWP criteria are weakly centralized, thereby causing (i) unsafe disposal of waste, (ii) weak 4Rs strategy, (iii) weak planning in implementing MSWM, (iv) incoherence of MSWM-related statistical data, and (v) unattainable consumer strategies.

2.1.1. Viability of energy recovery potential

The energy potential is determined by the by the volume of incinerated waste, its heating value, and the efficiency of combustion process (Korai et al., 2016). However, the energy recovery from MSW is greatly influenced by its composition. For instance, heterogeneous waste stream such as food, paper, plastic, glass, and metal etc. have significantly hamper energy recovery (Istrate et al., 2021). Some developing countries, for example, Brazil (Gutierrez-Gomez et al., 2021), China (Zhou et al., 2014), India (Breitenmoser et al., 2019), Jordan (Abu-Qudais and Abu-Qdais, 2000), Mexico (Escamilla-García et al., 2020), Malaysia (Kathirvale et al., 2012), Nigeria (Oghenejoboh et al., 2021), and Pakistan (Korai et al., 2016), assessed energy recovery from MSW through chemical, physical, and thermal parameters. Furthermore, the MSW's heterogeneous waste stream makes it hard to comprehend its physical and chemical combustion behavior due to various complex reactions occur during the process, all of which are dependent on the oxidation of the organic compounds at high temperatures (Reddy et al., 2016). As a result, the lack of specific compounds from the waste stream could improve or exacerbate the primary energy parameters (Nordi et al., 2017). Nevertheless, sampling and sample preparation are key aspects in MSW characterization influenced by spatial and temporal changes (Edjabou et al., 2020). Several studies reported potential of

energy recovery from excess sludge of activated sludge treatment plants (Facchini et al., 2021; Tsiakiri et al., 2021). Some have toxic effect on bioconversion, such as the presence of heavy metals in the sludge decreased the efficiency of the anaerobic digestion process, and the presence of toxic metals in organic solid waste such as Hg, Cd and Cr(III) must be avoided (Abdel-Shafy and Mansour, 2018).

Hospital waste such anatomical waste, clinical waste sharps, pharmaceutical etc, usually disposed by high temperature incineration (≥ 1100 °C) and produces residues materials such as bottom ash (Rizan et al., 2021). Alternatively, Pyrolysis, gasification, and plasma technology are all high-temperature technologies for converting waste into liquid or synthesis gas fuels that can be used to create electricity or steam (Rizan et al., 2021). However, the presence of items like glass, electronic waste (e-waste), metals, and other inert materials in the waste stream feeding the process lowers the heating value and increases the amount of residues materials (Bianchini et al., 2019).

3. WTE conversion technologies

The handling of rural solid waste is significantly simpler than urban waste, as there are large quantities of industrial waste in metropolitan areas. The more significant part of solid waste may be reused by generation in rural regions since the rural area's generation rate is much lower than the urban area. Waste avoidance methods are often called 4Rs techniques, are accessible in rural regions (reuse, reduce, recycle and recover).

Rural solid waste comprises primarily organic waste, little inorganic waste, and no harmful waste. Separate organic waste may be composted according to various studies with adequate composting and digesting technologies, and inorganic recyclable waste may be sold to federal recyclers. The remaining portion of non-recyclable material is transferred to the local municipalities for ultimate disposal (Penteado and Castro, 2021; Saxena et al., 2021; Srivastav and Kumar, 2021).

It is not simply a good means to create energy because a WTE supply chain offers a joint solution to the issue, including waste management, GHG emissions, which helps build a sustainable environment and inclusive economy. With more than 1300 million inhabitants, India is nearly a fifth of the world's population and 30% of the worldwide average energy usage per capita (Alshehrei and Ameen, 2021; Khatri et al., 2021; Sebastian and Louis, 2021). Conventional fossil fuels that do not renewable are used intensively to address the energy requirements, which constitute a severe danger to our future generation. In addition, improper MSW management, which does not entail waste separation, non-use of state-of-the-art technology, and dumping, results in environmental degradation (Baidhe et al., 2021; Penteado and Castro, 2021; Sun et al., 2021).

Waste separation of inert and high moisture fractions in developing countries may optimize energy recovery and other beneficial possibilities. However, combined with waste technology, this brings several advantages, including power production, material recycling, and the minimum land requirement for disposal. MSW holds energy in chemical bonds, that release huge amounts of energy if disrupted. There are several advantages of MSW as a source of energy (Gruchlik et al., 2018; Julinová et al., 2018; Mo et al., 2018; Yadav et al., 2021). For example, energy waste generates substantially fewer emissions than power generated by fossil fuels (excluding natural gas).

With paradigm shift (i.e., linear to a circular economy), activities of waste conversion into energy play a significant part. The organic content of MSW has a significant calorific value, which may be recovered and utilized suitably for proper waste processing and processing technologies (Jacob et al., 2018; Nsenga Kumwimba et al., 2020; Salleh et al., 2021). WTE approach may be used as a stopgap solution for waste treatment; as it offers a pathway not alone for waste treatment but also solves critical concerns such as land usage, demand for electricity, and overreliance on fossil fuels (da Silva et al., 2020; Kumar and Agrawal, 2020; H. B. Sharma et al., 2020). Major increases in the use of

waste-to-energy technology have been recommended, although this relies on location, environment, area, and other socioeconomic variables.

3.1. Thermochemical conversion

The fundamental idea of organic waste breakdown by heat action is used in the thermochemical conversion process. This means that biomass is converted into biofuels. Thermochemical transformation seldom involves chemical addition and may utilize a multitude of feedstocks within a given period. It includes, amongst other activities, methods such as incineration, pyrolysis, and gasification (Fig. 2).

Incineration is a widely known technique that provides a cheap model for heat extraction (da Silva et al., 2020; Kumar and Agrawal, 2020; H. B. Sharma et al., 2020). The combustible component will react in the cremation process with oxygen, resulting in thermoelectricity, gases, and ash, at temperatures more than 800 °C. The main objective is to create steam, generating energy via controlling waste combustion with heat recovery. This approach is preferable because of a compact installation space, good performance, and increased reduction in waste volumes.

Due to the dense composition, moisture content, and proportion of inert components in the waste, net energy output from this procedure is calculated (da Silva et al., 2020; Kumar and Agrawal, 2020; H. B. Sharma et al., 2020). Ash may be utilized for making cement and building materials, and other items as a by-product for solid waste combustion that is generally inert. In the combustion facilities, exhaust gas is monitored and processed, with high costs and significant disadvantages. The authors have experimented with an analysis of the progress of exergy and an evaluation of the influence on the environment of the incineration system and its energy recovery potential (Owusu-Twum and Sharara, 2020; Penteado and Castro, 2021).

An examination of MSW's advanced exergy and the environmental effect was given while the vapor cycle was undergoing a combustion and energy recovery plant for electricity re-generation. Thermodynamic performance indicators have been created to detect the components and the extent of exergy destruction. Using these data, the company estimated that a possible 8.4% reduction in total exergy destruction might be achieved in the plant by boosting the effectiveness of plant components responsible for the destruction of exergy (Mankad et al., 2019; Owusu-Twum and Sharara, 2020; Penteado and Castro, 2021; Potysz et al., 2018). Pyrolysis is the mechanism of thermal waste breakdown in the absence of air to produce solid carbon (biochar), liquid (bio-oil), and non-condensable gases. The output and composition of pyrolysis products change owing to many factors such as feedstock form, reactor type, and composition, and syngas production through an MSW pyrolysis using dolomite as a catalyst has been proven (Santagata et al., 2021; Sharma et al., 2018; Singh and Kumari, 2019). The output of syngas ranged between 47 and 47 mol%. The outcome demonstrated that the application of dolomite had a major effect on the production and composition of syngas. These studies also showed that higher temperatures produced greater returns. Pyrolysis generates more energy than traditional MSW incinerators, as in the pyrolysis processes are created with the help of inert atmospheres, low oxides of nitrogen (NO_x), and oxides of sulfur (SO_x) (Santagata et al., 2021; Sharma et al., 2018; Singh and Kumari, 2019).

The partial oxidation of carbon-based feedstock gas includes the use of heat and an oxygen-reduced atmosphere for the production of energy. In the partial oxidation process, the waste material is transformed into gaseous products by a regulated oxygen supply under high temperatures. This is achieved by several procedures involving fuel gases, smaller gases char, ash, and syngas quantities (Yaqoob et al., 2021). To produce gas enriched with hydrogen, the process of gasification may be an effective and clean technique. Overall methods for gasification must be classified according to gasifier type and medium of oxidation. Generalized gasification occurs at temperatures greater than pyrolysis:

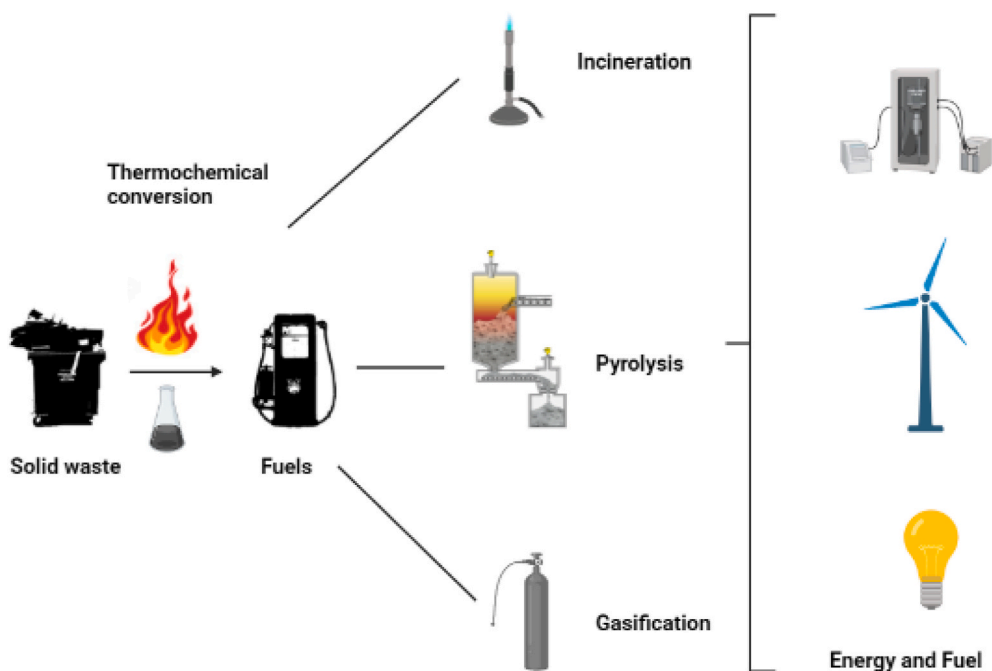


Fig. 2. Thermochemical conversion technologies for solid waste.

550–900 °C, whereas higher temperature (1000–1600 °C) is required when pure oxygen/or steam is utilized. This technique yields syngas as a precious commodity, whereas tar generation is one of the biggest issues (Golwala et al., 2021).

In the product gasification process, tars, halogens, and alkaline compounds are emitted and may create environmental and technical problems. Recently, authors studied the thermochemical transformation path for generating energy from MSW and plastic solid waste (PSW), employing plasma co-gasification (Chen et al., 2021; Dastjerdi et al., 2021). In an integrated plasma gasification cycle, they employed a particular waste combination as a feedstock. They utilized air as their primary gas and oxygen or steam as their secondary flux.

The study determined that MSW's clean air shows the highest overall efficiency of gasification of plasma alone. They noted that the fraction of oxygen gas to plasma gas was increased as waste mixes increased. The plant demonstrated its highest efficacy by roughly 38%, with pure oxygen as plasma gas used as feedstock and with 70% MSW and 30% plastic SW. In addition, with 34% of the plasma gas vapor ratio for a combination equivalent to MSW and PSW, maximum efficiency of 21.7% was attained (Kumar and Agrawal, 2020; Patwa et al., 2020).

3.2. Biochemical conversion

Composting is the most suitable treatment in rural regions for solid waste since rural waste consists predominantly of a large proportion of organic waste. However, the conversion of organic matter into manure required a few weeks, thereby unable to recover nutrients immediately in the soil. The biodegradation process of organic substances is managed according to composting a microbial population under different forms of composting therapy such as natural, forced, passive aerobic, anaerobic and vermin-composting.

Aerobic composting uses aerobic microbes (which require oxygen) that degrade organic waste and transform it into CO₂, NO₂, and NO₃ (CPHEEO, 2016). Anaerobic composting products are mostly methane (CH₄) and hydrogen sulfide (H₂S) compounds. Compared to anaerobic composting, the aerobic composting process takes less time to complete (da Silva et al., 2020; Schnell et al., 2020). Nevertheless, the presence of toxic compounds such as heavy metals and batteries can interrupt the application of these processes (Wuana and Okieimen, 2011), such as Cu

and other heavy metals in circuit boards which are an example of this challenge (Yousefzadeh et al., 2020).

Another strategy is vermicomposting; a method used to decompose and digest organic substances by earthworms, where the material becomes granular and nitrogen-rich (Patwa et al., 2020). Compared to composting, the temperature is low in vermicomposting due to the minimal microbial activity in the treatment, (Kumar and Agrawal, 2020). Also, a sustainable approach for the processing of organic waste is vermicomposting technology. The bio-oxidant process in which earthworms, microorganisms, and other degradable communities interact and accelerate decomposing organic waste processes is called vermicomposting.

Compared with regular composting, the C/N relationship drops fast with earthworms. In minerals, oxygen rises throughout time as a result of the mineralization of organic molecules. According to Adi and Noor (2009), fungal production is advantageous since earthworms utilize it as nutrients. High humidity in the vermicomposting pit is roughly 80% anaerobic. The optimal feed rate may be set at 0.75 kg per kg worm/day, and the ideal moisture level for the feed-made material is set at 60% of the total weight.

Communities that use vermicomposting as a strategy for energy recovery can apply their products for the regeneration of soils, energy as liquids, and combustible gases (Aguila Del Aguila Juárez et al., 2011). On the other hand, has been reported that the end product of vermicomposting is known as vermi-wash which is a liquid portion that contains a high quantity of humic acid (Ahmed et al., 2019). Humic acid can be used to produce electricity in microbial fuel cells technology (Sharma and Li, 2010; Thygesen et al., 2009).

According to Shak et al. (2014), better outcomes with the worm weight from 0.23 to 0.30 g/worm. Globally, there are roughly 3600 earthworm species, largely burrowing and not burrowing, that are split into two categories. Burrowing earthworms, including *Pertama Elongata* and *Pertama Asiatica*, reside in deeper soil. Non-burrowing earthworms, e. g., *Eisenia Fetida* and *Eudrilus Eugeniae* that ingest 10% of soil and 90% of organic materials, are found in the higher levels (A. V Shah et al., 2021). Earthworms of burrowing kind are faster than the other. The pH of the compost is affecting the population of earthworms since earthworms are sensitive to the ion concentration of hydrogen (A. V Shah et al., 2021).

Windrow composting separates and inserts waste into a long narrow

pile in the triangular or trapezoidal form to decompose organic waste. Composting material turning improves the passive ventilation of the pile and makes it aerobic (CPHEEO, 2016). Two forms of wind composting are traditional wind composting and forced ventilated wind composting. Parallel material stacks placed in the triangular form are not covered by normal wind composting, which means natural aeration occurs (Das et al., 2021a; A. V. Shah et al., 2021).

In the case of hospital waste, which can be classified as *risk waste* and *non-risk waste* needs to be carefully handled, because of its risk to biological contamination. Still, *risk waste* is further divided into 7 types, such as radioactive, infectious, genotoxic, pharmaceutical, chemical, pathological, and sharp wastes (Wang et al., 2020), being all these wastes are treated extremely carefully and are not considered for energy recovery. On the contrary, *non-risk waste* is usually blended with the normal MSW and is not considered dangerous, presenting any greater risk. The known non-risk waste comes from different hospital departments and sections of common use, such as offices, restaurants or cafeterias, worker stations such nurses, doctors, and cleaning employees, among others. These wastes can be food residues, paper, packages, and disposable non-hazardous materials (Wang et al., 2020).

Reynnells et al., 2014, discussed that Europe and the United States, have been developing and promoting the recycling culture and many states and cities had created composting services which offer the recollection of the compostable waste from homes, factories, offices, and hospitals.

In the case of *risky waste*, biohazardous waste is not intended to be processed for energy recovery, neither to be composted nor recycled. This can be due because the proportion of *risk waste* is a small portion compared to regular MSW and no economic advantage is seen for these residues. Despite that, laboratory animals corpses which are usually disposed of using alkaline hydrolysis can be used as fertilizers (Ali et al., 2016; Wang et al., 2020). It's important to note that some hospitals possess composting programs that recollect hospital non-risk waste (Ali et al., 2016).

Wind piles for density, porosity, and open-air space. In the process of forced aeration, the aeration of the material provided by the mechanical blower is the same as in the standard procedure. There are several different techniques of creating an aeration-based compost pile that include a static pile, a passively aerated pile, compost-covered, aerated pile, and rotated and pushed winding machines. Fixed aerated vermin-compost stacking technique minimizes the smell issue and speeds up composting. The effectiveness of the composting relies on the size of the windpipe, the weather cannot be resisted by too big a windpipe, and the windpipe must be 2–5 m wide on the bottom and 1–3 m high in effective size. During the wind, odor, structural instability, and leaching happen in the first 15–20 days of composting food waste, manure, and bulking agent's issue, dismantling of fecal coliforms and *E. coli* in the wind composting of the spreader (A. V. Shah et al., 2021; Bashir et al., 2021).

Lack of fuel in communities has pushed locals to gather wood for cooking. The use of biogas is more appropriate for use in homes. The anaerobic process can produce biogas or bio-methanation by breaking down organic waste, cow manure, and toilet waste slurry. Biogas is a gas mixture produced by the decomposition of organic waste by methanogenic bacteria. Biogas comprises 50%–70% CH₄, 30%–45 Liquefied petroleum gas (LPG), burning with a clear blue flame. Cow dung gas produces 0.04 m³/kg of dung and 0.085 m³/kg of waste from cooking waste.

A household of 4 individuals with two animals may produce 1 m³ biogas (SBMG, 2015). The biogas plant consists of a slurry feeding chamber, a slurry drainage chamber for digested material from the tank, an organic waste digestion tank, and a biogas chamber collection chamber. Biogas and digested sludge are two valuable results from the biogas plant. Nutritional value of biogas plant manure (nitrogen, phosphorus and potassium), SBMG (2015) shows that N-1.3%, P-0.85% and K-1.5% is P-0.85%. Manure is N-1.5%, P-0.3%, and K-1.3%, according to Balasubramanian and Bai (1992).

There is a significant number of nutrients included in digestate, such as N–P–K. The *biological oxygen demand* (BOD), *chemical oxygen demand* (COD), and organic carbon decreased accordingly by 50%, 10.6%, and 74.3% throughout the digesting process. The digestive pH is neutral or somewhat alkaline. The digestion of alkaline enhances soil volatility (Golwala et al., 2021). The digestive content of phosphorus, potassium, and 0.4 mg per 100 g increased correspondingly after digestion by 5.9 mg, 9.2 mg, and 0.4 mg. In solid digestate, the level of heavy metals (Co, Cu, Ni, and Zn) in comparison with mud is comparably low. In comparison to mineral fertilizer, they have a low level of Cd and Cr. Table 4 shows the comparison of different treatment methods used for SW.

Another important source of energy recovery is bio-wasted sludge (Ahmadi et al., 2020). Bio-wasted sludge contains a significant amount of organic matter becoming a good source of energy recovery. It is important to remark that some particular houses and municipal wastewater treatment plants can produce sludge with high content of organic matter due to septic tanks. For instance, digestion of bio-wasted sludge can result in a high quantity of CH₄/g of the total solids (TS) (Holliger et al., 2017; Ahmadi et al., 2020).

Nowadays, a considerable quantity of bio-waste sludge is thrown away and high potential energy is wasted, hence it is highly recommended to propose eco-friendly methods and energy-efficient to recover energy from this kind of waste, such is the case of the anaerobic digestion technology which one of its main characteristics is to prevent pollution and secondary effects on the environment (Dai et al., 2016). For the anaerobic digestion approach, a bioreactor is needed to industrialize the recovery of energy from bio-sludge waste. Between the products obtained from this treatment are several gases such as biogas, natural gas, oilfield gas, and methane, amongst others, all these gases are maintainable, clean, and inexpensive energy sources (Li et al., 2018; Ahmadi et al., 2020).

4. Status of MSWM around the world

The world's waste generation is anticipated to reach 27 billion tons annually by 2050. Asia now creates one-third total waste from China 0.44–4.3 kg/capita/day, and India (0.50–0.9) kg/capita/day. On the other hand, Gulf Cooperation Council (GCC) countries (i.e., Saudi Arabia, Bahrain, UAE, Qatar, Oman, and Kuwait) overpasses the world average (1.2 kg/capita/day) waste generation. In continuing the scenario, waste production is expected for the Indian continent from (334–661) MT/day, compared to China East Asia Pacific (468–714) MT/day according to current figures. The expected worldwide increase in MSW, including the C&D and industrial waste, is (7–10) billion tons/year.

It is established that the MSW composition varies from developing to developed countries, and even varies with local municipalities within the same country. For instance, a higher content of organic waste in MSW is found in East Asia and the Pacific (62%) followed by the Middle East and North African (61%) countries (Fig. 3). Around 65–80% of the energy is stored in organic materials which can be recovered in the form of heat that could support power facilities (Chakraborty et al., 2013). Unfortunately, a higher portion of collected waste (>90%) is directed to open dumping or unlined landfills. As a result, Air pollution, Ground water pollution, Health effects, Soil or land pollution, Economic costs, and Landfill fires are the common problems associated with open dumping or unlined landfills in most developing countries. Serious direct health impacts such as skin and eyes infections, respiratory issues, high blood lead levels caused by open burning at dumping site and dysentery yellow fever, typhoid, hepatitis, diarrhea, malaria, and cholera due to contamination of ground water, and soil (UNEP, 2011; Shorholy et al., 2008).

The present situation and future prediction compared to other global locations have also been identified by the *World Bank*; this shows that the average waste production per person a day for 2016 ranges from (0.09–0.60) kg for the area of lower-income, (0.16–0.79) kg for the

Table 4

Comparison of different treatment methods of MSW (Malini R. Capoor and Parida, 2021; Kumar and Agrawal, 2020, 2020; Patwa et al., 2020; H. B. Sharma et al., 2020).

S. No.	Items	Vermicomposting	Windrow composting	Biogas technology	Indore and Bangalore method
1	Contamination level	Less odor, less GHG emission, and no leachate seepage	Odor pollution and water pollution, high GHG's emission.	Reduce odor and no pollution from leachate.	infiltration of leachate.
2	Economics	Cost-effective and less land requirement.	Low cost, if aeration provided-cost increases.	Less economical	Very economical
3	Heavy metals	Low concentration	Zn and Cd exceeds the standard limit while Pb, Cu, and Cr are in limit	More heavy metal concentration in digestate	High conc. of Zn, Cu, Co, Ni
4	NPK value, % By mass	N-1.1-2.6 P-0.7-1.9 K-1.1-1.2	N-1.1-2.1 P-0.3-1.2 K-2.1-3.1	N-1.3 P-0.85 K-1.5	N-0.8 P-0.3-0.5 K-1.15
5	Composting duration	45-90 days	45-78 days	32 days retention time	145 days

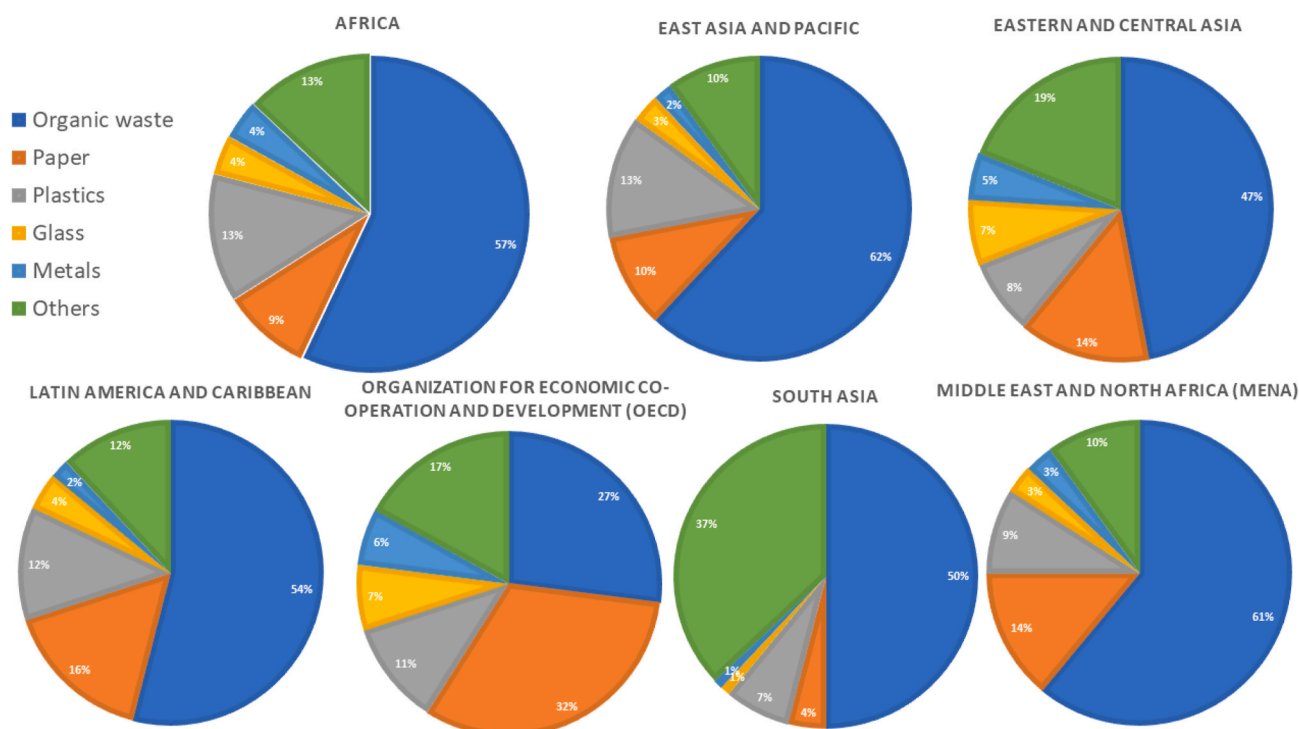


Fig. 3. Pie-chart showing solid waste composition around the world (Hoorweg and Bhada-Tata, 2012; Cardoen et al., 2015a).

group of lower medium income to (0.1–0.12) kg for the group of lower medium income. With the 2016–2050 prediction, this regional waste generation pattern throughout the globe would further double as expected by 2050.

On the other hand, in some low-income countries, non-septic hospital-based waste is blended to domestic waste and treated at the same time. This type of waste should be treated carefully specialty considering the huge amount of their production (Ansari et al., 2019). In the case of the recycling of heavy metals of batteries in solid waste. Usually, damaged or destroyed NiCd batteries for example and accumulators remain in residual waste, they are landfilled or incinerated (Friege et al., 2018). In Europe, most of the MSW is incinerated for energy and metal recovery in the Western, Central, and Northern regions of Europe and disposed of without any treatment in the Southern and Eastern regions of Europe. On the other hand, the separation of the waste and recycling culture is still low in countries with great numbers of landfill residual waste (Bartl, 2015). Batteries for example end up in landfills and their potential for energy recovery is wasted. Since, Hawkins, Matthews, and Hendrickson, reported in 2006, that the United States throw away 83% of the cadmium (Cd) coming from disposed of batteries, more efforts had been made to recycle these metals.

Metallic batteries and accumulators need years to dissolve and when they are transported there is a high risk of leachate contaminating the soil. The leaching process depends on the oxygen concentration, pH, concentration of organic and inorganic residues which creates complexes with heavy metals, that is the case of insoluble cadmium sulfide (CdS) and their related salts, which are dissolved under aerobic conditions decrementing the pH (Raghab et al., 2013). Also, has been reported that cadmium leachates are more commonly found than Pb, Cr, Zn, and other metals (Morf et al., 2013).

When all these metals are incinerated together with the MSW, metallic salts get concentrated in the fly ash due to their fugacity. Morf et al., 2013, reported a partition coefficient of cadmium in waste and cadmium in fly ash in a range of 0.85 and 0.90 respectively, demonstrating the concentration phenomenon of metals when are incinerated.

Respecting a treatments process for metal waste in MSW, the electrostatic precipitator (ESP) and boiling produce substances that are classified as hazardous waste. Despite that, the choice of these treatments depends on the circumstance of the country and particular cities, for example, in Norway applied first the neutralization of acid waste and lay up all waste in lime mines, on the other hand, France solidifies with cement the accumulated wastes in landfilling, and Germany backfills in

salt mines their waste, amongst others. On the same matter, the air pollution control residues are usually applied as aggregated fillers in cement and related materials such as asphalt (Hawkins et al., 2006).

Finally, the dispersion of pollutants such as heavy metals from building materials must be evaded. Hence in the construction industry, before the commencement of a construction project, a waste management plan should be made to handle the residues and control the quantity of material used in such projects, so when the building is demolished, no major consequences of the waste appear. For all the above, the International Solid Waste Association (ISWA) approves just landfilling in the underground or at the surface level just after their solidification to mitigate an important impact on nature (Morf et al., 2013).

5. MSWM challenges under COVID-19 outbreak

Due to fear of human-to-human transmission of coronavirus, waste workers avoided direct collection of waste without safety waste management systems (Das et al., 2021; Mol and Caldas, 2020; Kampf et al. 2020). Several studies from developing countries such as Guyana and Nigeria, South Africa, Saudi Arabia, Malaysia, India, Brazil, Iran, China reported that COVID-19 could spread from MSW (Oyedotun et al., 2020; Nzediegwu and Chang, 2020; Osra et al., 2021; Brohan et al., 2021; CPCB, 2020; Penteado and Castro, 2021; Zand and Heir, 2020; Yang et al., 2021). COVID-19 patients are being treated at home, thereby producing infectious waste disposed of as MSW (Mol and Caldas, 2020), which can pose risks to waste laborers and employers (United States Department of Labor 2020). However, developed countries also faced similar challenges.

During the COVID-19 outbreak, China reported a sixfold increase in medical waste from 40 to 240 tons/day (ADB, 2020). In the context of developing countries, due to the lack of funds and safety facilities such as gloves, boots, uniforms, masks, glasses, and ear protectors, it is difficult to provide safety against the exposure of contagious COVID-19 to municipal workers.

Several International organizations and associations such as ADB (Asian Development Bank), CDC (*Centers for Disease Control and Prevention*), EU (*European Commission*), IGES (*Institute for Global Environmental Strategies*), ISWA (*International Solid Waste Association*), OSHA (*Occupational Safety and Health Administration*), SWANA (*Solid Waste Association of North America*), USEPA (*United States Environmental Protection Agency*), WHO (*World Health Organization*), WIEGO (*Women in Informal Employment: Globalizing and Organizing*) have already issued guidelines for SWM under COVID-19 pandemic (Table 5). However, these guidelines targeted both developed and developing countries, and only a few developing countries releases specific guidelines in context to COVID-19 waste management, including China, Brazil, and India.

6. MSWM challenges

It is a time to have a sound system of waste management that preserves useable resources and helps society shift from waste dumping to resource recovery. Cleaner manufacturing will depend on the separation of waste at the source and the use of special waste processing plants to separate recycled materials. There is substantial public involvement in the handling of waste and the absence of community responsibility for waste; this should promote a sense of community awareness. Given the total implications of landfilling on energy technologies, the notion of waste resource recovery as a long-term aim would lead the way to cleaner production. Recent technical developments have increased the efficiency of waste management and enhanced energy recovery. The efficiency of energy recovery has been boosted with the use of thermal technologies like incineration, pyrolysis, gasification, as well as biochemical processes like composting and aerobic digestion (Dutta and Kumar, 2021; Ho et al., 2021).

Biochemical approaches are less environmentally damaging but

Table 5

Key considerations associated with waste management in COVID-19 pandemic (Based on guidelines from international organizations and associations) (UNEP, 2020).

S. No.	Key considerations	MSW management strategies for COVID-19 or similar pandemic in future
1.	Segregation at source	<ul style="list-style-type: none"> Masks, gloves, and tissues should be separated from waste Use double bagged for potentially infectious waste Keep recyclable items and non-medical hazardous waste (such as e-waste and batteries) for a specific period of time in double-bagged containers Outreach to generators to raise awareness Encouraged citizens to follow instructions on safe waste handling and decontamination when difficulty in separating waste at the source.
2.	Dispose and collection	<ul style="list-style-type: none"> Use two layers plastic bags Disinfect plastic bags after they are 2/3rd full, and attach a label identifying infectious waste. Collaboration between municipal waste collection and biomedical waste treatment plant operators Discharge to a community collection station or outside is halted Linkage of municipal collection operator with biomedical waste treatment facility operator Dispose of infectious (contaminated) waste at a designated collection service
3.	Transfer	<ul style="list-style-type: none"> Arrange special collection service to collect infectious (contaminated) waste Consider temporary licensing to a capable waste management service provide Consider inter-city collaboration Make it illegal to open plastic bags for the purpose of separation Provide and train personnel on how to use personal protective equipment (PPE) Direct transport to a treatment facility or disposal location Maintain a safe social distance and, if feasible, keep windows open Disinfect the collection vehicle Occupational Safety and Health (workers) Treat infectious waste the same as healthcare waste Consider temporary licensing to a skilled waste management service provider
4.	Treatment	<ul style="list-style-type: none"> Inter-city cooperation Accept recyclable materials after a specific time. Provide and train personnel on the proper usage of personal protective equipment (PPE). Maintain social distance and, if possible, keep windows open in facilities. Disinfect machines and equipment Occupational Safety and Health (formal and informal industries)
5.	Ultimate disposal	<ul style="list-style-type: none"> Treat infectious waste the same as healthcare waste disposal Manage disposal site (designated pit, no entry but authorized personnel only, no waste picking) Inter-city collaboration Provide appropriate PPE and instructions to on-site workers. Disinfect machines and equipment Occupational Safety and Health (formal and informal sectors)

more environmentally sensitive. Advances in thermal and biochemical technology have made it possible to make energy recovery more efficient and economical. Moreover, MSW is widespread globally, as opposed to fossil fuels, and hence efficient waste management could minimize the reduction and recovery of waste management problems (Breitenmoser et al., 2019; Siyal et al., 2020).

The present solid waste condition implies that the average per capita quantity of solid waste is significantly less than in the globe, but it causes serious trouble for the very dense population. The Indian solid waste composition mostly comprises the organic component with high

moisture content. Other industrialized nations create packaging waste with low moisture content, such as paper, cardboard, plastic, and more (Gruchlik et al., 2018; Mo et al., 2018).

Differences also vary in number, quality, and typology when compared in the Indian States and regions. In most cities and states, high moisture content and low heat value are often found. The available resources/budget are significantly differing, methods and planning techniques are used and differentiated from the accessible lands, the size of the recycle and processing facilities necessary. For Indian towns, the major difficulty is to separate waste from its source (Das et al., 2021a; A. V. Shah et al., 2021). Social taboos regarding waste and its related group are usually a matter of priority for marginalized individuals in society. Citizens must be informed of the development of the waste management system.

The effect of SWM on the environment and health must be addressed and evaluated in this context. Policies from the government and their execution did not work properly; just a few communities could build an efficient door-to-door collecting process. Solid waste storage is particularly troublesome since trucks cannot collect every day. The secondary tanks typically have leachate spills and ragpickers, which struggle with other creatures, such as street dogs, cows, and rats. Due to poor infrastructure, the transport of solid waste is currently being developed. The decentralized treatment of waste is not performed due to the paucity of land in congested metropolitan areas.

Table 6 shows the different technologies used for MSW management. Unplanned budget and bad infrastructure in solid waste treatment and recycling are becoming tougher since most existing waste has ceased operating or run short of high-calorification solid waste in energy and recycle facilities. In the formalized system, the unorganized informal waste sector must be included. Moreover, unskilled personnel without security equipment, who have to be lifted promptly, often handle MSW.

The remaining inorganic (dry) component may be used as *refuse-derived fuel* (RDF), and a centralized and decentralized combustion mechanism may be set up. Initial investments of finance, along with the particular scientific supervision of the infrastructure and land are required for technology such as pyrolysis and solid waste gasification. Recently, the *government of India* revised/developed the guidelines individually for building and demolition waste, waste, and other hazardous waste to handle frequent evaluations/monitoring.

In certain areas, it might be advantageous to introduce user charges, penalties, and compensation systems to encourage an effective system for SWM. In addition, it may be advantageous to swiftly sensitize the public by using sophisticated technology such as *geographic information system* (GIS)/Remote Sensing, Internet of Services (IoT), and *information, education, and communication* (IEC) based education information and communication system. This involves the participation of private

Table 6
Summary of technologies used for MSW management with different energy generation approaches.

S. No.	Treatment method	By-product	Constraint	Energy generation	References
1.	Incineration	Heat, bottom ash, fly ash	Ash production	By heat	Sharma et al. (2020)
2.	Pyrolysis	Heat, biochar, bio-oil	High initial cost	By pyrolysis	Patwa et al. (2020)
3.	Gasification	Heat, syngas, tar	High initial cost	By syngas	Kumar and Agrawal (2020)
4.	Anaerobic digestion	Biogas, digestate	High power cost due to aeration	By biogas	Shah et al. (2021)
5.	Composting	Heat, compost	Time-consuming	By heat	Shah et al. (2021)

stakeholders, non-governmental organizations (NGOs), self-help organizations, and all the departments involved, which might lead MSWM in the future to success, demand in energy and materials, and profits gain in India.

7. Immediate action and future policy under COVID-19

Due to social separation, lock-out, and exit restrictions across cities and provinces, everyday activities are being disturbed, and the planned MSW collection has been impacted. To achieve the planned MSW collection, the collection frequency should be extended. COVID-19 waste collection by well-trained personnel and suitable trucks should be organized. Safe transport involves sterilizable vehicles, skilled waste collectors and drivers, specialist routes, and equipment for waste tracking (ADB, 2020). For personnel exposed to COVID-19 wastes, specific training must be provided. The route and timing should avoid overcrowding and rush hour. After loading and unloading, the storage space and vehicles should be disinfected. The collection frequency of biodegradable waste may be altered by the area's waste, while the transport unit's availability may lower recyclable waste collection frequencies.

During the lock-down, there is an increase in food waste from homes. The citizen may be encouraged to keep recyclable waste for longer periods in double-sealed bags. The *Association of Cities and Regions for Sustainable Resource Management* also proposes a delay in the waste pickup schedule of 72 h. On the other side, special waste trucks might be necessary to gather COVID-19 waste from the hospitals, medical institutions, and quarantine centers and increase the collection frequency. To prevent mixing MSW with contaminated waste, such as is done in Korea, a specific hazardous waste pickup programmed from houses must be developed. It may be necessary to make technical modifications, such as enhanced feeding design.

In contrast, deep COVID-19 waste burial should be taken in secure landfills in the region with limited centralized treatment capabilities or no thermal treatment facilities. Protected employees shall finish the direct handling of toxic materials at COVID-19 sites. Local authorities should monitor their residents' responsibilities and advise them to do so. The job of recycling should be decreased by the correct separation of homes and should constantly be up to date with the COVID-19 waste management recommendations. Sustainable communications and awareness efforts must increase awareness of people about waste management throughout the epidemic.

A major difficulty in developing nations where most of the waste is disposed of at non-hygienic waste or dumpsite observed activities of scavengers or informal ragpickers. Unsegregated waste usually needs more time for manual sorting at the dumping site, so ragpickers are longer and more exposed to hazardous waste. The possibilities of diseases like the COVID-19 virus being transmitted are hence increased if not sufficiently protected. During the COVID-19 pandemic, the emergency pit may be employed in nations with lower or developing income with insufficient access to the healthcare facility. Safe burial on the ground is possible for relatively limited durations (i.e., 1–2 years) and a modest amount of waste (for a total of 5–10 tons), and WHO offers detailed information. In short, the waste collected is buried in a tight fuel pit (2 × 5 m) at the bottom with a layer of clay, or geosynthetic. Fresh soil or a combination of solid limbs must be poured for covering after wastes have been placed in the hole. The cement or wire meshes should cover the top layer of the pit. Subsequently, 50 cm above the wire mesh should be covered. By constructing cable barriers, the pit regions should be segregated from human and animal activity. A secure burial at the current dumpsite may be planned and considered after the incinerators reached their maximum capacity during the COVID-19 epidemic.

8. Conclusion

This review assessed the alarming issues of solid waste management

in developing countries where populations are increasing exponentially, thereby a lack of municipal budget for waste management. Many developing countries are diverted MSW to open dumping sites to confront with the problem of handling enormous volumes of MSW. Hence, this review summarizes, discussed, and proposed available and affordable strategies to transform solid waste into energy. For this, thermochemical and biochemical conversion techniques are appropriate concerning energy. In the thermochemical conversion approach, the main activities are incineration, pyrolysis, and gasification, whereas, for the biochemical conversion, bio composting is the most affordable and efficient method. Despite all these technologies and strategies for energy recovery, developing countries current situation still demands best practices and implementation of sustainable SWM. Besides, there are numerous other issues such as political, financial, and regulatory barriers in developing countries, such as a shortage of funds, inconsistent laws and rules, needs to be discussed. Finally, this review provided several recommendations to address these cumulative issues in developing countries where a mutual collaboration of the general population, stakeholders and governmental and non-governmental (NGO) support needs to strengthen current waste management facilities.

Credit author statement

The corresponding author hereby confirm that the given information is correct as per his knowledge. Even though at various stages of work contribution roles were often interchanged however the table below presents the primary contribution of individual author. **Afzal Husain Khan:** Curation/Resources, Data /Writing Original draft, Investigation/Writing – original draft. Data curation, Conceptualization/Validation. **Eduardo Alberto López-Maldonado:** Curation/Resources, Data /Writing Original draft, Investigation/Writing – original draft. Data curation, Conceptualization/Validation. **Luis Jesús Villarreal-Gómez:** Curation/Resources, Data /Writing Original draft, Investigation/Writing – original draft. Data curation, Conceptualization/Validation. **Nadeem A. Khan:** Curation/Resources, Data /Writing Original draft, Investigation/Writing – original draft. Data curation, Conceptualization/Validation. **Faris M. Munshi:** Review& Editing, Methodology/Supervision, Resources/Editing. **Abdullah H. Alsabhan:** Review& Editing, Methodology/Supervision, Resources/Editing. **Kahkashan Perveen:** Review& Editing, Methodology/Supervision, Resources/Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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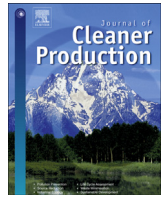
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Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*)

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ABSTRACT

Global population growth has led to an urgent need for more efficient food production systems. Moreover, as income levels increase, dietary preferences are shifting to more animal-based products. However, current feed protein sources deplete wild fish populations and contribute to rainforest deforestation. Capturing the resources in organic waste could help alleviate environmental impacts of food production. The larvae of the black soldier fly (*Hermetia illucens*) are ferocious feeders on decomposing organic material and could be used as protein source in animal feed. This study evaluated development of black soldier fly larvae on eight urban organic waste fractions and two control substrates. Principal component analysis was conducted to identify substrate properties that contributed to treatment efficiency and larval development. The main treatment factors found to be affected by substrate were waste-to-biomass conversion ratio, larval development time and final prepupal weight. The substrate properties with the greatest impact on biomass conversion ratio and larval development time were content of total volatile solids and protein content, while only total volatile solids content affected final prepupal weight. It was concluded that black soldier fly larvae are versatile in their feedstock preferences and can be used to treat a variety of organic waste streams, provided that the total volatile solids and nitrogen content are sufficiently high to support larval development. Abattoir waste, food waste, human faeces and a mixture of abattoir waste – fruits & vegetables are waste streams that are highly suitable for fly larvae treatment.

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1. Introduction

The world's population will have exceeded 9 billion by 2050, with more than half of this global population growth occurring in Africa (United Nations, 2015). According to FAO estimates, food production will have to increase by 70% in order to feed the global population and this growth will be accompanied by increased income levels, and thus a shift in food consumption with a higher demand for meat, especially fish and poultry (van Huis et al., 2013). However, instead of consuming fish directly, around one-third of global fish catches are processed into fish oil and fishmeal for use in livestock and aquaculture feeds (Tveterås and Tveterås, 2010). For example, with a Fish-in-Fishout ratio of 1.9–2.9 for carnivorous fish aquaculture, as conservatively calculated by IFFO (International Fishmeal and Fish Oil Organisation) (Seafish, 2011), the pressure on

wild fish is increasing with the growing aquaculture industry. From 1990 to 2014, worldwide aquaculture production grew by 7.8% annually (FAO, 2014). As a consequence, the price of fishmeal, today a major ingredient in feed, tripled from 2000 to 2015 and it will become increasingly unaffordable for fish and meat production. Already today, 60–70% of production costs in animal husbandry derive from feed purchasing (animal meal, fishmeal, soybean meal). Meeting these needs will require the development of new animal feed production systems (FAO, 2009), so alternative sources of protein of animal origin are therefore being explored.

Insect farming can be a viable new source of animal protein. Insects can be farmed in high densities with small space requirements and they have a high bioconversion ratio (Ooninx and de Boer, 2012). Furthermore, many insects can be reared on waste streams, which keeps the environmental footprint low and assists in recycling of refuse (Smetana et al., 2016). Consequently, the use of fly larvae in waste management has started to gain attention (Čičková et al., 2015; Pastor et al., 2015). One species that has gained more attention than others is the black soldier fly (BSF), *Hermetia*

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illucens L. (Diptera: Stratiomyidae), whose polyphagous larvae (BSFL) are known to feed and develop on a wide range of feed sources, such as kitchen waste (Diener et al., 2011; Nguyen et al., 2015), dairy manure (Myers et al., 2008b), chicken manure (Zhou et al., 2013) and human faeces (Banks et al., 2014; Lalander et al., 2013). One reason why this species is of particular interest is because the fly does not feed and thus is not a vector in disease transmission (Sheppard et al., 2002). Another reason is that, when the larvae stop feeding in the final larval stage, they are higher in fat than other fly larvae (Čičková et al., 2015). This makes BSFL of particular interest for use as a protein and fat source in animal feed (Wang and Shelomi, 2017) and for the production of biodiesel (Surendra et al., 2016).

However, the economic feasibility of a BSF system depends, among other factors, on the larval biomass produced from a certain amount of waste, in other words, the waste-to-biomass conversion ratio. This varies with the nature of input materials and may range from as little as 3% for biogas digestate to 23% on a wet-weight basis when working with fresh human excreta (Banks et al., 2014; Lalander et al., 2015; Newton et al., 2005; Spranghers et al., 2016).

There are many factors that affect the growth of insects. Assuming unlimited access to a selected material, development of insect larvae depends in the first instance on the presence of essential nutrients (Table 1).

Shortages, or even lack, of essential nutrients result in reduced growth and lowered survival rates (Cohen et al., 2004). However, even when the nutrients are present, they have to be bioavailable to the animal. Bioavailability is greatly dependent on the species of the animal in question and the type of food in which the nutrient is present. Unfortunately, almost nothing is known of the bioavailability of nutrients in insects. The majority of fly larvae, just like larvae of many species from other insect groups (e.g. beetles, true bugs, hymenoptera), feed on materials that are originally solids and converted into a liquid slurry before ingestion (Cohen et al., 2004). Such solid-to-liquid feeding or extraoral digestion is necessary as they lack biting and chewing mouthparts.

The main objectives of this study were to investigate the effect of different substrates on fly larvae composting in terms of larval growth (biomass conversion ratio, final larval weight), larval development time, waste reduction and amino acid profile of the larvae, and to identify the substrate parameters that influence the fly larvae composting process.

2. Material and methods

2.1. Animals

Eggs of the black soldier fly, *H. illucens* L. (Diptera: Stratiomyidae), were obtained from a laboratory colony located at the Research Institute of Organic Agriculture (FiBL, Switzerland). Newly

Table 1
Essential nutrients in insect diets (Cohen et al., 2004).

Amino acids	Lipids	Vitamins	Minerals
Arginine	Cholesterol	Ascorbic acid (C)	Calcium
Histidine	B-Sitosterol	Thiamine (B ₁)	Chlorine
Isoleucine	Stigmasterol	Riboflavin (B ₂)	Copper
Leucine	Campesterol	Pyridoxine (B ₆)	Iron
Lysine	24-Methylcholesterol	Nicotinic acid (B ₃)	Magnesium
Methionine	Linoleic acid	Pantothenic (B ₅)	Manganese
Phenylalanine	Linoenic acid	Biotin (B ₇)	Phosphorus
Threonine		Folic acid (B ₉)	Potassium
Tryptophan		Choline	Sodium
Valine		Cyanocobalamin (B ₁₂)	Sulfur
		Inositol	Zinc

hatched larvae used for the experiments were reared on chicken feed (Granngården Hönsfoder Start, metabolisable energy content = 11.2 MJ kg⁻¹, 80% moisture) for around 10 days. They were then transferred to one of the 11 substrates listed below.

2.2. Substrates

Poultry feed: Dry poultry feed (Granngården Hönsfoder Bas, ME = 10.9 MJ kg⁻¹) was dissolved in water to 40% dry matter (DM).

Dog food: Dry dog food (Purina Pro Plan puppy, ME = 16.0 MJ kg⁻¹) was dissolved in water to 40% DM.

Food waste: Food waste was collected from the local restaurant at Ultuna campus (Swedish University of Agricultural Sciences), Uppsala, and minced in a grinder (Palmia) with grinder plates Ø 5 mm.

Fruit & vegetables: Lettuce (50%), apples (30%) and potatoes (20%) were minced in a food processor (Moulinex, Masterchef 3000).

Abattoir waste: Abattoir waste was collected from a sheep farm in mid-west Sweden and was chopped with a knife and mixed manually in order to represent the content of abattoir waste in low and middle-income countries. It comprised 48% stomach contents, 16% blood (cattle blood bought in a retail outlet), 12% manure, 16% meat and 8% organs (lungs, heart).

Abattoir-fruit & veg. waste: Abattoir waste was mixed with fruit and vegetables in a 1:1 ratio based on wet weight.

Poultry manure: Fresh poultry manure (laying hens) was collected from the Swedish University of Agricultural Sciences experimental farm at Funbo-Lövsta, Uppsala.

Human faeces: Human faeces were collected fresh in plastic bags and stored at -20 °C.

Primary sludge: Dewatered primary wastewater sludge was sent under cooling from Hammarby sjöstadsverket in Stockholm.

Undigested sludge: Sewage sludge was retrieved before the digestion step (activated sludge) at Uppsala municipal wastewater treatment plant (Kungsängens reningsverk, Uppsala). The DM content was very low at the time of collection and the sludge was dewatered through a cloth, achieving a DM content of around 8%.

Digested sludge: Dewatered, anaerobically digested wastewater sludge was collected at Uppsala municipal sewage treatment plant (Kungsängens reningsverk, Uppsala).

All substrates were divided into feeding portions, bagged in freezer bags and stored at -20 °C until use.

2.3. Experimental set-up

The experiments were conducted in triplicate in plastic containers (Smartstore classic 2, 21 cm × 17 cm × 11 cm) with netted lids, kept at 28 °C. In each box, 200 larvae (>0.2 cm in size, 10 ± 2 d old) were placed, giving a larval density of 0.6 larvae cm⁻². The substrates were applied every second or third day, with a feeding rate of 40 mg DM larva⁻¹ d⁻¹. The substrate portions were thawed and brought to room temperature before feeding. When 50% of the larvae had transformed into prepupae, feeding was stopped but the experiment continued until all larvae had either turned into prepupae or had died. The survival rate was determined at the end of the experiment by enumerating all emerging prepupae and dividing this number by the total number of larvae added at the start of the experiment.

2.4. Sampling and analysis

All substrates were weighed when applied, as was the total remaining material at the end of the experiment. On all feeding occasions, the combined weight of 10 larvae was recorded. These

larvae were collected, washed in water, dried on a piece of paper and weighed, after which they were placed back on the substrate. All emerged prepupae were counted and weighed within one day of emerging. When no prepupae emerged on two subsequent analysis occasions, the remaining prepupae and larvae found in the material were picked out, counted and weighed. All dead larvae were counted, but were not taken into account when calculating the substrate-to-biomass conversion ratio (BCR).

Samples of all substrates and of the compost residue at the end of the experiments were taken for analysis of dry matter (DM) and total volatile solids (VS). Samples were dried at 80 °C for 48 h. After drying, the material was combusted in a muffle oven at 550 °C for 4 h for determination of VS. The pH was analysed five days after the start of the experiment, once a week during the duration of the experiment and at the end of the experiment. For these pH measurements, a radiometer electrode at room temperature was used: 10 g of sample were diluted with 50 mL deionised water and left to settle for 1 h at room temperature prior to analysis. At the end of the experiment, the prepupae were dried at 50 °C for 48 h and sent to Eurofins Food & Agro Testing Sweden AB (Swedac accredited lab) for amino acid profiling. The Swedish standard method (ISO 13903:2005) was followed for amino acid profiling.

For analysis of total nitrogen, the samples were boiled in concentrated sulphuric acid according to the method described in Lalander et al. (2015). Following acid boiling, the samples were neutralised to pH > 3 using 10 M NaOH, diluted 50-fold in deionised water and then digested using Spectroquant® Crack-Set 20 (1.14963.0001). The nitrate concentration in the digested diluted sample was determined at 340 nm using Spectroquant® nitrate test with concentration range 0.4–25 mg L⁻¹ (1.09713.0002).

2.5. Calculations

The percentage material reduction on a dry matter basis (Mat. red._{DM}) was calculated as:

$$\text{Mat. red.}_{DM} = \left(1 - \frac{\text{sub.in}_{DM}}{\text{mat.out}_{DM}}\right) \times 100, \quad (1)$$

where sub.in_{DM} and mat.out_{DM} was the dry matter of the substrate feed and of the residue after the experiment, respectively.

The percentage waste-to-biomass conversion ratio on a dry matter basis (BCR_{DM}) was calculated as:

$$\text{BCR}_{DM} = \frac{\text{pp}_{DM}}{\text{sub.in}_{DM}} \times 100, \quad (2)$$

where pp_{DM} and sub.in_{DM} was the total dry matter in the prepupae (pp) and the substrate (sub.in), respectively.

The percentage protein conversion ratio on a dry matter basis (PrCR_{DM}) was calculated as:

$$\text{PrCR}_{DM} = \frac{\text{pp}_{DM} \times \%Pr_{pp}}{\text{sub.in}_{DM} \times \%Pr_{sub.in}} \times 100, \quad (3)$$

where pp_{DM} and sub.in_{DM} was the total dry matter and %Pr_{pp} and %Pr_{sub.in} was the percentage crude protein (% of DM) in the prepupae (pp) and the substrate (sub.in), respectively.

Values for carbohydrate content of similar substrates were taken from the literature. The total protein content (% of DM) was used to verify the similarity between the substrates tested in this study and those described in the literature. No reliable comparable literature value was found for the digested sludge. Based on the literature values of protein and carbohydrate concentration, the carbohydrate to protein ratio (CHO/Pr) was calculated.

The carbon to nitrogen ratio (C/N) was calculated by dividing the percentage of organic carbon by the percentage of total nitrogen, on a dry matter basis. The percentage of organic carbon was estimated by dividing the percentage of VS by 1.8 (Haug, 1980).

2.6. Statistical analysis

The Brown-Forsythe-Levene test was performed to verify equal variance between the data on the different substrates. Analysis of variance (ANOVA) with 95% confidence interval was performed to identify statistically significant differences between substrates. When a significant difference was found, Tukey post-hoc test with 95% confidence interval was performed. Principal component analysis (PCA) was performed to find the variables that mostly contributed to the data variance, while generalised linear regression was used to evaluate the variables selected in the PCA. All statistical analyses and graphical illustrations were carried out using RStudio (RStudio Team, 2016).

3. Results

The dry matter content of the different substrates varied between 41% for poultry feed and 8% for undigested sludge, while the VS content on a dry matter basis varied between 93% for dog food and 63% for undigested sludge (Table 2). Dog food had the highest protein concentration (40% of DM) and fruit & vegetables the lowest (13% of DM). The pH after five days of BSF composting ranged between 4.3 (dog food, fruit & vegetables) and 8.9 (poultry manure). Fruit & vegetables had the highest CHO/P ratio and slaughterhouse waste the lowest. Poultry feed had the highest C/N ratio, while abattoir waste had the lowest.

The highest waste-to-biomass conversion ratio (BCR) was achieved with the abattoir waste (15% DM) and the highest material reduction occurred for poultry manure, of which 85% was reduced on a DM basis (Table 3). Undigested sludge had the lowest conversion ratio (2% DM) and material reduction (13% DM). Poultry feed had the highest protein conversion ratio (PrCR), while digested sludge had the lowest. The larvae developed rapidly on abattoir waste, abattoir waste-fruit & veg., dog food, poultry feed, food waste, human faeces and poultry manure (Fig. 1). By day 14 of the experiment, the first prepupae had emerged from these substrates and by day 19, 50% or more of the prepupae had emerged (Table 3). The prepupae in these substrates were quite large in all cases (>210 mg larva⁻¹) except those reared on poultry manure (165 mg larva⁻¹). The largest prepupae were those reared on abattoir waste-fruit & vegetables, which weighed just over 250 mg larva⁻¹ on average. Larval development was slowest on the digested sludge, where it took 30 days for the first prepupa to emerge and around 50 days for 50% of the prepupae to emerge. The prepupae that emerged from the different sludges were smaller than those on the other substrates; around 140 mg larva⁻¹ for those reared on undigested and primary sludge and 70 mg larva⁻¹ for those on digested sludge. Larval development was also slow on the fruit & vegetables substrate, 28 days for the first prepupa to emerge and around 28 days for 50% of the prepupae to emerge. However, in that case the average prepupal weight was quite high (220 mg larva⁻¹).

Principal component analysis was conducted in order to distinguish the most important parameters affecting BSF composting (Fig. S1). The BSF composting variables found to be affected by substrate properties were waste-to-biomass conversion ratio (% DM), larval development (time for first prepupa and for 50% of prepupae to emerge) and prepupal final weight (mg prepupa⁻¹). The survival rate did not vary greatly between the different substrates. The variables found to contribute most to BCR and larval development were VS and protein feeding rates. Volatile solids

Table 2
Physico-chemical and nutritional properties of substrates tested for their suitability as feed for BSFL. Experimentally determined values, presented as mean \pm standard deviation ($n = 3$). (Literature (Lit.) values presented for comparison).

	Dry matter (%)	Total volatile solids (% of DM)	N-tot (mg g ⁻¹)	Crude protein (Pr) (% of DM)**	Lit. crude protein (% of DM)	Lit. carbohydrate (CHO) (% of DM)	CHO/Pr ratio	C/N ratio***	pH [‡]
Poultry feed	41.2 \pm 0.0	90.0 \pm 0.0	9.6 \pm 0.9	17.3	17.8 ^a	60 ^a	3.4 ^a	18.1	4.9 \pm 0.0
Dog food	37.7 \pm 0.0	93.3 \pm 0.3	20.4 \pm 0.4	33.9	32.6 ^b	36.4 ^b	1.1 ^b	9.6	4.3 \pm 0.0
Food waste	24.3 \pm 1.9	89.8 \pm 4.0	8.6 \pm 0.7	22.2	22.3 ^c	55 ^c	2.5 ^c	14.0	6.5 \pm 0.4
Fruits & veg.	11.1 \pm 0.5	93.0 \pm 2.0	2.3 \pm 0.3	13.2	12.3 ^d	72.6 ^d	5.9 ^d	24.4	4.3 \pm 0.2
Abattoir waste	18.0 \pm 3.0	89.3 \pm 4.0	16.2 \pm 0.5	56.3	53.4 ^e	2 ^e	0.1 ^e	5.5	8.5 \pm 0.1
Abattoir -fruits & veg.*	14.5	91.2	9.3	34.8	27.9	37.4	1.3	9.0	6.8 \pm 0.7
Poultry manure	31.2 \pm 0.3	83.6 \pm 0.3	11.4 \pm 0.9	22.8	24.2 ^f	38.0 ^f	1.5 ^f	12.7	8.9 \pm 0.1
Human faeces	21.9 \pm 0.2	87.1 \pm 0.1	12.4 \pm 3.5	35.5	38.8 ^g	31.0 ^g	0.8 ^g	8.5	7.3 \pm 0.2
Primary sludge	17.5 \pm 0.6	77.8 \pm 0.2	4.7 \pm 0.5	16.9	21.8 ^h	38.9 ^h	1.8 ^h	16.0	8.6 \pm 0.0
Undigested sludge	8.3 \pm 0.1	77.1 \pm 0.5	4.2 \pm 0.1	31.5	28 ^{i,j}	18 ^{i,j}	0.6 ⁱ	8.5	6.8 \pm 0.1
Digested sludge	28.7 \pm 0.1	63.2 \pm 0.2	6.8 \pm 0.2	14.7	na	na	na	14.9	8.8 \pm 0.0

* Average of abattoir waste and Fruits and veg.; ** N-tot \times 6.25; [‡] % of COD; *** Org-C/N-tot, org-C estimated as VS (% of DM)/1.8 (Haug, 1980), [‡] Determined after five days in treatment.

^a Granngården Hönsfoder Bas.

^b Purina Pro Plan puppy.

^c Kjos et al. (2000).

^d Livsmedelsinfo.nu.

^e Skrede and Nes (1988).

^f Feedipedia.

^g Rose et al. (2015).

^h Nielfa et al. (2015).

ⁱ Raunkjær et al. (1994).

Table 3
Process efficiency and larval development properties to the final larval stage prepupae (pp) in BSFL composting with different substrates. Values within columns marked with same letters are not significantly different ($p < 0.05$). Values presented are mean \pm standard deviation ($n = 3$).

	Process efficiency			Larval development properties			
	Biomass conversion ratio (% DM)	Protein conversion ratio (%)	Material reduction (% DM)	Time to first pp (d start of exp.)	Time to 50% pp (d start of exp.)	Prepupal weight (mg)	Survival rate (%)
Poultry feed	12.8 \pm 0.7 ^{a,d}	80.4 \pm 1.2	84.8 \pm 3.6 ^d	14	16	251 \pm 6 ^a	93.0 \pm 2.9 ^{a,b}
Dog food	13.4 \pm 0.9 ^{a,b}	46.3 \pm 2.8 ^{a,b}	60.5 \pm 1.5 ^{b,e}	15	18	252 \pm 6 ^a	89.3 \pm 6.6 ^{a,b,c}
Food waste	13.9 \pm 0.3 ^{a,b}	58.7 \pm 1.3	55.3 \pm 4.1 ^{a,b,e}	14	19	212 \pm 4 ^b	87.2 \pm 0.5 ^{a,b,c}
Fruits & veg.	4.1 \pm 0.2 ^{e,f}	34.3 \pm 1.1 ^c	46.7 \pm 3.1 ^{a,b,e}	28	42–47	218 \pm 4 ^b	90.7 \pm 5.6 ^{a,b,c}
Abattoir waste	15.2 \pm 1.6 ^a	30.8 \pm 2.8 ^c	46.3 \pm 2.9 ^a	12	17	248 \pm 3 ^a	101.5 \pm 2.8 ^a
Abattoir waste –fruits & veg.	14.2 \pm 1.9 ^{a,b}	47.7 \pm 6.6 ^a	61.1 \pm 10.7 ^{a,b,e}	12	17	252 \pm 13 ^a	96.3 \pm 5.2 ^{a,b}
Poultry manure	7.1 \pm 0.6 ^e	37.8 \pm 3.4 ^{b,c}	60.0 \pm 2.3 ^{a,b,e}	14	19	164 \pm 14	92.7 \pm 3.3 ^{a,b}
Human faeces	11.3 \pm 0.3 ^{b,d}	31.6 \pm 0.6 ^c	47.7 \pm 1.1 ^{a,b}	12	19	245 \pm 5 ^a	91.8 \pm 4.5 ^{a,b,c}
Primary sludge	2.3 \pm 0.1 ^{c,f}	15.0 \pm 0.5 ^d	63.3 \pm 1.9 ^{b,e}	16–21	28–32	137 \pm 5 ^c	81.0 \pm 1.5 ^{b,c}
Undigested sludge	2.2 \pm 0.2 ^{c,f}	7.8 \pm 0.6 ^{d,e}	49.2 \pm 3.7 ^{a,b,e}	30	46–51	145 \pm 5 ^c	76.2 \pm 7.1 ^c
Digested sludge	0.2 \pm 0.0 ^c	1.9 \pm 0.3 ^e	13.2 \pm 0.8 ^c	39–42	NA	70 \pm 5	39.0 \pm 4.4

feeding rate (VS_r) was found to be the most important parameter, contributing to 60% of the variance in BCR (Table 3). When the protein feeding rate (Pr_r) was included in the linear model, close to 80% of the variance in BCR was explained (Fig. 2). The model including both VS and protein feeding rate took the form $y_{VS+Pr} = a \times VS_r + b \times Pr_r$, where a and b are model-derived constants representing the estimated slope in the correlations of VS_r and Pr_r with response variables. This model was not as strong in explaining the development time, but the degree of explanation increased greatly from the simpler model (y_{VS}), from 30% to 60% (Fig. 2c and d). For the prepupal final weight, VS feeding rate was by far the strongest factor; including protein feeding in the model only increased the model strength from 0.87 to 0.9 (Table 4; Fig. S2). The only substrate property investigated that was found to explain the variation in PrCR was VS feeding rate, while inclusion of protein feeding rate did not improve the model.

The average crude protein content of the prepupae in this study was 41.2% (Table 5) and it did not vary greatly between the

prepupae reared on the different substrates. The highest protein content was found for the prepupae reared on abattoir waste (44%) and the lowest for those reared on human faeces (39%). The combined amino acid component of the dry matter comprised $36 \pm 0.6\%$ (Table S1). The differences in amino acid profiles in the prepupae reared on different substrates were not large, although some were significant (Table 5).

4. Discussion

This study investigated how different substrates affect BSFL composting in terms of larval growth (biomass conversion ratio, final larval weight), larval development time and waste reduction. It has already been established in other studies that larval density, feeding rate and feeding frequency have a great impact on the efficiency of the process (Banks et al., 2014; Parra Paz et al., 2015), so those parameters were not analysed in this study. The same larval density (0.6 larvae cm⁻²), feeding rate (40 mg DM day⁻¹ larva⁻¹)

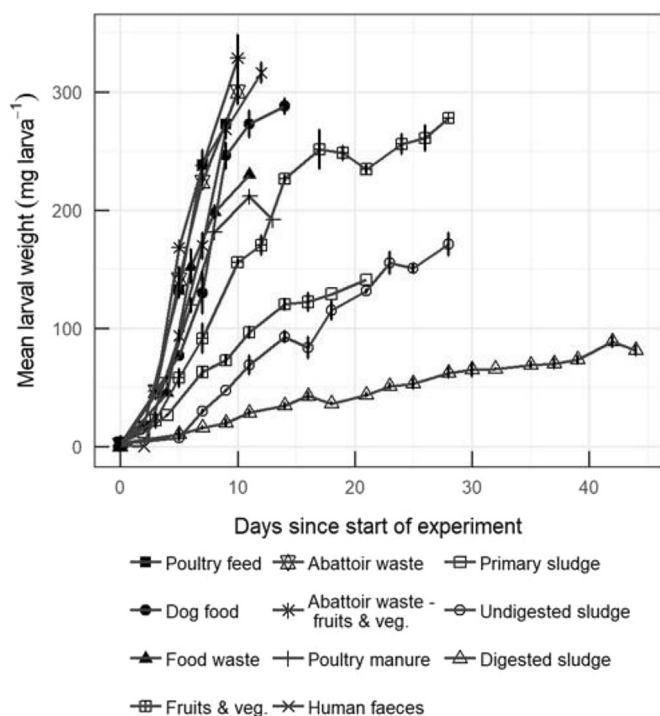


Fig. 1. Larval mass gain (mg) over time (days) in the different substrates: points represent the mean ($n = 3$) and error bars the standard error of the mean.

and feeding frequency (every 2nd or 3rd day) were employed for all 11 substrates tested, in order to investigate the impact of the substrate itself. These variables are by no mean the most optimised, but were those used in this study. Dog food and poultry feed were included in the study, since these substrates have been used as model substrates in previous studies.

4.1. Substrate properties affecting the process

The two main factors found to contribute to the BSFL composting process were VS content of the substrate and nitrogen feeding rate (mg larva^{-1}) (Table 4). In contrast, the C/N ratio was not found to directly correlate to the response variables (Fig. S1). Rehman et al. (2017b) stressed the importance of a good balance between VS and nitrogen in BSFL substrates. They found that BCR in BSFL composting was higher on soybean curd residue than on dairy manure, while mixtures of the two substrates yielded even higher BCR, which those authors attributed to better nutrient balance (C/N ratio) in the composite substrate. In this study, human faeces and undigested sludge had the same C/N ratio (8.5), but the BCR for human faeces was around 11%, while that of undigested sludge was just over 2% (Table 3). This is probably because the VS content of the undigested sludge was too low, even though the ratio of nitrogen to carbon was within a range similar to other substrates with higher BCR (dog food and abattoir - fruits & veg.). As the feeding rate was regulated by dry matter content in this study, the VS and protein feeding rates varied for the different substrates. To capture the variations in the amount of VS and protein received by the larvae reared on the different substrates, daily VS and protein feeding rates were calculated. The model including VS and protein feeding rates ($y_{\text{VS+Pr}}$) was able to capture the variations in BCR for the different substrates (Fig. 2b). However, that model did not describe the variations in larval development time as well, e.g. larvae reared on the fruit & vegetables substrate, which had a high VS and low protein content, had a longer development time than estimated by

the model for that VS and protein feeding rate. The BCR did not correlate with the protein conversion ratio (PrCR): although there was no significant difference in the PrCR of fruit & vegetables, abattoir waste, poultry manure and human faeces, the BCR of these waste fractions varied between 4% (fruit & veg.) and 15% (abattoir waste). Interestingly, the PrCR for the mixture of abattoir waste and fruit & veg. (48%) was higher than that of the pure abattoir waste fraction (31%), although the BCR of the two substrates was almost the same (14–15%). The nutrient balance was better in the mixture of abattoir waste-fruit & veg., as the carbon added by the fruit & vegetable fraction balanced the high nitrogen content of the abattoir waste, enabling the larvae to utilise the available nutrients to a higher degree.

4.2. Factor affecting larval size and development

The larvae grew largest on abattoir waste (including that mixed with 50% fruit & vegetables) and were smallest on undigested sludge (Table 3). On all substrates, the larval weight gain appeared to be linear. The correlation between VS feeding rate and the final weight of the prepupae was very strong (Table 4; Fig. S2), and is likely the strongest factor controlling the final prepupal weight.

The development of BSFL on cattle manure has been shown to be slower and the larvae considerably smaller (Myers et al., 2008a) than found for poultry feed (Diener et al., 2009). As observed in the present study, Nguyen et al. (2013) also found that the development of BSFL on fruit & vegetable waste was quite slow. However, the larvae fed fruit & vegetables in this study were considerably larger than in their study. The energy and protein content of the fruit & vegetables substrate in their study was lower than that of manure, yet the larvae fed fruit & vegetables grew larger and developed more quickly. This could be because, although the energy content was higher in manure, it consisted to a large extent of lignin, which the larvae could not degrade. Rehman et al. (2017a) found considerably lower BCR for dairy manure than for chicken manure even though the dairy manure had higher total organic carbon, because the proportion of lignin, cellulose and hemicellulose was higher. Another reason why the larvae fed the fruit & vegetables substrate were smaller for Nguyen et al. (2013) could be because they were handled to a greater extent (daily), which according to those authors can cause stress and thereby hamper growth.

The larvae reared on fruit & vegetables waste were quite large, but their development was slow compared with values reported in other studies on similar substrates. For example, in Spranghers et al. (2016) the required development time for the first prepupae to emerge was 19 days from the first feeding and in Meneguz et al. (2018) it was 20 days, compared with 28 days in this study. Fruit and vegetables are high in VS but low in protein, so the slow development could be due to a larger amount of substrate being required in order to attain a sufficient amount of protein for development. Interestingly, Meneguz et al. (2018) found a larger difference in development time between winery by-product waste and brewery waste (22 d and 8 d, respectively), where the winery by-product waste had similar properties to the fruit & vegetable waste in this study (8.3% DM, 90.9% VS and 12% protein on a DM basis), while the brewery waste had a considerably higher VS and protein content (23.2% DM, 96% VS and 20.1% protein on a DM basis).

It was also observed in the present study that, when a substrate was high in protein, the development was faster even when the VS content was not high. However, the larvae did not grow as large, as in the case of poultry manure. It appears that the larvae accumulated enough protein to continue their development, while consuming less energy, but this resulted in smaller larvae.

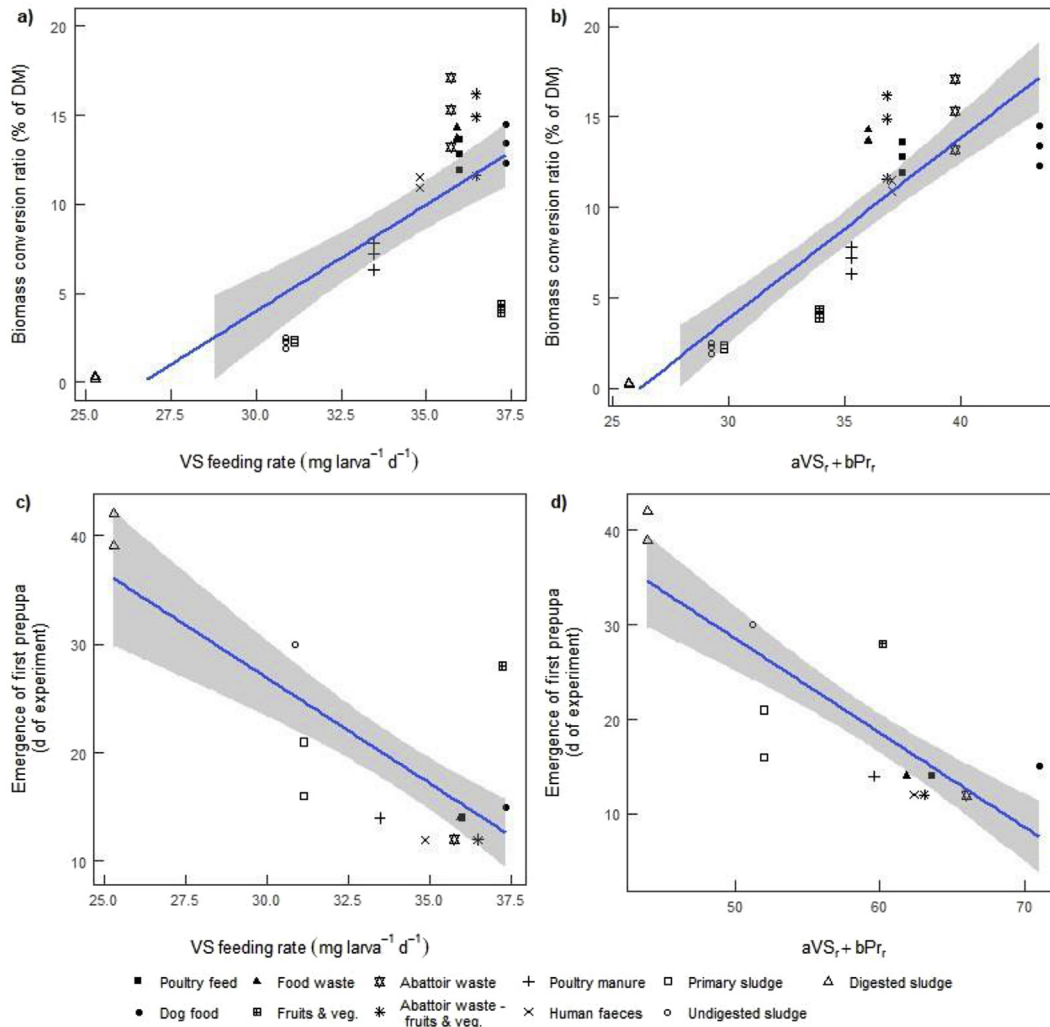


Fig. 2. Graphical representations of the correlations between biomass conversion ratio (% of dry matter) and a) volatile solids (VS) feeding rate (VS_r , $\text{mg larva}^{-1} \text{d}^{-1}$) and b) VS_r and the protein feeding rate (Pr_r) and the correlation between the emergency of first prepupa (days of experiment) and c) VS_r , d) VS_r and Pr_r .

Table 4
Model strength (R^2) and significance level of models describing the correlation between volatile solids (VS_r) and protein (Pr_r) feeding rate, alone and in combination, on biomass and protein conversion ratio (BCR and PrCR, respectively), prepupal emergence rate and prepupal weight.

	Model strengths (R^2) for response variables (y)			
	BCR _{DM}	PrCR _{DM}	Prepupal weight	Prepupal emergence
VS feeding rate (VS_r) $y_{VS} = a \times VS_r$	0.58***	0.55***	0.87***	0.54***
Protein feeding rate (Pr_r) $y_{Pr} = b \times Pr_r$	0.51***	0.15*	0.31***	0.33***
VS and protein feeding rate $y_{VS+Pr} = a \times VS_r + b \times Pr_r$	0.77***	0.56***	0.90***	0.63***

Significance level of model coefficients: $p < 0.001$ ***, $p < 0.5$ *

Sprangers et al. (2016) found that rearing BSFL on digested vegetable waste resulted in almost 40% lower larval biomass yield compared with rearing them on undigested vegetable waste, while the development time was not affected by consuming digested waste. In the present study, the larvae reared on digested sludge were the smallest (70 mg larva^{-1}) and had the longest development time, with BCR reduced by >90% compared with undigested sludge (Table 3). During anaerobic digestion, easily available carbon is reduced to methane, while nitrogen largely remains in the digestate (Zhang et al., 2014). The digested sewage sludge in this study had a low VS as well as protein feeding rate (Fig. 2), while the digested vegetables in Sprangers et al. (2016) had a lower VS but

higher protein content, as compared to the vegetable waste. The larvae reared in digestate were thus smaller but the development time unaffected. This supports our suggestion that the VS content influences the size of the larvae, while the VS and protein content together affect the development time of the larvae.

4.3. Other factors that could have an impact on larval growth

Volatile solids and protein content seemed to explain the variations in BCR and larval development to a great extent. However, other factors are also likely to contribute. The fat content was not analysed in this study, but is likely to have an impact, since BSF

Table 5

The crude protein content (% of DM) and amino acid profile of the larvae (g kg⁻¹ crude protein) reared in the different substrates. Where a significant difference between the larvae reared in the different substrates exist, values emphasised in bold font represent highest value for a given amino acid and the superscripted *i* represent significant difference ($p > 0.05$) to the highest value. Values are presented as mean ($n = 3$) \pm standard deviation. The essential amino acids for the larvae are in italic.

	Abattoir waste	Abattoir -fruits & veg.	Dog food	Digested sludge	Food waste	Fruits & veg.	Human faeces	Poultry feed	Poultry manure	Primary sludge	Undigested sludge
Crude protein (% of DM) ^{***}	44.2 ± 0.2	44.1 ± 0.6	42.8 ± 0.2	42.6 ± 0.3	39.2 ± 2.5 ⁱ	41.3 ± 1.0 ⁱ	39.1 ± 0.3 ⁱ	39.6 ± 0.2 ⁱ	41.6 ± 1.5 ⁱ	39.6 ± 0.3 ⁱ	40.0 ± 1.5 ⁱ
Alanine ^{***}	57.2 ± 1.1 ⁱ	52.2 ± 0.9 ⁱ	59.4 ± 1.1	48.2 ± 2.3 ⁱ	59.3 ± 0.9	54.8 ± 2.5 ⁱ	65.3 ± 0.9	58.8 ± 0.9	56.5 ± 3.7 ⁱ	55.7 ± 5.4 ⁱ	56.6 ± 1.6 ⁱ
Arginine	49.6 ± 0.7	46.5 ± 1.2	49.5 ± 0.6	44.9 ± 4.3	48.9 ± 0.7	45.4 ± 3.4	51.0 ± 1.8	48.3 ± 4.7	49.2 ± 3.2	49.4 ± 3.7	49.4 ± 0.8
Aspartic acid	92.8 ± 1.2	88.0 ± 2.4	91.1 ± 1.3	82.6 ± 7.5	90.8 ± 0.8	80.6 ± 7.2	90.0 ± 1.8	83.8 ± 7.2	92.6 ± 5.9	88.5 ± 7.8	89.0 ± 2.3
Cysteine ^{***}	6.0 ± 0.1	5.7 ± 0.1	6.5 ± 0.0	6.5 ± 0.5	5.3 ± 0.1 ⁱ	5.0 ± 0.6 ⁱ	6.7 ± 0.5	5.9 ± 0.5 ⁱ	5.5 ± 0.0 ⁱ	6.6 ± 0.8	6.7 ± 0.1
Glutamic acid ^{**}	100.0 ± 0.2	92.2 ± 1.2 ⁱ	104.2 ± 1.5	95.7 ± 5.6	98.4 ± 0.3	95.4 ± 4.9	105.9 ± 1.1	94.6 ± 2.8	96.6 ± 5.2	100.4 ± 9.5	103.8 ± 2.8
Glycine ^{***}	5.8 ± 0.7	54.1 ± 0.9 ⁱ	56.2 ± 0.6	48.3 ± 2.5	52.7 ± 1.1	52.4 ± 3.1	59.2 ± 0.4	51.1 ± 1.2	54.1 ± 3.5	56.0 ± 5.3	55.5 ± 1.6
Histidine	35.3 ± 0.6	31.6 ± 0.7	25.3 ± 8.1	19.8 ± 8.4	29.1 ± 11.3	26.3 ± 1.9	33.0 ± 1.2	29.2 ± 0.7	30.9 ± 11.3	29.7 ± 11.3	31.3 ± 1.0
Hydroxyproline	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
Isoleucine ^{**}	46.7 ± 1.3	45.3 ± 3.5	47.6 ± 0.9	39.0 ± 4.3 ⁱ	41.3 ± 0.3	43.0 ± 3.8	46.7 ± 0.7	45.3 ± 3.0	41.0 ± 2.9	45.0 ± 4.3	44.7 ± 1.9
Leucine ^{**}	68.4 ± 0.6 ⁱ	67.1 ± 0.6 ⁱ	80.1 ± 1.8	62.5 ± 2.2 ⁱ	67.9 ± 0.4 ⁱ	66.7 ± 5.8 ⁱ	70.0 ± 1.7	73.4 ± 8.9	66.1 ± 4.4 ⁱ	65.5 ± 5.5 ⁱ	75.6 ± 1.6
Lysine ^{***}	64.0 ± 0.5 ⁱ	57.6 ± 1.3 ⁱ	61.7 ± 0.9 ⁱ	61.7 ± 4.0 ⁱ	82.5 ± 5.0	51.4 ± 3.2 ⁱ	61.7 ± 1.1 ⁱ	59.5 ± 1.7 ⁱ	70.7 ± 10.0	59.4 ± 5.7 ⁱ	64.2 ± 2.1 ⁱ
Methionine ^{**}	17.7 ± 0.2	17.3 ± 0.7 ⁱ	18.1 ± 0.3	18.1 ± 2.0	18.4 ± 0.4	15.3 ± 1.3 ⁱ	18.5 ± 0.9	17.1 ± 1.2 ⁱ	20.5 ± 0.4	18.1 ± 1.7	18.3 ± 0.5
Ornithine	0.3 ± 0.1	0.4 ± 0.1	0.7 ± 0.0	<0.25	<1.3	<0.25	0.6 ± 0.1	0.6 ± 0.1	<1.3	<0.25	<0.25
Phenylalanine ^{**}	35.9 ± 1.6 ⁱ	38.6 ± 1.6	41.4 ± 0.9	37.3 ± 4.3	40.3 ± 0.3	34.5 ± 3.1 ⁱ	44.2 ± 3.7	38.6 ± 2.6	42.0 ± 3.0	37.6 ± 2.9	39.9 ± 1.1
Proline	50.6 ± 0.8	45.1 ± 1.5	58.7 ± 8.9	46.5 ± 1.9	51.2 ± 1.2	52.8 ± 2.8	57.9 ± 2.9	48.5 ± 3.3	52.0 ± 6.2	55.9 ± 3.1	53.5 ± 2.2
Serine	40.5 ± 1.4	38.7 ± 0.1	41.4 ± 0.8	36.6 ± 1.3	41.3 ± 0.9	38.6 ± 3.2	43.9 ± 4.9	39.9 ± 3.2	38.4 ± 2.6	40.6 ± 2.9	42.5 ± 0.4
Threonine	37.0 ± 0.4	35.9 ± 0.4	38.0 ± 0.7	33.1 ± 2.4	38.6 ± 0.2	34.6 ± 3.3	37.6 ± 1.5	36.8 ± 2.3	38.3 ± 2.3	36.0 ± 2.7	37.0 ± 0.7
Tryptophan ^{***}	16.7 ± 0.3	16.6 ± 0.5	13.6 ± 0.2 ⁱ	17.9 ± 0.3	13.8 ± 0.4 ⁱ	14.0 ± 0.3 ⁱ	16.9 ± 0.1	15.2 ± 0.9 ⁱ	16.2 ± 0.3 ⁱ	16.5 ± 0.1 ⁱ	17.1 ± 0.6
Tyrosine ^{***}	86.2 ± 2.6 ⁱ	57.0 ± 1.0 ⁱ	61.1 ± 0.3 ⁱ	62.6 ± 3.5 ⁱ	60.2 ± 0.3 ⁱ	55.0 ± 3.3 ⁱ	108.8 ± 0.6	58.4 ± 1.1 ⁱ	62.1 ± 4.4 ⁱ	60.2 ± 3.9 ⁱ	65.6 ± 2.6 ⁱ
Valine ^{**}	63.2 ± 1.8	61.7 ± 1.1	62.9 ± 1.0	52.8 ± 5.5	58.4 ± 1.9	59.5 ± 6.0	65.9 ± 1.1	61.3 ± 3.8	59.7 ± 3.5	61.6 ± 4.9	60.8 ± 2.7

larvae need to accumulate energy in the form of fat for the adult phase (Sheppard et al., 1994). A substrate too rich in fat could also be detrimental, e.g. Memon (2010) found that blowfly larvae reared on a high fat diet lived for a shorter time and did not survive to adulthood. In the present study, no factors affecting the survival rate were identified and quite a high survival rate was found for all substrates (Table 3). On the other hand, emergence to flies was not monitored. Moreover, it is difficult to compare BSF with other insects, even other flies, as they do not feed as adults.

4.4. Material reduction

In this study, no particular substrate property was found to contribute to the material reduction. One factor that was not taken into account in this study, but which could contribute, was the amount of easily available carbon relative to the amount of slowly digestible carbon compounds, such as long-chain fibre compounds e.g. cellulose, lignocellulose and lignin (Pérez et al., 2002). Agricultural wastes, such as cattle manure, contain high proportions of cellulose and lignin and generally a lower proportion of easily available carbon. Li et al. (2011) found that 50% of cellulose and nearly 30% of hemicellulose was reduced after 21 days of BSF composting, while the relative lignin content increased because lignin was not degraded. In a later study, Li et al. (2015) found a small reduction in lignin content after BSFL composting of anaerobically digested corn cobs, but pointed out that bacteria could be responsible for the lignin degradation, rather than the larvae themselves. The residence time in their fly larvae composting system was not reported. Lignin degradation is quite complex and is performed by either fungi or a consortium of bacteria (Brown and Chang, 2014). A material with high carbon content that comprises a great proportion of lignin could be expected to be broken down less well in BSFL composting, which is generally a quite fast process.

4.5. Protein content and amino acid profile of the prepupae

In the concept of waste management with black soldier flies, the larvae or prepupae could be used either as animal feed (Wang and

Shelomi, 2017) or for production of biodiesel (Leong et al., 2016). For use as feed, the protein content and the amino acid profile of the larvae/prepupae are important. In this study, the importance of waste substrate on the protein content and amino acid profile of the larvae was investigated. The results showed that protein content did not vary greatly on a DM basis, ranging between 44% (abattoir waste) and 39% (food waste and human faeces) (Table 5), while the combined amino acid component of the DM comprised $36 \pm 0.6\%$ (Table S1). That is well in line with data presented by Liland et al. (2017), who showed that the deviation in gross protein and actual protein is related to the nitrogen content in the chitin compounds in the larvae, giving a misleading gross protein value. No factor was found to correlate with the protein content of the larvae (Fig. S1). Despite the protein content of the larvae not varying by much, the size of the larvae/prepupae varied considerably ($70\text{--}250\text{ mg larva}^{-1}$), as discussed above (Table 3).

There were some differences in the amino acid profile of the larvae/prepupae reared in different substrates (Table 5). The content of the non-essential amino acids tyrosine and lysine varied by 40–50% between the different substrates, while there was no significant difference in the essential amino acids arginine, histidine and threonine. The variation in the other amino acids was smaller ($\pm 20\%$). On comparing the results of this study to average values found in other studies using swine and dairy manure as feedstocks (Kroeckel et al., 2012; St-Hilaire et al., 2007; Stamer, 2015; Zhang et al., 2007), some differences were found. In general, the literature values were higher than the average obtained for the substrates evaluated in this study (Table S1). The methionine content found here was 1.8% of the crude protein content, while the average of the above studies was 2.1% of the crude protein content. The prepupae grown on the poultry manure substrate had a methionine content of around 2% of the crude protein content, which is comparable to that found in other studies. However, the methionine content of the larvae reared on poultry manure only differed significantly from that of the larvae reared on abattoir waste-fruit & veg., poultry feed and fruit & vegetables. So although substrate type appears to have some effect on the amino acid profile of BSF larvae, this effect does not appear to be large, confirming findings in other

studies (Sprangers et al., 2016).

4.6. Fly larvae treatment for different waste fractions

Based on the findings of this study, the most suitable substrates in terms of biomass yield for BSFL composting are those that contain a large proportion of easily available carbon and a sufficiently high protein content to support larval development. Abattoir waste, abattoir - fruits & vegetables, food waste and human faeces are examples of substrates that provide good conditions for larval growth, and for which BSFL composting would be a good option. Substrates that contain a high proportion of easily available carbon, but a low content of nitrogen, do not support larval development and thus the efficiency of the process is reduced. Thus in this study, the BCR of the fruit & vegetables substrate was 4%, compared with 15% for abattoir waste. The total biomass, and hence the potential revenue from treating fruit & vegetables waste in a BSFL composting system, would thus be much smaller. As the development time for the larvae would be considerably longer, the efficiency would be even lower, resulting in quite expensive treatment for small revenue.

The BSFL composting process was not optimised in this study, and thus the efficiencies can be expected to increase for some of the more promising waste fractions, e.g. abattoir waste, food waste and human faeces (Table 3). One way of increasing the possible revenue in waste management operations is by mixing waste fractions that have a high protein content with fractions that are high in easily available carbon, so that the larvae to a higher degree can make use of available nutrients (as in the abattoir waste-fruit & veg. mixture in this study). The conversion into larval biomass of protein-poor fractions could be increased, and the treatment process time decreased, by addition of a protein-rich substrate, while higher utilisation of the available nutrients could be expected on combining a substrate rich in easily available carbon with a protein-rich substrate.

For any waste substrate, the total revenue from potential products would have to be evaluated based on the current demand and market value at the production location (Lohri et al., 2017). For example, it might be more profitable to anaerobically digest the waste prior to BSF treatment in locations where vehicle gas has a higher value than animal feed protein, whereas the opposite may be true in a different location (Lalander et al., 2018).

5. Conclusions

The main substrate properties affecting BSFL composting were found to be VS and protein content of the substrate. The BSFL were effectively reared on many waste streams, including food waste, human faeces and abattoir waste. However, the larvae did not grow particularly well on different sewage sludges, as their VS content was too low. Larval growth on fruit & vegetable waste was slower and biomass conversion ratio quite low compared with other substrates, but the prepupae grew large. The amino acid profile of the prepupae did not vary greatly, with only smaller variations in the amino acid profiles of the prepupae reared on different substrates. The protein content of larval biomass varied only slightly (39–44% of DM), while great variations were found in final larval weight. The larvae of BSF are robust and can feed on a variety of substrates, provided that the VS and protein contents are sufficiently high to support larval development. Abattoir waste, food waste, human faeces and a mixture of abattoir waste – fruits & vegetables are highly suitable substrates for BSFL composting, while pure fruit & vegetable waste and different sewage sludges are less suitable.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2018.10.017>.

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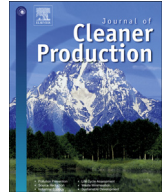
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Corrigendum to “Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*)” [J. Clean. Prod. 208 (2019) 211–219]



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The authors regret that there was a mistake in Equation (1) in the original article. The correct form of Equation (1) for the calculation of the percentage material reduction was:

$$\text{Mat. red.}_{DM} = \left(1 - \frac{\text{mat.out}_{DM}}{\text{sub.in}_{DM}}\right) \times 100, \quad (1)$$

where mat.out_{DM} and sub.in_{DM} were the dry matter of the substrate fed and of the residue after the experiment, respectively.

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Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) – Possibilities and limitations for modification through diet



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ABSTRACT

Black soldier fly larvae (*Hermetia illucens*; BSFL) can convert organic wastes into a nutrient-rich biomass suitable in animal feed, which could be a way to achieve more sustainable production of food. However, little is known about how the diet fed to BSFL affects their nutritional value, especially their fatty acid composition. In this study, BSFL were fed 11 diets based on four different organic waste sources (mussels, bread, fish and food waste). Fatty acid and proximate composition (dry matter, crude fat, crude protein and ash) were analysed in the diets, in two-week-old larvae and substrate residues. Larval weight, survival and feed conversion were also recorded. The diet was found to affect all parameters investigated. Irrespective of diet, the larval fat consisted mainly of lauric acid and other saturated fatty acids and these were found to be synthesised by the larvae. However, both the fatty acid composition of the substrate, and the larval weight were found to affect the fatty acid profile of the larvae. In general, larvae with a higher weight contained a higher percentage of saturated fatty acids and a lower percentage of unsaturated fatty acids, such as eicosapentaenoic (EPA) and docosahexaenoic acid (DHA). It was concluded that the possibilities to tailor the fatty acid composition of the BSFL through the diet are limited; thus, the BSFL fat may not be suitable to replace fish oil, but has potential of inclusion in other food, feed and fuel products. © 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

In the coming 30 years, the global population is estimated to reach 10 billion (UN, 2017). By then, global food production will need to produce sufficient food and nutrients for the increased population and also address the environmental impacts of food production, such as greenhouse gas emissions, loss of biodiversity and unsustainable use of water (Foley et al., 2011). One approach for achieving this is to use insects as feed and food (van Huis et al., 2013). Insects are associated with high feed conversion efficiency and lower emissions of greenhouse gases than conventional livestock, as well as a nutritional composition that makes them potentially suitable as food and animal feed (van Huis and Tomberlin, 2017). The larvae of the black soldier fly (BSF; *Hermetia illucens* (L.), Diptera: Stratiomyidae) have received great attention for their ability to convert organic waste into high-value biomass (van Huis et al., 2013).

Black soldier fly larvae (BSFL) are able to feed on a variety of organic materials (Tomberlin and Cammack, 2017). Examples include cow manure, fish offal, brewery by-products, restaurant waste and sewage sludge (Lalander et al., 2019; Meneguz et al., 2018; Spranghers et al., 2017; St-Hilaire et al., 2007a). Their nutritional composition can vary depending on the rearing substrate, but in general BSFL contain around 40% protein and 30% fat on a dry matter basis (Barragan-Fonseca et al., 2017). Because of their nutritional composition, BSFL have been used as an ingredient in feed for various animals such as poultry and fish (Schivavone et al., 2018; St-Hilaire et al., 2007b). However, under current legislation in Europe and the US, use of BSFL in animal feed is permitted mainly within aquaculture (Meneguz et al., 2018; Tomberlin and Cammack, 2017). Since the growing aquaculture industry has a currently unsustainable dependency on fish meal and fish oil (Tocher, 2015), BSFL could be a more sustainable alternative source of both protein and fat in feeds used in aquaculture.

Earlier studies have shown that BSFL meal can replace 50% of fish meal in the diet of Atlantic salmon (Lock et al., 2016) and 25% of fish meal in the diet of rainbow trout (St-Hilaire et al., 2007b), without negatively affecting growth of the fish. One prob-

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lem is that inclusion of BSFL in the feed decreases the content of α -linolenic acid (ALA; C18:3), eicosapentaenoic acid (EPA; C20:5) and docosahexaenoic acid (DHA; C22:6) in fish fillets (St-Hilaire et al., 2007b). Omega-3 (n-3) fatty acids, especially EPA and DHA, are essential for optimal growth and reproduction in both fish and shrimps (Tocher, 2015), and are also associated with health benefits for humans upon consumption (WHO, 2003). Therefore, lower concentrations of n-3 fatty acids in fish fed BSFL could be a problem for both producers and consumers.

In comparison with other insects, BSFL have been found to contain a high amount of fat, especially in the form of saturated fatty acids (SFA) (Ramos-Bueno et al., 2016). However, it may be possible to modify the nutritional composition of BSFL through the diet (Barragan-Fonseca et al., 2017; Meneguz et al., 2018; Spranghers et al., 2017). Furthermore, BSFL fed fish offal and algae have been found to incorporate significant amounts of EPA and DHA (Liland et al., 2017; St-Hilaire et al., 2007a). However, while findings in these earlier studies suggest that it is possible to modify the fatty acid composition of BSFL, it is not known which fatty acids the larvae produce by themselves, or to what extent the fatty acid composition of the diet influences the final fatty acid composition of the BSFL. Knowledge of these characteristics is of great importance if BSFL are to be grown on different waste substrates and used as an ingredient in animal feed. The aim of this study was thus to investigate how the properties of the diet affect the fatty acid and proximate composition of BSFL biomass, larval growth and feed utilisation.

2. Materials and methods

2.1. Materials

2.1.1. Black soldier fly larvae

Black soldier fly larvae from a colony continuously maintained since 2015 at the Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden, were used in the study.

2.1.2. Experimental diets

In Trial 1, four substrates (bread, food waste, fish and mussels) were used to create six diets. These diets contained: **bread**, coarsely mixed reclaimed bread obtained from the bread company Fazer (Uppsala, Sweden); **food waste**, homogenised household waste obtained from Eskilstuna waste treatment facility (Strängnäs Energi och Miljö AB; Eskilstuna, Sweden); **fish**, rainbow trout (*Onchorhynchus mykiss*) from the Department of Animal Nutrition and Management at SLU (Uppsala, Sweden) mixed to a 5:1 ratio (by wet weight) with wheat bran from Lantmännen Foder (Uppsala, Sweden); **fresh mussels**, crushed blue mussels (*Mytilus edulis*) from St. Anna mussel farm (Vattenbrukscentrum Öst; Inre Kärrö, Sweden) used upon arrival at the BSFL facility; **ensiled mussels**, crushed blue mussels ensiled with 3% formic acid and stored at room temperature (30 °C) for 2 weeks; and **rotten mussels**, crushed blue mussels stored at room temperature (30 °C) for 1 week.

In Trial 2, five diets were prepared from **bread and mussels** by mixing crushed blue mussels (*Mytilus edulis*) from Ecopelag (Värmdö, Sweden) with reclaimed bread received from the bread company Fazer (Uppsala, Sweden) in ratios where the mussels contributed 10, 20, 30, 40 and 50% of the total volatile solids content in the mixture.

2.1.3. Chemicals

For fatty acid analysis, the following chemicals were used: chloroform (VWR, CAS No. 67-66-3), methanol (Merck Millipore, CAS

No. 67-56-1), sodium chloride (Merck Millipore, CAS No. 7647-14-5), sodium hydroxide (Merck Millipore, CAS No. 1310732), anhydrous methanol (Merck Millipore, CAS No. 67-56-1), 20% boron trifluoride-methanol complex in methanol (VWR, CAS No. 373-57-9) and hexane (Fisher Chemicals, CAS No. 110-54-3). Methyl 15-methylheptadecanoate (Larodan, Sweden) was used as internal standard in gas chromatography. Methyl laureate (Larodan, Sweden) and the fatty acid methyl ester mix GLC68D (Nuclechek Prep Inc., Minnesota) were used to identify fatty acids through retention time in chromatograms. All fatty acid methyl esters used were of *cis*-configuration.

2.2. Experimental set-up

In total, 11 diets were evaluated in this study (Fig. 1). In Trial 1, the impact of bread, food waste, fish and fresh, ensiled and rotten mussels was investigated. In Trial 2, five diets with bread and mussels were investigated, in order to: (1) gain a better understanding of how different concentrations of EPA and DHA in the diet affect incorporation into larval fat; and (2) identify the ratio at which BSFL production on mussels is feasible in terms of technical process characteristics (separation of larvae from the substrate residues). Fatty acid and proximate analysis (dry matter, ash, crude fat and crude protein) was carried out on the diets and on the surviving BSFL and, in Trial 2, also on substrate residues (remains of the diet). The larvae were weighed and counted after the experiments.

In both trials, newly hatched larvae were raised on chicken feed for 5 d prior to being introduced to the diets. Before the start of the experiments, samples were collected of the 5-day-old larvae (triplicate) and the diets (singlets) and stored at -80 °C until further analysis. All experiments were carried out in triplicate at 28 °C for 14 d, a time period earlier found sufficient for development of BSF prepupae (on substrates suitable for the BSFL process) by Lalander et al. (2019). In Trial 1, the larvae fed bread, food waste and fish received 200 mg volatile solids per larva, with a larval density of 3–6 larvae cm^{-2} (Table S1). Due to differences in substrate properties, the larvae fed fresh, rotten and ensiled mussels received 1–2 g volatile solids per larva, and the larval density was 0.3 larva cm^{-2} . In Trial 2, all larvae received 300 mg volatile solids per larva, with a larval density of 2 larvae cm^{-2} . At the end of the experiments, the larvae were separated from the substrate residues by sieving, rinsed with water and dried on paper towels. The total weight was recorded for all surviving larvae and the substrate residues. Approximately 50 larvae were counted and their total weight was recorded in order to estimate the average larval weight. One sample of larvae and one sample of substrate residues (only in Trial 2) were collected in each of the three replicate experiments. These samples were stored at -80 °C until further analysis.

2.3. Chemical analysis

2.3.1. Lipid extraction and fatty acid analysis

Lipids were extracted using a modified version of the method described by Folch et al. (1957) followed by methylation according to Appelqvist (1968) and analysis by gas chromatography. A sample of 2 g was homogenised for 3×30 s in 50 mL chloroform:methanol (2:1, v/v) using an Ultra-Turrax T25 homogeniser (Janke and Kunkel, Germany). The sample was filtered, 12.5 mL 0.9% NaCl solution were added (giving a chloroform:methanol:water ratio of 8:4:3) and the mixture was transferred to a separating funnel. The lower phase (containing the lipids) was transferred to a round bottle flask. The chloroform and methanol were evaporated using a rotary evaporator (Büchi Labortechnik, Switzerland). From the resulting lipid extract, 5 mg were weighed into a centrifugation tube and 1 mg internal standard (methyl 15-methylheptadecanoate) and 2 mL

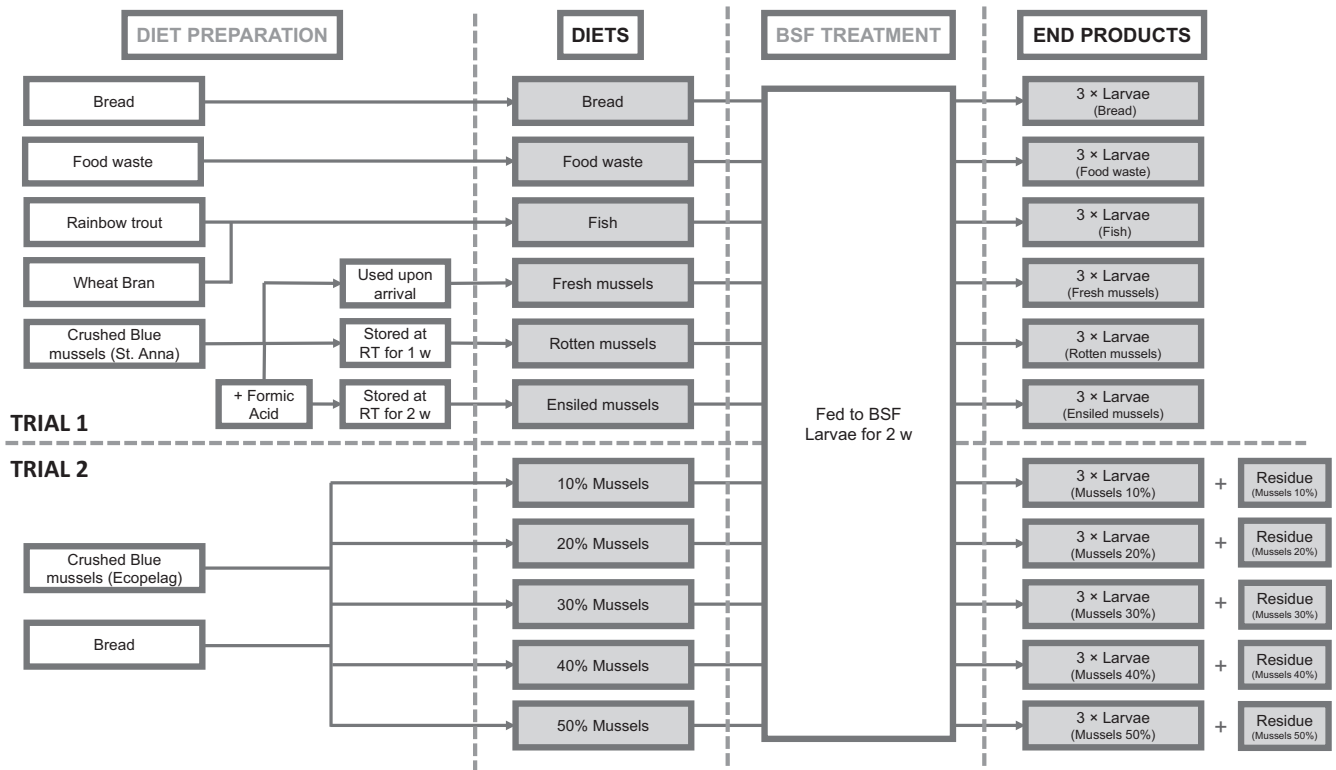


Fig. 1. Schematic illustration of the experimental set-up used for Trial 1 and Trial 2.

0.01 M NaOH in water-free methanol were added. Methylation was catalysed by 3 mL 20% BF₃-methanol complex in methanol. To extract the fatty acid methyl esters, 2 mL 20% NaCl and 2 mL hexane were added, followed by centrifugation for 5 min at 500 xg in a Z383 K centrifuge (Hermle Labortechnik, Germany). The upper hexane phase (containing the fatty acid methyl esters) was removed and 1 µL was injected (split ratio 1:10) with an Agilent 7683 auto sampler (Agilent, California) onto a Agilent 6890 system with a flame ionisation detector (FID) attached (Agilent, California). Hydrogen was used as the carrier gas at a constant flow of 1 mL min⁻¹ and separation was conducted on a SGE BPX70 capillary column (50 m × 0.22 mm × 0.25 µm; SGE/Trajan, Australia). The oven was maintained at 158 °C for 5 min, ramped up to 220 °C at 2 °C min⁻¹ and held for 8 min. The temperature of the FID was 250 °C, with flow rates of hydrogen, oxygen and N₂ (make-up gas) of 40, 400 and 50 mL min⁻¹. Fatty acids were identified from retention times of standards (see Section 2.1.3). The weight of each fatty acid was estimated using the internal standard, and the fatty acid composition was expressed as percentage of identified fatty acids.

2.3.2. Proximate analysis

Proximate analysis was carried out at the Department of Animal Nutrition and Management, SLU (Uppsala, Sweden). All samples were freeze-dried for 72 h and milled before further analysis. Pre-dried samples were dried at 103 °C for 16 h (Trial 1) or 80 °C for 48 h (Trial 2) to determine the dry matter content, followed by incineration at 550 °C for 3 h to determine the ash content. Total nitrogen was measured using the Kjeldahl method in accordance with NMKL (1976). To estimate the protein content, a conversion factor of 4.76 was used, as suggested by Janssen et al. (2017) for more accurate estimation of the protein content in BSFL. Crude fat content was determined by hydrolysis in hydrochloric acid followed by extraction in light petroleum, as described by European Commission (1998).

2.3.3. Larval survival and process efficiency

The larval survival ratio (SR) was calculated as:

$$SR = \left(\frac{Lv_{Out}}{Lv_{In}} \right) \times 100 \quad (1)$$

where *Lv* is the total number of larvae at the beginning (*In*) and end of the experiment (*Out*).

The waste-to-biomass conversion ratio (BCR) was calculated on a wet weight (WW) and a volatile solids (VS) basis. The nitrogen conversion ratio (NCR) was calculated similarly, but on a total nitrogen (N) basis. The conversion ratio was calculated as:

$$BCR_{WW/VS} \text{ or } NCR = \left(\frac{Lv_{WW/VS/N}}{Sub_{WW/VS/N}} \right) \times 100 \quad (2)$$

where WW/VS/N is the total wet weight (WW), weight of volatile solids (VS) and nitrogen (N) content of the larval biomass (*Lv*) at the end of experiments and in the initial substrate (*Sub*).

2.3.4. Fatty acid production value and retention

The fatty acid production value (FAPV) was calculated as described by Liland et al. (2017) for each fatty acid in the larvae within Trial 2 as:

$$FAPV = \frac{FA_{Lv}}{FA_{Sub} - FA_{Res}} \quad (3)$$

where *FA_{Lv}*, *FA_{Sub}* and *FA_{Res}* are the total mass of a specific fatty acid in the total larval biomass (*Lv*), the initial substrate (*Sub*) and the substrate residues (*Res*), respectively.

To estimate how much of a specific fatty acid was transferred from the substrate to the larvae and how much was left in the residues, retention values in larvae (*Ret_{Lv}*) and substrate residues (*Ret_{Res}*) were calculated as described by Liland et al. (2017) :

$$Ret_{Lv/Res} = \frac{FA_{Lv/Res}}{FA_{Sub}} \times 100 \quad (4)$$

where FA is the total mass of a specific fatty acid in the total larval biomass (L_v), the substrate residues and the initial substrate (Sub).

2.4. Statistical analysis

Minitab (Minitab Inc., Pennsylvania) was used to create linear regression models between larval weight and the fatty acid composition of substrates and larvae. It was also used for one-way analysis of variance (ANOVA) to identify statistically significant differences between the larvae. The level of significance was set at $p < 0.05$. A Tukey *post-hoc* test was performed in cases with statistically significant differences. None of the R^2 -values presented are adjusted. Microsoft Excel 2013 (Microsoft, Washington) was used for creating graphical representations of the data.

3. Results

3.1. Larval growth and feed conversion

In Trial 1, the highest larval weight (230 mg) and highest survival rate (89%) were observed for the BSFL fed fresh mussels (Table 1). The highest biomass conversion ratio (volatile solids basis; 35%) and nitrogen conversion ratio (66%) were achieved for the BSFL fed food waste. The lowest larval weight (25 mg), survival (11%) and conversion ratio (<0.1%) were observed for the BSFL

fed ensiled mussels. Low survival rates were also found for the larvae fed fish (18%) and rotten mussels (55%). Differences were also observed in the colour of the larvae: the larvae fed with bread and fish had a lighter colour, while the larvae fed with food waste and mussels were darker, indicating that they had started developing into prepupae. In Trial 2, the highest biomass conversion ratios (11–13%) and nitrogen conversion ratios (26–32%) were found for the BSFL fed a diet with $\leq 20\%$ mussels. No significant differences were found in larval weight or survival rate, but numerical differences were observed: BSFL fed the diet with 50% mussels were found to have the lowest larval weight (130 mg) and survival rate (54%), in addition to the lowest biomass and nitrogen conversion ratio. The larvae in Trial 2 had lower weight and survival rate, but higher conversion ratio than those fed only fresh mussels. Compared with BSFL fed only bread, the larval weights and survival were higher or similar in Trial 2, while the conversion ratio was generally lower.

3.2. Proximate composition

In Trial 1, variations were observed especially in the crude fat (11–58%) and ash content of BSFL (4–33%) fed the different diets (Table 2). The extremes were represented by the larvae fed bread and ensiled mussels. In this trial, dry matter content ranged between 27 and 36% and crude protein content between 28 and

Table 1

Final larval weight, survival rate, bio-conversion ratio and nitrogen conversion ratio of the larvae in Trial 1 and Trial 2. Values shown are mean \pm standard deviation (SD; $n = 3$). Different letters represent significant differences column-wise within the trials (Trial 1: lower-case, Trial 2: upper-case), with the level of significance set to $p < 0.05$.

	Larval weight (mg)	Survival rate (%)	BCR _{WW} (%)	BCR _{VS} (%)	NCR (%)
<i>Trial 1</i>					
Bread	137 \pm 7 ^{b,c}	69.8 \pm 9.8 ^b	24.1 \pm 3.3 ^a	13.4 \pm 1.8 ^b	39.5 \pm 7.2 ^b
Fish	89 \pm 18 ^{c,d}	18.4 \pm 2.6 ^c	3.2 \pm 0.1 ^c	2.4 \pm 0.2 ^c	2.9 \pm 0.1 ^c
Food waste	191 \pm 19 ^{a,b}	89.1 \pm 6.0 ^a	18.9 \pm 2.4 ^b	34.8 \pm 3.8 ^a	66.4 \pm 6.5 ^a
Fresh mussels	235 \pm 15 ^a	89.3 \pm 6.8 ^a	0.8 \pm 0.1 ^c	3.5 \pm 0.3 ^c	2.9 \pm 0.2 ^c
Ensiled mussels ¹	25 ^d	11.0 \pm 4.5 ^c	<0.1 ^c	<0.1 ^c	–
Rotten mussels	106 \pm 29 ^c	55.1 \pm 11.2 ^b	0.2 \pm 0.0 ^c	1.0 \pm 0.0 ^c	0.6 \pm 0.0 ^c
<i>Trial 2</i>					
Bread and mussels (10%)	133 \pm 39	86.2 \pm 2.1	11.5 \pm 3.6 ^A	13.0 \pm 3.4	31.7 \pm 8.4 ^A
Bread and mussels (20%)	181 \pm 10	82.1 \pm 13.2	10.5 \pm 1.4 ^A	13.0 \pm 1.9	25.5 \pm 3.8 ^{A,B}
Bread and mussels (30%)	168 \pm 2	68.0 \pm 13.2	7.4 \pm 1.1 ^{A,B}	10.4 \pm 1.7	16.5 \pm 3.1 ^{B,C}
Bread and mussels (40%)	138 \pm 21	77.1 \pm 25.2	5.7 \pm 2.1 ^{A,B}	8.8 \pm 3.4	12.9 \pm 5.3 ^{B,C}
Bread and mussels (50%)	131 \pm 20	54.3 \pm 34.4	3.6 \pm 2.6 ^B	6.1 \pm 4.0	8.2 \pm 6.1 ^C

BCR_{WW} = bio-conversion ratio on wet weight basis; BCR_{VS} = bio-conversion ratio on volatile solids basis; NCR = nitrogen conversion ratio.

¹ Due to poor growth, the amount of material was not sufficient for analysis of nitrogen. Larval weight was estimated on a small sample (<10 larvae).

Table 2

Proximate composition of larvae in Trial 1 and Trial 2. All values shown are mean \pm standard deviation (SD; $n = 3$) for percentage on a wet weight (%_{WW}) or dry matter basis (%_{DM}). Different letters represent significant differences column-wise within the trials (Trial 1: lower-case, Trial 2: upper-case), with the level of significance set to $p < 0.05$.

	Dry matter (% _{WW})	Crude fat (% _{DM})	Crude protein (factor 4.76) (% _{DM})	Crude protein (factor 6.25) (% _{DM})	Ash (% _{DM})
5-day larvae	32.7 \pm 5.0	9.7 \pm 3.8	34.1 \pm 2.6	44.7 \pm 3.4	15.9 \pm 3.1
<i>Trial 1</i>					
Bread	35.5 \pm 1.1 ^a	57.8 \pm 1.5 ^a	29.8 \pm 2.0 ^{b,c}	39.2 \pm 2.6 ^{b,c}	3.9 \pm 0.3 ^d
Fish	27.0 \pm 2.1 ^b	46.7 \pm 1.5 ^b	40.1 \pm 1.7 ^a	52.6 \pm 2.2 ^a	5.7 \pm 0.3 ^d
Food waste	33.0 \pm 1.3 ^{a,b}	40.7 \pm 2.3 ^c	27.9 \pm 0.2 ^c	36.6 \pm 0.2 ^c	16.3 \pm 1.8 ^c
Fresh mussels	31.3 \pm 0.8 ^{a,b}	33.1 \pm 1.2 ^d	34.0 \pm 1.1 ^b	44.6 \pm 1.4 ^b	18.7 \pm 1.4 ^{b,c}
Ensiled mussels ¹	27.3 ^{a,b}	11.2 ^e	–	–	33.0 ^a
Rotten mussels	27.5 \pm 0.4 ^b	29.7 \pm 0.3 ^d	32.2 \pm 0.3 ^b	42.3 \pm 0.4 ^b	22.6 \pm 1.2 ^b
<i>Trial 2</i>					
Bread and mussels (10%)	40.5 \pm 1.1 ^A	20.4 \pm 0.7 ^A	25.0 \pm 0.8 ^C	32.8 \pm 1.0 ^C	30.9 \pm 3.2
Bread and mussels (20%)	35.7 \pm 0.8 ^B	19.6 \pm 1.1 ^A	26.1 \pm 0.2 ^{B,C}	34.2 \pm 0.3 ^{B,C}	31.1 \pm 0.5
Bread and mussels (30%)	34.2 \pm 1.4 ^B	17.9 \pm 0.3 ^{A,B}	25.8 \pm 0.5 ^{B,C}	33.8 \pm 0.7 ^{B,C}	30.7 \pm 1.1
Bread and mussels (40%)	33.2 \pm 1.6 ^B	17.9 \pm 0.8 ^{A,B}	27.5 \pm 0.4 ^{A,B}	36.1 \pm 0.5 ^{A,B}	30.9 \pm 1.4
Bread and mussels (50%)	32.6 \pm 1.1 ^B	16.1 \pm 2.3 ^B	28.8 \pm 1.8 ^A	37.9 \pm 2.3 ^A	29.6 \pm 2.7

¹ Due to poor growth, the amount of material was only sufficient for analysis of dry matter, crude fat and ash, using a single sample.

40% (conversion factor 4.76), with the larvae fed fish having the highest protein content (40%). In Trial 2, significant differences ($p < 0.05$) were found for all parameters except ash content, albeit smaller than those found in Trial 1. Compared with larvae fed only bread and fresh mussels in Trial 1, the crude fat (16–20%) and crude protein content (25–29%; conversion factor 4.76) were in general lower in Trial 2, while the dry matter (33–41%) and ash content (30–31%) were higher. The larvae fed the diet with 10% mussels contained the highest percentage of dry matter and crude fat and the lowest percentage of crude protein in Trial 2.

3.3. Fatty acid composition

Most of the larvae contained a high percentage of SFA (up to 76%), followed by monounsaturated fatty acids (MUFA; up to 32%) and polyunsaturated fatty acids (PUFA; up to 23%) (Table 3). Of the SFAs, lauric acid (C12:0) was a major constituent (up to 52%). In addition, palmitic acid (C16:0) and oleic acid (C18:1 n-9) made up a high percentage of the fatty acids identified in the larvae (12–22% and 10–25%, respectively). Fatty acids with a carbon chain length of 12–18 carbons (C12:0 to C18:3) were found in all larvae, irrespective of diet. Arachidonic acid (C20:4) and EPA (C20:5) were found in all larvae except those fed bread. DHA (C22:6) was not found in the larvae fed bread or those fed food waste.

3.3.1. Factors impacting larval fatty acid composition

The results from Trial 1 and 2 were combined to investigate possible predictors of larval fatty acid composition. Larval weight was found to be positively correlated to the percentage of lauric acid (C12:0; $R^2 = 0.8$) and total SFA ($R^2 = 0.7$) in the larvae, and negatively correlated to total MUFA ($R^2 = 0.5$) and PUFA ($R^2 = 0.7$) (Fig. 2).

The larval weight and the concentration of fatty acids in the diets were combined in the following model:

$$FA\%_{Lv} = a + b \times LW + c \times FA\%_{Sub} \quad (5)$$

where FA% is the percentage of a specific fatty acid in the larvae (Lv) and the corresponding substrate (Sub), and LW is the weight of the larvae. This model had a better fit to the measured data for content of EPA (C20:5; $R^2 = 0.9$), DHA (C22:6; $R^2 = 0.8$) and total n-3 PUFA ($R^2 = 0.8$) in the larvae (Fig. 3). The percentage of these three fatty acids in the larvae was negatively correlated to larval weight and positively correlated to their percentage in the diet (coefficient $c > 0$).

3.3.2. Fatty acid production and retention values

Fatty acid production values (FAPV) and retention values were calculated for larvae and residues in Trial 2. A FAPV above 1.0 indicates net production of a particular fatty acid, which was found for four SFA and three MUFA, but no PUFA (Table S4). In the case of lauric acid (C12:0), the FAPV was above 100, and in some cases above 1000. However, for vaccenic acid (C18:1 n-7) the FAPV was above 1.0 only for the larvae fed the diet with 20–30% inclusion of mussels.

According to the larval retention values, up to 40% of the initial EPA (C20:5) and 10% of the DHA (C22:6) in the substrate were transferred to the larval fat (Table S5). The highest retention was found for larvae fed the diet with 10% mussels. However, when calculated on a weight basis, the larvae fed the diet with 30–50% mussels contained the greatest amount of EPA and DHA. The residue retention values indicated that 20–60% of the EPA and DHA remained in the substrate residues. A higher percentage of EPA and DHA remained in the substrates with higher inclusion of mussels.

Table 3 Content of selected fatty acids¹ in the larvae in Trial 1 and Trial 2. Each fatty acid (C12:0-C22:6) and the fatty acid totals (SFA, MUFA, PUFA, n-3 PUFA) are presented as percentage of identified fatty acids. Identified fatty acids are presented on a dry matter basis (%DM). All values shown are mean ± standard deviation (SD; n = 3). Different letters represent significant differences row-wise within the trials (Trial 1: lower-case, Trial 2: upper-case), with the level of significance set to $p < 0.05$.

Identified fatty acids (% DM)	Trial 1 – Different substrates					Trial 2 – Bread and mussels				
	5 d larvae					Rotten mussels				
	Bread	Fish	Food waste	Fresh mussels	Ensilaged mussels	10%	20%	30%	40%	50%
C12:0	6.7 ± 2.9 ^d	39.3 ± 1.5 ^b	34.5 ± 1.2 ^b	26.5 ± 0.9 ^c	7.0 ± 0.7 ^d	21.5 ± 2.6 ^c	15.5 ± 1.0	14.1 ± 0.9	14.1 ± 0.3	13.8 ± 1.3
C14:0	7.5 ± 1.9 ^c	28.6 ± 2.1 ^b	39.9 ± 5.1 ^b	52.1 ± 1.8 ^a	13.4 ± 3.9 ^e	32.3 ± 7.6 ^b	47.4 ± 0.8 ^A	43.6 ± 2.6 ^A	42.0 ± 4.3 ^A	35.3 ± 1.6 ^B
C14:1 (n-5)	2.3 ± 0.4 ^d	6.1 ± 0.4 ^c	6.7 ± 0.3 ^{bc}	8.0 ± 0.5 ^b	5.8 ± 0.4 ^c	10.1 ± 0.1 ^a	8.7 ± 0.2 ^A	8.5 ± 0.1 ^{AB}	7.8 ± 0.4 ^C	6.8 ± 0.3 ^D
C16:0	0.0 ± 0.0 ^d	0.2 ± 0.0 ^c	0.2 ± 0.0 ^c	0.3 ± 0.0 ^b	0.4 ± 0.1 ^c	0.6 ± 0.0 ^a	0.2 ± 0.0 ^b	0.2 ± 0.0 ^{AB}	0.3 ± 0.0 ^A	0.2 ± 0.0 ^{AB}
C16:1 (n-7)	19.2 ± 1.9 ^{ab}	12.6 ± 0.4 ^d	16.3 ± 1.0 ^{bc}	11.9 ± 1.3 ^d	21.9 ± 0.6 ^a	19.8 ± 2.1 ^{ab}	13.9 ± 0.4 ^B	14.7 ± 0.7 ^{AB}	14.6 ± 0.9 ^{AB}	15.8 ± 0.3 ^A
C18:0	0.8 ± 0.1 ^f	4.8 ± 0.5 ^d	2.6 ± 0.3 ^e	6.9 ± 0.8 ^e	14.1 ± 0.4 ^a	9.8 ± 1.2 ^b	3.1 ± 0.2 ^D	3.8 ± 0.3 ^{CD}	5.2 ± 0.4 ^{AB}	5.9 ± 0.7 ^A
C18:1 (n-9)	6.9 ± 0.6 ^a	1.5 ± 0.3 ^d	2.2 ± 0.2 ^{cd}	1.6 ± 0.3 ^d	4.0 ± 0.3 ^b	3.3 ± 0.6 ^{bc}	2.7 ± 0.2	2.7 ± 0.2	2.8 ± 0.4	3.1 ± 0.3
C18:1 (n-7)	26.6 ± 3.4 ^a	12.0 ± 1.2 ^c	19.1 ± 2.1 ^b	10.3 ± 2.3 ^c	14.0 ± 0.4 ^{bc}	12.9 ± 2.1 ^c	13.3 ± 0.4 ^{AB}	11.7 ± 0.3 ^B	13.2 ± 1.2 ^{AB}	14.0 ± 1.0 ^A
C18:2 (n-6)	1.1 ± 0.1 ^b	0.1 ± 0.1 ^c	0.4 ± 0.1 ^c	1.3 ± 0.3 ^b	2.2 ± 0.2 ^a	1.5 ± 0.2 ^b	0.8 ± 0.0 ^b	1.2 ± 0.1 ^A	1.2 ± 0.2 ^A	1.5 ± 0.2 ^A
C18:3 (n-3)	31.4 ± 1.4 ^a	12.5 ± 0.3 ^b	9.9 ± 0.8 ^c	2.6 ± 0.3 ^e	4.5 ± 0.4 ^e	4.2 ± 0.7 ^e	5.6 ± 0.4 ^{AB}	4.5 ± 0.0 ^C	4.5 ± 0.5 ^C	5.9 ± 0.2 ^A
C20:4 (n-6)	3.6 ± 0.3 ^a	1.6 ± 0.1 ^b	1.8 ± 0.2 ^b	1.3 ± 0.2 ^a	3.6 ± 0.6 ^a	1.1 ± 0.1 ^b	2.6 ± 0.1 ^{BC}	2.2 ± 0.1 ^C	2.7 ± 0.1 ^B	3.4 ± 0.1 ^A
C20:5 (n-3)	0.0 ± 0.0 ^c	0.1 ± 0.0 ^{bc}	0.2 ± 0.0 ^b	0.2 ± 0.0 ^{bc}	1.3 ± 0.2 ^a	0.1 ± 0.0 ^{bc}	0.1 ± 0.0 ^{CD}	0.2 ± 0.0 ^{BC}	0.3 ± 0.1 ^B	0.4 ± 0.0 ^A
C22:6 (n-3)	0.0 ± 0.0 ^c	0.0 ± 0.0 ^c	0.0 ± 0.0 ^b	0.0 ± 0.0 ^b	8.2 ± 1.0 ^b	1.9 ± 0.2 ^b	0.9 ± 0.0 ^C	3.0 ± 0.4 ^B	3.5 ± 0.7 ^B	4.8 ± 0.5 ^A
ΣSFA	36.2 ± 4.6 ^d	75.6 ± 1.4 ^a	65.2 ± 3.7 ^b	73.7 ± 1.6 ^{ab}	45.3 ± 3.5 ^{cd}	65.6 ± 4.7 ^b	72.8 ± 0.8 ^A	69.2 ± 1.8 ^{AB}	67.4 ± 3.5 ^B	61.3 ± 1.2 ^C
ΣMUFA	28.7 ± 3.4 ^{ab}	15.1 ± 1.4 ^d	22.4 ± 2.6 ^{bc}	19.5 ± 1.4 ^{cd}	32.1 ± 0.4 ^a	26.2 ± 3.7 ^{ab}	17.6 ± 0.3 ^C	18.8 ± 1.0 ^{BC}	20.3 ± 1.8 ^{AB}	22.2 ± 0.5 ^A
ΣPUFA (all)	35.0 ± 1.6 ^a	18.7 ± 0.4 ^b	12.4 ± 1.1 ^c	6.8 ± 0.3 ^d	22.6 ± 3.1 ^b	8.2 ± 1.0 ^d	9.6 ± 0.5 ^{BC}	9.3 ± 0.2 ^C	12.0 ± 0.8 ^B	16.6 ± 1.0 ^A
ΣPUFA (n-3)	3.6 ± 0.3 ^{bc}	5.9 ± 0.2 ^b	2.3 ± 0.3 ^c	3.8 ± 0.3 ^{bc}	16.5 ± 2.5 ^a	3.4 ± 0.3 ^{bc}	3.8 ± 0.1 ^C	4.4 ± 0.2 ^C	7.2 ± 1.1 ^B	9.9 ± 0.8 ^A

ΣSFA = sum of all saturated fatty acids; ΣMUFA = sum of all monounsaturated fatty acids; ΣPUFA (all) = sum of all polyunsaturated fatty acids; ΣPUFA (n-3) = sum of all omega-3 polyunsaturated fatty acids. ¹ The content of C20:0, C20:1, C20:2, C20:3, C22:0, C22:1, C24:0 and C24:1 is not presented due to low (<0.5%) concentrations.

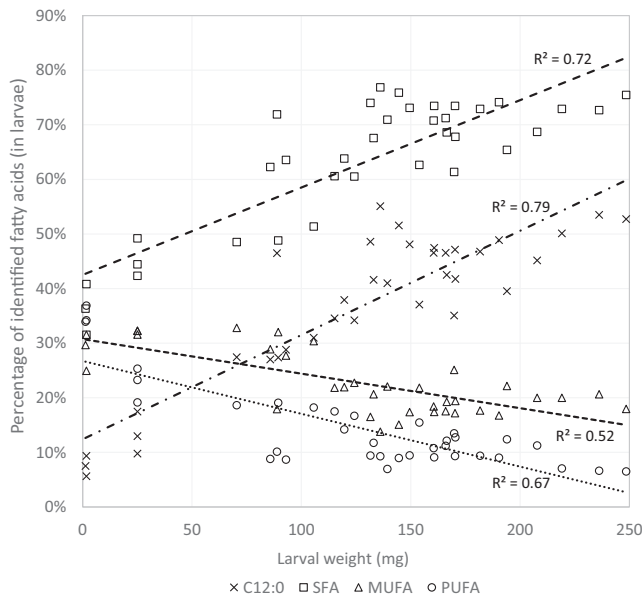


Fig. 2. Graphical representation of the percentage of lauric acid (C12:0) and total SFA, MUFA and PUFA in the larvae, in relation to larval weight. The model for each displayed component displayed along with the model fit (R^2).

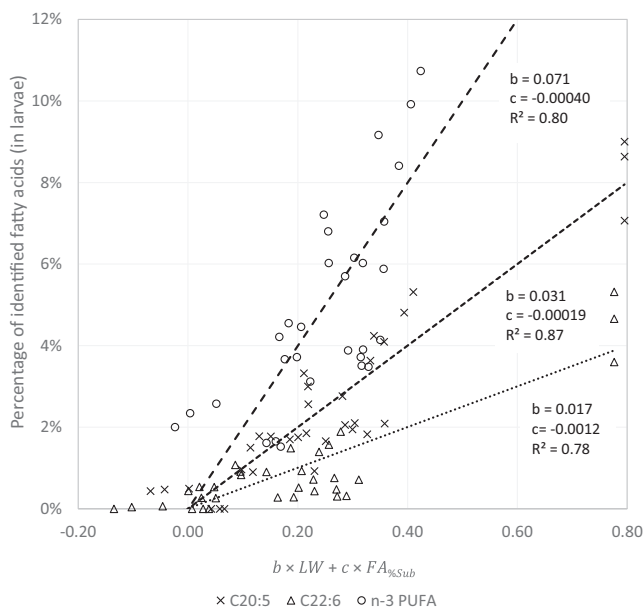


Fig. 3. Graphical representation of percentage of EPA (C20:5), DHA (C22:6) and total n-3 PUFA in the larvae, in relation to predicted percentages (of the same fatty acids in the larvae) from the model described in Eq. (5) based on larval weight (LW) and percentage of the specific fatty acid in the substrate ($FA\%_{Sub}$). Model parameters (constants b and c; and model fit through R^2) for each displayed fat component presented.

4. Discussion

4.1. Main fatty acid components in the larvae

Irrespective of diet, SFA was found to be the main group of fatty acids in all larvae (Table 3) the single most common fatty acid was lauric acid (C12:0), followed by palmitic (C16:0) and oleic acid (C18:1 n-9). These results are in line with findings in several earlier studies (Barroso et al., 2017; Liland et al., 2017; Meneguz et al., 2018; Spranghers et al., 2017; St-Hilaire et al., 2007a). In the

studies by Barroso et al. (2017) and Liland et al. (2017), linoleic acid (C18:2) was also found in high percentages (12–24%) in larvae fed diets of fish meal and chicken feed, or wheat and brown algae. This is slightly higher than the levels found in this study (3–13%). There were great similarities between the fatty acid composition of the larvae and the substrate: palmitic, oleic and linoleic acid were some of the most common fatty acids found in the substrates (range 8–32%, 6–42% and 4–36%, respectively; Table S2). These are some of the most commonly found fatty acids in plant and animal tissues (Tvřizicka et al., 2011). Therefore, the chances of excluding these fatty acids from the larval diet are low, and thus it seems as though the main fatty acid components in BSFL will be very similar, irrespective of the diet composition.

Lauric acid (C12:0) was present at high levels (13–52%) in all larvae, but in very limited amounts in the diets (0–1%; Table S2). This strongly indicates that it is synthesised by the larvae, as suggested by Spranghers et al. (2017). Those authors also suggest that the larvae synthesise lauric acid from the carbohydrates in the substrate. This would explain why BSFL grown on bread (79% carbohydrates; Table S2) contained the highest levels of lauric acid (28% on dry matter basis). A positive correlation was found between larval weight and percentage of lauric acid (C12:0) and total SFA in the larvae (Fig. 2), suggesting that these fatty acids accumulate most as the larvae gain weight. Similar trends were observed by Liu et al. (2017), who found that BSFL in later stages of development contained higher percentages of SFA and lauric acid. A high content of SFA has been demonstrated to differentiate BSFL from other insect larvae (Ramos-Bueno et al., 2016). Since adult BSF do not feed (Tomberlin and Sheppard, 2002), the fatty acids in the larvae are most likely a way to store energy for this later life stage. The reason for storing energy in the form of SFA in particular could be because these fatty acids are less prone to oxidation than unsaturated fatty acids, as suggested by Ushakova et al. (2016).

Besides lauric acid (C12:0), the FAPVs obtained in this study also indicated that six other fatty acids (C14:0, C14:1, C16:0, C16:1, C18:0 and C18:1 n-7) are synthesised by BSFL (Table S4). While Liland et al. (2017) did not delve into specific fatty acids, the FAPVs they present indicate that SFAs, and to some extent MUFAs, are synthesised by BSFL. Most insect species have been found to synthesise myristic (C14:0), palmitic (C16:0) and stearic acid (C18:0) *de novo*, and possess the enzymes required for production of myristoleic (C14:1), palmitoleic (C16:1) and oleic acid (C18:1 n-9) (Stanley-Samuelson et al., 1988). It is therefore surprising that the FAPVs obtained indicated that vaccenic acid (C18:1 n-7), and not oleic acid (C18:1 n-9), is produced by BSFL. The enzyme $\Delta 11$ desaturase, which enables production of vaccenic acid (C18:1 n-7), has only been found in a few insect species (Stanley-Samuelson et al., 1988), which makes it less likely that BSFL are able to produce this fatty acid. It is possible that the levels of vaccenic acid found in the larvae in Trial 2 (0.8–1.5%) were too low to allow accurate estimates of whether this fatty acid is produced by BSFL. However, this hypothesis needs further testing.

4.2. Polyunsaturated fatty acids

The FAPVs do not suggest that the BSFL are able to synthesise PUFA (Table S4), a conclusion also drawn by Liland et al. (2017). Therefore, linoleic acid (C18:2) and ALA (C18:3), as well as EPA (C20:5) and DHA (C22:6), found in larvae most likely originated from the substrate. To date, the enzymes required for production of linoleic acid and ALA (the precursor for EPA and DHA) have been found mainly in plants and marine algae (Tvřizicka et al., 2011). Therefore it seems unlikely that BSFL can produce these fatty acids. Some insect species, e.g. crickets and cockroaches, have been found capable of producing linoleic acid *de novo* (Stanley-Samuelson et al., 1988). However, these species are not very closely related

to BSF (Diptera), since they are of different taxonomic orders (Blattodea and Orthoptera).

One difference in the larval fatty acid composition in this study was the high percentages of EPA (C20:5) and DHA (C22:6) (Table 3). The larvae fed ensiled mussels contained 8% EPA and 5% DHA, which is considerably higher than the 2% EPA and 2% DHA reported previously (Barroso et al., 2017; Liland et al., 2017; St-Hilaire et al., 2007a). According to the linear regression model LW/FA (Eq. 5; Fig. 3), the percentage of EPA and DHA increased in the larvae when they represented a higher percentage of the total fatty acids in the diet, while it decreased as the larvae grew. Similar trends have been found by others, e.g. Liland et al. (2017) found a positive correlation between the percentage of EPA in total fatty acids in the larvae and in the diet, while Liu et al. (2017) found a decrease in unsaturated fatty acids over time as BSFL grew older. The decrease in EPA and DHA is most likely because lauric acid and SFA increase at a higher rate as BSFL grow.

The larvae that incorporated the highest percentage of EPA (40%) and DHA (10%) were those fed the diet with 10% mussels (Table S5). When a higher percentage of mussels was mixed into the diet, the larval retention decreased and most of these fatty acids remained in the residues. This suggests that production of BSFL with high levels of EPA and DHA would result in less efficient utilisation and higher waste of these fatty acids. There seems to be a difference in retention between EPA and DHA. It is possible that there are mechanisms in BSFL that favour incorporation of EPA over DHA, as suggested by Barroso et al. (2017).

4.3. Other nutritional components of the larvae

Considerable differences in crude fat, crude protein and ash were observed between the BSFL in this study. This is in line with earlier findings by Meneguz et al. (2018), but contradicts findings by Lalander et al. (2019) and Spranghers et al. (2017) of only minor differences in the protein content of BSFL fed different substrates. However, one important difference between these studies and this study is the larval stage of the larvae analysed. Their larvae were collected in the prepupal stage, whereas all larvae in this study were analysed after two weeks. Since larval development time is affected by parameters such as the substrate (Lalander et al., 2019) and feeding rate (Diener et al., 2009), the larvae in this study were most likely at different larval stages. Differences were observed in the colour – from light to dark – of the larvae after two weeks, especially in Trial 1. This indicates that the larvae fed with some substrates had reached the prepupal stage, while others had not. Significant differences have previously been found in crude fat, crude protein and ash content of BSFL at different larval stages (Liu et al., 2017).

The crude fat content seems to be closely linked to the percentage of “identified fatty acids” in the larvae. This suggests that the fraction termed “crude fat” in the larvae mainly consists of fatty acids. Besides stage of larval development, it also seems that the carbohydrate content of the diet impacts the crude fat content of the larvae. Spranghers et al. (2017) found a strong correlation between the crude fat of prepupae and non-fibrous carbohydrate content in the substrate. This could explain why the larvae fed bread were so high in fat. Moreover, Li et al. (2015) found increasing amount of lipids in BSFL on adding increasing levels of glucose and xylose to the diet.

The larvae in this study were found to contain up to 33% of ash on a dry matter basis (Table 2), which is much higher than the level reported previously (Liland et al., 2017; Meneguz et al., 2018; Spranghers et al., 2017). Spranghers et al. (2017) found a strong correlation between the ash content of the substrate and BSF prepupae. Therefore it is likely that the high levels of ash found in many larvae are explained by the high levels of ash in the diets

with mussels (26–84%; Table S2). No mussel shells were observed in the intestine of the larvae, but it is still possible that small fractions of shells were included in the analysis of ash content.

4.4. Implications for future use of larval fat

In this study two different factors were found to affect the fatty acid composition of the BSFL: the fatty acid composition of the substrate and the larval weight. Both of these two factors can be linked to the substrate, since the larval growth is affected by substrate properties (Lalander et al. 2019). This opens up for the possibility to engineer the fatty acid profile of the BSFL, by substrate selection and BSFL harvesting time.

Depending on the substrate, most larvae in this study contained EPA (C20:5) and DHA (C22:6) at different levels, fatty acids that are of great interest for aquaculture. In theory it seems possible to design the fat profile of BSFL to contain a higher percentage of these n-3 fatty acids by altering the fatty acid profile of the diet. However, the percentages of EPA and DHA were low in larvae of higher weight, and the retention decreased when higher amounts were included in the diet. Based on these results, it seems that the possibilities for modification of BSFL fatty acid composition through the diet are limited, as earlier suggested by Spranghers et al. (2017) and Oonincx et al. (2015).

It could be possible, to alter the percentage of MUFA and PUFA in the larvae by selecting the larval stage by which they are harvested, since these fatty acids were negatively correlated to the larval weight. However, there are some issues with this method. First of all, a lower larval weight would result in a lower yield of larvae, which makes the process less efficient from a waste management perspective. Also, a higher percentage of a certain fatty acid does not necessarily mean that the total weight of the fatty acid is higher, it all depends on the fat percentage and the total biomass. For these two reasons, the harvesting of larvae at the earlier larval stages may not be an efficient way for altering the fatty acid composition of the BSFL.

The possibilities for modification of the fatty acid profile appear to be somewhat limited, thus it may be advisable to focus on the major fatty acid constituent, i.e. the SFA, in particular lauric acid, rather than the minor constituents (such as EPA and DHA) when evaluating possibilities for future applications of the BSFL fat. Replacement of fish oil with BSFL fat, as suggested by St-Hilaire et al. (2007a), may not be a viable option, whereas the replacement of vegetable oils could be a fruitful route to take. Li et al. (2016) found that it was possible to replace 100% of the soybean oil in the diet of Jian carp (*Cyprinus carpio* var. Jian) with BSFL fat, without negative impacts on growth performance. Schiavone et al. (2018) report similar results, but for broilers. It has also been found that the fatty acid content of BSFL is similar to that of palm oil and coconut fat, and therefore it may be possible to use BSFL fat within the food industry and other relevant industries where these fats are used (Matthäus et al., 2019). Furthermore, Surendra et al. (2016) found that the fatty acids in BSFL are suitable for the production of high-quality biodiesel. Thus, there seems to be good potential for using BSFL fat in the production of feed, food and fuel.

5. Conclusions

In this study, BSFL were fed 11 different diets composed of mussels, bread, fish and food waste. The larvae, diets and residues were analysed for proximate and fatty acid composition, and larval growth and feed conversion were measured. The fatty acid composition of the BSFL was found to be affected by the diet and the larval weight, but the possibilities for modification were hypothesised to be somewhat limited. The larvae contained mainly

SFA (especially lauric acid) and MUFAs, fatty acids which the larvae seem able to produce by themselves. It is possible to incorporate n-3 fatty acids such as EPA (C20:5) and DHA (C22:6) from the diet into the larval fat, but when the larvae gain weight, the percentage of these fatty acids decreases. Thus the potential for using BSFL fat as a substitute for fish oil seems small. Instead, based on its major fatty acid components, it is recommended that BSFL fat be used e.g. as a substitute for vegetable oils in food and feed, and for the production of biofuel.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wasman.2019.10.014>.

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Life cycle assessment of pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and case study of commercial plants

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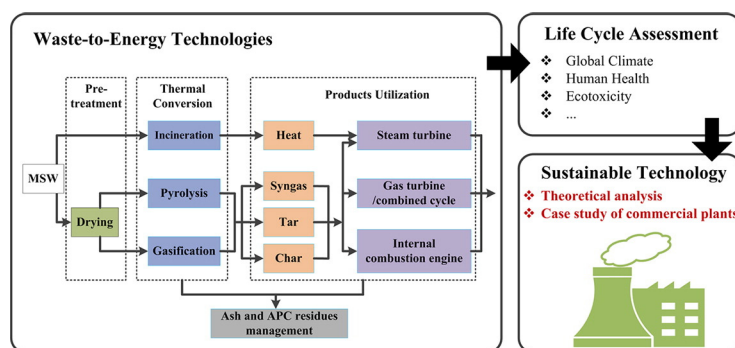
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HIGHLIGHTS

- Pyrolysis, gasification and incineration Waste-to-Energy are compared by LCA.
- Seven multi-stage system configurations are modeled as theoretical analysis.
- Four types of large-scale Waste-to-Energy plants are compared as case study.
- Non-toxic and toxic environmental impacts are assessed with a sensitivity analysis.
- Potential improvements and impediments to the further development are suggested.

GRAPHICAL ABSTRACT



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ABSTRACT

Municipal solid waste (MSW) pyrolysis and gasification are in development, stimulated by a more sustainable waste-to-energy (WtE) option. Since comprehensive comparisons of the existing WtE technologies are fairly rare, this study aims to conduct a life cycle assessment (LCA) using two sets of data: theoretical analysis, and case studies of large-scale commercial plants. Seven systems involving thermal conversion (pyrolysis, gasification, incineration) and energy utilization (steam cycle, gas turbine/combined cycle, internal combustion engine) are modeled. Theoretical analysis results show that pyrolysis and gasification, in particular coupled with a gas turbine/combined cycle, have the potential to lessen the environmental loadings. The benefits derive from an improved energy efficiency leading to less fossil-based energy consumption, and the reduced process emissions by syngas combustion. Comparison among the four operating plants (incineration, pyrolysis, gasification, gasification-melting) confirms a preferable performance of the gasification plant attributed to syngas cleaning. The modern incineration is superior over pyrolysis and gasification-melting at present, due to the effectiveness of modern flue gas cleaning, use of combined heat and power (CHP) cycle, and ash recycling. The sensitivity analysis highlights a crucial role of the plant efficiency and pyrolysis char land utilization. The study indicates that the heterogeneity of MSW and syngas purification technologies are the most relevant impediments for the current pyrolysis/gasification-based WtE. Potential development should incorporate into all process aspects to boost the energy efficiency, improve incoming waste quality, and achieve efficient residues management.

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1. Introduction

In the transition towards more sustainable development, treatment technologies for municipal solid waste (MSW) have made considerable progress (Zhao et al., 2009). The last decades witnessed a gradually decreased proportion of landfill as required by the European Landfill and Waste Framework Directives (Council of European Communities, 1999; The European Parliament and the Council of European Communities, 2008). In contrast, waste-to-energy (WtE) is gaining increasing interest. Until recently, incineration is the most widespread WtE technology with more than 1400 incineration plants in operation around the world (Leckner, 2015). However, even the last generation of MSW incinerators is limited by a low electricity efficiency up to about 22–25% (Panepinto et al., 2015), due to the limitation in the maximum steam temperature of the boiler, normally less than 450 °C to prevent corrosion by gaseous HCl (Belgiorno et al., 2003). Although modern and well-operated incinerators can fulfill the requirements of an environmentally sound technology, potential risk of PCDD/Fs still present as a debate for the public. As a consequence, technological development towards more environmental-friendly and energy-efficient alternative WtE options are still required.

In recent years, there is considerable interest in new WtE technologies particularly pyrolysis and gasification, which attain the possibility to obtain a syngas suitable for different applications (Funari et al., 2016; Khoo, 2009). About energetic use in WtE plants, there is a general perception that pyrolysis and gasification could achieve a higher efficiency by supplying the syngas with a more efficient energy conversion device such as a gas turbine/combined cycle (gas turbine/CC) or an internal combustion engine (Arena, 2012). Even if in a steam cycle plant, the limitation of efficiency could be overcome by adding gas pre-treatment before it goes into the burner, to allow the removal of HCl and an improvement in steam temperature of 520–540 °C (Belgiorno et al., 2003). Besides, pyrolysis and gasification have the potential to diminish PCDD/Fs (Noma et al., 2012), thus reducing the total generation of pollutants if the downstream syngas oxidation is processed efficiently. However, using of the newly developed WtE options does not automatically guarantee the total sustainability of the whole multi-stage thermal conversion and energy utilization chain (Ning et al., 2013; Wang et al., 2015). The “raw” syngas, which contains a variety of contaminants such as H₂S, tar, NH₃ and particulate matter (PM), needs to be purified to meet the stringent requirement of entering an engine (Wood et al., 2013). The configuration of different energy cycles downstream may also influence the overall environmental effects: the consumptions and losses of gasification and syngas clean-up may cause the overall energy efficiency be close or lower to incineration. It is not a simple procedure to select an optimal WtE technology. A comprehensive assessment of different WtE process configurations is necessary to understand if pyrolysis/gasification-based WtE may become potential alternative or improvement for the current incineration.

Guided by ISO standards (ISO, 1997), life cycle assessment (LCA) is benefited from the quantification of the entire life cycle impacts. This can help identify the most critical process for environmental burdens (Millward-Hopkins et al., 2018), and provide a benchmark for new technologies. LCA has provided reliable evaluation of MSW treatment technologies (Kaplan et al., 2009; Lundie and Peters, 2005; Morselli et al., 2008; Wäger and Hirschler, 2015). However, LCA of WtE technologies is rarely performed other than incineration. This is mainly because the operational practice using pyrolysis and gasification is quite limited despite that a number of applications do exist (Molino et al., 2016; Panepinto et al., 2015), making comparisons very difficult. The existing studies are focused mainly on the thermal conversion process itself, while few of them examine the downstream use of syngas in detail. The environmental performance of WtE options depends on many factors such as emission levels, energy efficiencies, type of end-use applications, and energy source. However, the LCA studies available on pyrolysis and gasification are often based on varying assumptions and

insufficient to thoroughly study these issues. This may limit the LCA comparisons between different WtE technologies on a consistent and common basis.

The goal of this work is to provide a detailed life cycle investigation of different WtE technologies. In response to the incompleteness and scarcity of data on pyrolysis and gasification, this study is striving to conduct both theoretical analysis of the possible configuration of WtE technologies and real case studies of several commercial plants. In the first part, a general and extensive theoretical analysis of seven multi-stage WtE systems involving thermal conversion (pyrolysis, gasification, incineration) and energy utilization (steam cycle, gas turbine/CC, internal combustion engine) is modeled, using the most typical and well-accepted reported data. In the second part, four large-scale commercial operation WtE plants (pyrolysis, gasification, gasification-melting, modern incineration) are compared. Besides, a sensitivity analysis is carried out to identify key parameters responsible for the environmental impacts. This study aims at understanding how the current WtE could get a benefit towards a more environmentally sustainable technology. Potential improvements and impediments to the further development of pyrolysis and gasification-based WtE technologies are also discussed and suggested.

2. Methodology

2.1. System definition

The system boundaries (Fig. 1) of the study attain at the moment when MSW enters the WtE plant. Four basic processes are included: (1) MSW pre-treatment, (2) thermal conversion, (3) utilization of acquired products, and (4) ash and air pollution control (APC) residues management. MSW can either be thermally converted by adding sufficient amount of air (incineration), where the MSW is fully oxidized into process heat; or by supplying an air deficiency, where the waste is pyrolyzed (in the absence of air) or gasified (in a partial oxidant amount lower than stoichiometric combustion). The latter case produces intermediated products including syngas, tar and char, which can recover energy in several pathways (Molino et al., 2016): to be combusted in a boiler and connected with a steam turbine; or, after a purification step, to be used in a gas turbine/CC or an internal combustion engine. Thus a total of seven scenarios are formed. S1 is defined as MSW direct incineration to represent the current WtE. S2, S3 and S4 represents pyrolysis coupled with steam turbine, gas turbine/CC and internal combustion engine, respectively; gasification combined with those energy devices are defined as S5, S6 and S7. MSW pre-treatment mainly refers to drying and shredding with the aim of size reduction and homogenization. While incineration plants could process MSW directly (Evangelisti et al., 2015), pre-treatment is basically needed prior to pyrolysis/gasification (McKendry, 2002). Detailed flowchart of each system is illustrated in the Supplementary Material (Fig. S1).

The functional unit is set at one ton of MSW as received at the plant. Upstream production of fuels and materials including diesel, electricity, lime, etc. is considered as the ‘cradle to grave’ type of calculation. The benefits from useful co-products, such as electricity and heat, are allocated by system expansion. The recovered electricity is assumed to substitute that provided by the “energy mix” of a specific region, here the European average (42.7% fossil fuels, 26.5% nuclear, 30.0% renewable energies, 0.7% waste and 0.1% other in 2015) is selected (Eurostat, n.d.-a, n.d.-b). The produced heat displaces an equal amount of heat generated by “heat mix”, of which the heat production data based on European average is again used (69.3% fossil fuels, 0.2% nuclear, 22.9% renewable energies, 4.8% waste and 2.7% other in 2015) (Eurostat, n.d.-a, n.d.-b). The database Gabi 7.0 provides the remaining, mainly indirect burdens, of the background system.

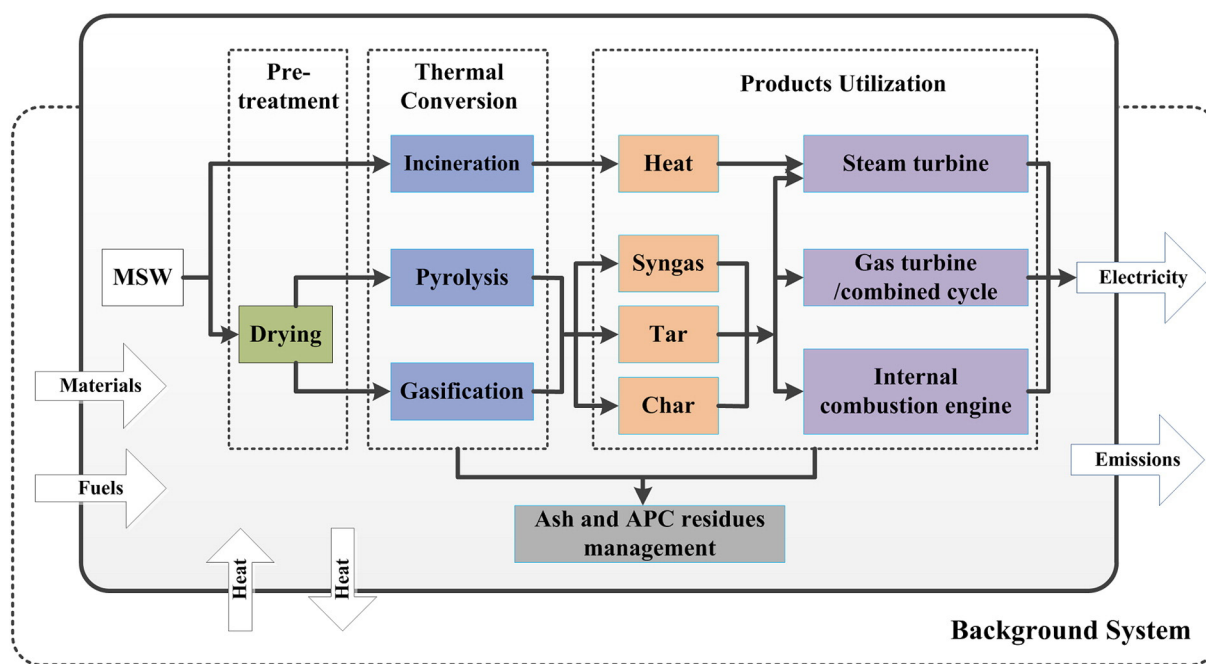


Fig. 1. System boundaries of the study.

2.2. MSW characteristics

The MSW typically treated in the WtE plant is the residual from the source-separated collection of dry recyclables and wet organic fractions. The waste characteristics in different countries have a high variability depending on the culture, climate and socioeconomic (Vergara and Tchobanoglous, 2012). Therefore, a typical MSW, reflects the average waste composition in Europe (Arena et al., 2015), is selected as the basis for comparison (Table 1).

2.3. Data source for theoretical analysis

The data utilized for theoretical analysis are mainly derived from industrial practice, peer-reviewed literature, standards, and recent research reports. The data are regionalized in the sense that they refer to the situation of Europe. For each of the WtE system, the modeling of material consumptions, emissions and energy recovery is analyzed on basis of mass and energy balance, the detailed calculations are available in the Supplementary Material (Section SM-8). Each unit process and the main data source are presented as following.

2.3.1. MSW pre-treatment

A pre-treatment step is assumed to be conducted before pyrolysis and gasification process. In order to facilitate homogenization, the incoming MSW is shredded to an average size of a few hundred millimeters (e.g. a size of around 100 mm in practice). The estimated energy use

Table 1
Characteristics of the MSW as received at the plant.

Characteristics (wt%, as received basis)	
C	25
H	4
N	0.84
S	0.13
O (by difference)	12
Moisture	34
Ash	24
Lower heating value, MJ/kg	9.8

for mechanical treatment is set at 100 kWh of electricity and 25 kWh of natural gas per ton of MSW (Kourkoumpas et al., 2015). The waste then undergoes drying to a final moisture content of around 10%. The heat required by the dryer is internally supplied with a thermal efficiency of 90% (Roberts et al., 2009). For systems using gas turbine/CC and internal combustion engine (S3, S4, S6 and S7), the heat derives from the syngas purification unit which recovers the sensible heat of the hot syngas during cooling. For S2 and S5, the heat is supplied by the hot flue gas.

2.3.2. Thermal conversion (pyrolysis, gasification and direct incineration)

For pyrolysis, the proportion of each product (syngas, tar and char) is strongly dependent on the reaction temperature, residence time and heating rate (Van de Velden et al., 2010). For waste processing, a running temperature of 500–550 °C is widely used in industrial plants (Chen et al., 2015). This pyrolysis technology, represented by the RWE-ConTherm[®] process (Hauk et al., 2004), is considered in this analysis, since it is the most typical pyrolysis process presently available in the European market. The pyrolysis reactor is a rotary kiln type, with a residence time of approximately 1 h. About 85% of the energy will be converted into the hot gas (i.e., hot gas efficiency), with cold gas efficiency attaining around 50%. The cold gas efficiency can be defined as the ratio of the energy content of the cold syngas to that of the feedstock. The balance is char, and its mass proportion is around 30%. The data are based on average reported values of the industrial plants (DGEEngineering - The rotary kiln engineers, July, 2009a, 2009b). We assume the reliability is high because they can be cross-checked extensively.

Gasification owns the sole objective to produce syngas, although the generation of tar is inevitable along with the gas. In comparison to pyrolysis, gasification occurs at a generally higher temperature: 550–900 °C in air gasification and 1000–1600 °C if using pure oxygen, oxygen-enrich gas or steam (Arena, 2012). Based on several operation data from the existing plants, the cold gas efficiency is in a range of 50–80% (Arena, 2012). Here a cold gas efficiency of 70% is used as a conservative estimate (Panepinto et al., 2015; Yassin et al., 2009). A hot gas efficiency of 90% is assumed in the case syngas is directly used in a boiler without any pre-cooling.

MSW direct incineration is well-proven and has greater operational reliability than pyrolysis and gasification. The assumed incineration is

based on a moving grate. The waste is directly combusted to heat up water in the boiler to generate steam. A heat loss is also inevitable, for example the discharge of the ash and flue gas will cause a high loss of the sensible heat. However, we do not tend to assume this efficiency, since it will be reflected in the overall plant efficiency.

While the incineration process is exothermic, gasification can also achieve heat self-sustaining around an equivalence ratio of 0.3–0.4 (Zhang et al., 2011), i.e. no any external thermal assistance is needed, the same under which in the real plants (Arena and Di Gregorio, 2014). Nevertheless, pyrolysis requires an additional thermal energy to maintain the reaction. The input energy is around 9% of the MSW energy according to the research of Baggio et al. (Baggio et al., 2008). The heat is assumed to be supplied by the hot flue gas as it is commonly preferred in the plants.

2.3.3. Energy utilization cycles

Each WtE plant in this study is assumed to be an integrated facility, in which the final energy utilization is operated on-site. The electrical efficiency of the incineration plant is set at 22.5% (Arena, 2012; Morris and Waldheim, 1998), which represents an average of the modern dedicated waste combustion systems. For pyrolysis and gasification systems, steam cycle is the simplest option because the hot syngas could undergo combustion in the gas boiler without purification. A higher efficiency can be achieved (set at 27.8% in this study), since the homogenous and gas-phase combustion is more controllable and effective (Consonni and Viganò, 2012). The syngas can also be burned in a gas turbine/CC or an internal combustion engine. Potentially, the electrical efficiencies would be higher (set at 35.5% and 25.0% for gas turbine/CC and engine, respectively (Belgiorno et al., 2003; Morris and Waldheim, 1998)). However, the syngas needs to be cooled and purified to meet the stringent inlet gas quality requirement. To ensure the transparency of the data, the values of plant efficiencies are determined by extensively searching and comparing with similar set-up in the literature and reports (see details in Table S2). Additionally, a range of variations of each plant efficiency will be discussed in the sensitivity analysis. For all the systems analyzed, 20% of the generated electricity is assumed to be self-consumed in the plant, with the remaining 80% sent to the power grid.

For systems using gas turbine/CC and internal combustion engine (S3, S4, S6 and S7), cleaning the syngas allows the chemical energy to be conserved. The sensible heat is recovered assuming an efficiency of 75% (Yi et al., 2013). As stated earlier, the heat is used for MSW pre-treatment; the excessive amount is transferred to the needs of the end user. The formed pyrolysis char can either be combusted at the facility to generate more energy or be used as a product (biochar). The former application is considered as the baseline, while the latter case will be discussed in the sensitivity analysis. The pyrolysis char is assumed to be sent into the boiler and combusted together with the gas in the S2 system, which is in accordance with the real operation in reference plants. If a gas turbine/CC or internal combustion engine is used, the char is assumed to be combusted in a separated boiler for heat production at a thermal efficiency of 75%, which is a typical value for industrial heating boilers in operation (Roberts et al., 2009).

2.3.4. Emissions at the stack

In attempt to better perform a transparent evaluation, the emission factors used in this theoretical analysis are estimated using the European pollution control standards, i.e., the exhaust flue gas from each WtE system is assumed to meet the requirements of specified emission standards (Directive 2007/76/EC (The Commission of the European Communities, 2007) and Directive 2010/75/EU with some adaptations (Directive, 2010)). The real emission data from industrial plants will be analyzed in the second part (case studies). Table 2 summarizes the related emission factors. These data have been used in conjunction with estimates of flue gas volumes per functional unit of MSW produced to derive the final mass release rates. Details on the standards,

adaptations and calculations can be found in the Supplementary Material (Section SM-5).

2.3.5. Ash and air pollution control residues management

The amount of solid residues produced by incineration and pyrolysis/gasification plants are assumed to be 180 kg/t-MSW and 120 kg/t-MSW, respectively, as reported by UK's waste report (DEFRA UK, 2004). The solid residues may be recycled as road construction materials or concrete aggregate (Sakai and Hiraoka, 2000). However, only landfill is considered in the theoretical analysis and the potential benefit will be included in the case studies of the commercial plants. The APC residues, including mainly fly ashes and exhausted sorbents, are assumed to be stabilized before final disposal in landfill. Emissions, mainly heavy metals to the soil, are estimated according to the UK's waste report (DEFRA UK, 2004).

2.4. Data source for commercial operation WtE plants

Four large-scale commercial operation WtE plants (pyrolysis, gasification, gasification-melting, modern incineration) are modeled as case studies. The selected plants could represent the most typical modern state-of-the-art plants, therefore reflecting the actual environmental sustainability of different WtE technologies. The selected plants are all in connection with a steam turbine cycle, i.e., in a similar configuration of the S1, S2 or S5 system. Table 2 and Table S5 summarize the related emission factors and information of these plants, respectively; with a brief introduction of each plant presented as following.

- **Incineration plant (C1):** Silla 2 incineration plant, located in Milan, Italy, is studied as a typical case of the modern incineration. The plant is equipped with 3 moving grate combustion lines, having a treatment capacity of 450,000 t/a. MSW is incinerated at 850 °C to produce electricity and district heating at an efficiency of 24% (net) and 6%, respectively (Turconi et al., 2011). The flue gas cleaning includes electrostatic precipitator, acid gas neutralization (NaHCO₃ injection), fabric filter and a SCR unit for NO_x abatement (Amsa, April, 2008). After combustion, metals are sorted from the bottom ash and recycled. 88% of the bottom ash is utilized in road construction, while the remaining fraction is landfilled and the APC residues are safely disposed.
- **Pyrolysis plant (C2):** The selected plant, located in Hamm, Germany, has a capacity of 100,000 t/a, although it is no longer in operation after the chimney collapse in 2009. The pyrolysis process belongs to the RWE-ConTherm[®] technology (DGEngineering - The rotary kiln engineers, July, 2009a). After shredded to 200 mm, the MSW is decomposed in the absence of air in a rotary kiln at 500 °C with a residence time of 1 h, using natural gas as the heating source. The products, hot syngas and char, are incinerated in the boiler of a coal-fired plant for electricity production. The residues are considered to be landfilled and the metals are recycled. The plant electricity efficiency (gross) is around 22% (Stein and Tobiasen, 2004).
- **Gasification plant (C3):** The selected plant, Lahti II, located in Finland, has started its commercial operation in 2012 with an annually capacity of 250,000 tons (Lahti Energia, n.d.). The feedstock is solid recovered fuels (SRF), i.e., high calorific waste unsuitable for recycling. The gasifier is a circulating fluidized bed operated at 850–900 °C. The syngas generated undergoes cooling at 400 °C to remove heavy metals and PM. The cleaned syngas enables a more efficient heat recovery boiler at 121 bar and superheated steam at 540 °C. The plant attains final 27% of electricity efficiency (net) and 61% of heat efficiency (Savelainen and Isaksson, 2015). The flue gas cleaning system consists of a bag house filter with additive injections (NaHCO₃ and activated carbon) and a SCR for NO_x reduction. From the plant outlet, the bottom ash is removed to landfill disposal and the APC residues are safely disposed.
- **Gasification-melting plant (C4):** The reason to select this technology

Table 2
List of emission factors used in theoretical analysis and case studies of commercial WtE plants (Unit: mg/Nm³).

	Theoretical analysis ^a				Commercial WtE plants ^b			
	Incinerator	Gas boiler-steam turbine	Gas turbine/CC	Internal combustion engine	Incineration	Pyrolysis	Gasification	Gasification-melting
CO	50	50	100	100	5.5	10	2	6.2
SO ₂	50	35	15	15	0.44	8	7	3.3
NO _x	200	200	120	100	41.4	166.9	161	20.9
HCl	10	10	0	0	1.9	5.1	1	3.7
PM	10	5	0	0	0.09	1.4	2	1
PCDD/Fs (ng-TEQ/m ³)	0.1	0.1	0.1	0.1	0.005	0.001	0.002	0.006
Hg	0.05	0.05	0.05	0.05	0.002	0.011	0.0001	0.02
Cd	0.05	0.05	0.05	0.05	0.001	0.006	n.a. ^c	n.a. ^c

^a MSW incineration accords with the Directive 2007/76/EC; while pyrolysis and gasification plants meet the limits of the Directive 2010/75/EU with some adaptations (see detailed assumptions in Supplementary Material).

^b Data based on four commercial operated WtE plants (see plant information and data source in Supplementary Material).

^c Data not available.

is its possibility to recover materials effectively (Tanigaki et al., 2012). The selected plant, having a total throughput of 80 MW, is located in Japan and is one of the largest gasification-melting facilities in the world. The MSW is charged into a shaft-furnace type gasifier from the top with coke and limestone, and the ash is melt at the bottom by O₂-rich air at 1000–1800 °C. No pre-treatment of the incoming waste is required. The syngas is transferred to be combusted to generate steam at 400 °C and 3.92 MPa. The electricity efficiency (gross) attains at 23% (Tanigaki et al., 2012). The flue gas cleaning applies a quencher, a baghouse with Ca(OH)₂ injection for desulfurization, a

re-heater and a SCR for NO_x reduction. The molten materials from the gasifier are magnetically separated into slag and metals, which can be completely recycled; while the APC residues are further treated.

2.5. Life cycle inventory

By combining all unit processes input-output data, a detailed LCI table is compiled (see Table S6 and Table S7). Biogenic CO₂ is assumed

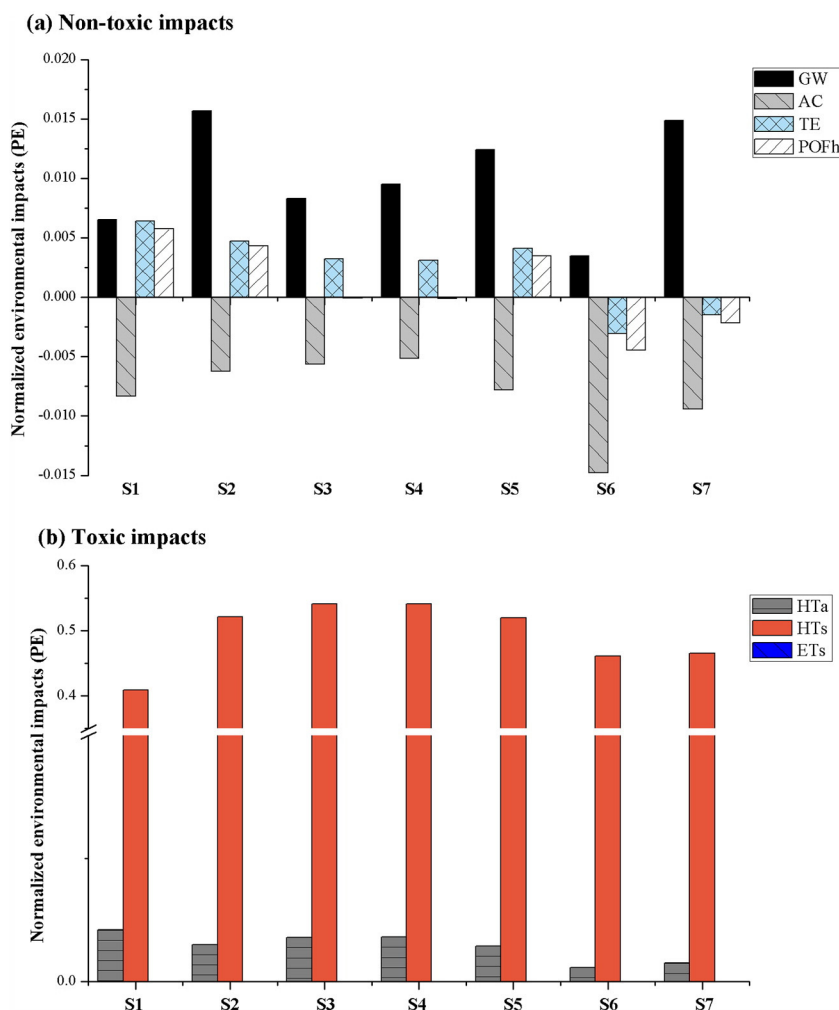


Fig. 2. Normalized environmental impacts of different systems based on the theoretical analysis: (a) non-toxic impacts; (b) toxic impacts.

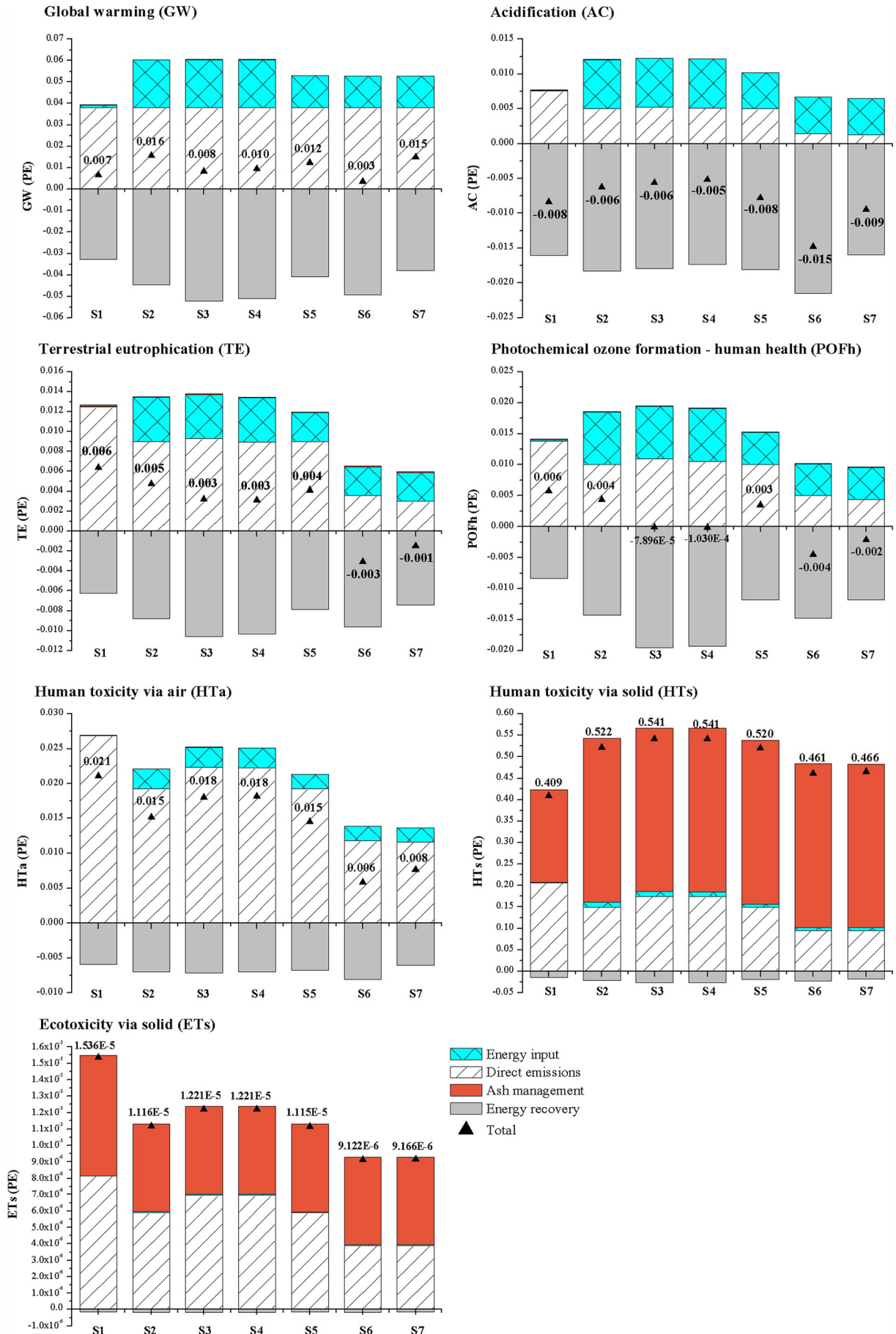


Fig. 3. Contributory analysis for each environmental impact based on the theoretical analysis.

to be carbon neutral to global climate change. For the specific MSW in this study, the fraction of biogenic carbon contributes 64% of the received MSW. Emissions to the water are not included, since modern WtE systems are commonly designed with wastewater treatment and reused equipment to meet a 'zero discharge' target (Chen and Christensen, 2010).

2.6. Life cycle impact assessment

The well-accepted Danish EDIP methodology is used to aggregate the LCI data (Hauschild and Potting, 2005; Wenzel et al., 1997). Seven impact categories are considered: global warming (GW), acidification (AC), terrestrial eutrophication (TE), photochemical ozone formation to human health (POFh), human toxicity via air (HTa) and solid (HTs), and ecotoxicity via solid (ETs). Results based on normalized values are used to reflect the relative magnitude of different impacts into person equivalence. A summary of the normalization references is available in Table S8.

3. Results

3.1. Theoretical analysis results

Fig. 2 reports the overall environmental performance of different systems. Compared to direct incineration (S1), pyrolysis and gasification are effective to lessen the environmental impacts of TE, POF, HTa and ETs, yet increase the burdens of GW and HTs. For a direct comparison of different WtE processes, gasification systems (S5–S7) lead to a lower impact than pyrolysis systems (S2–S4). For systems using

different energy cycles, gas turbine/CC (S3, S6) has surpassed steam turbine (S2, S5) and internal combustion engine (S4, S7) and becomes the most preferred energy utilization approach.

To give a clear and transparent explanation of the aforementioned results, the overall impact is divided into four stage-wise contributors: energy input, direct emissions, ash management and energy recovery. As shown in Fig. 3, the environmental savings for non-toxic impacts are primarily brought by energy recovery, which compensates a significant amount of emissions generated by fossil fuel-based energy production. In particular, negative values appear for several systems regarding AC, TE and POFh, indicating that the environmental benefit has balanced the loading and a net environmental saving is achieved. The highest recovered energy has been found for systems equipped with gas turbine/CC (S3, S6). This reveals the advantage brought by a more efficient energy device that is able to counterbalance an increasing amount of emissions. Besides, pyrolysis equipped with combustion engine (S4) also exhibits significant avoided impacts due to the additional savings from process heat (mainly from tar and char combustion), which highlights the importance of heat recovery in improving the total recovered energy.

Direct emissions also have a large influence to the total impacts. Different systems show negligible difference of GW, because CO₂ emission is decisively contributed to GW and it mainly derives from the fossil-origin carbonaceous compounds contained in MSW. However, there is a dramatic difference in direct emissions among all the systems, if consulting the impacts of AC, TE and POFh. Compared with incineration (S1), 21–34% and 28–83% decrease in those indicators are achieved for pyrolysis and gasification systems, respectively. The principal contributors for AC, TE and POFh are acid gases including NO_x, SO₂, HCl and HF.

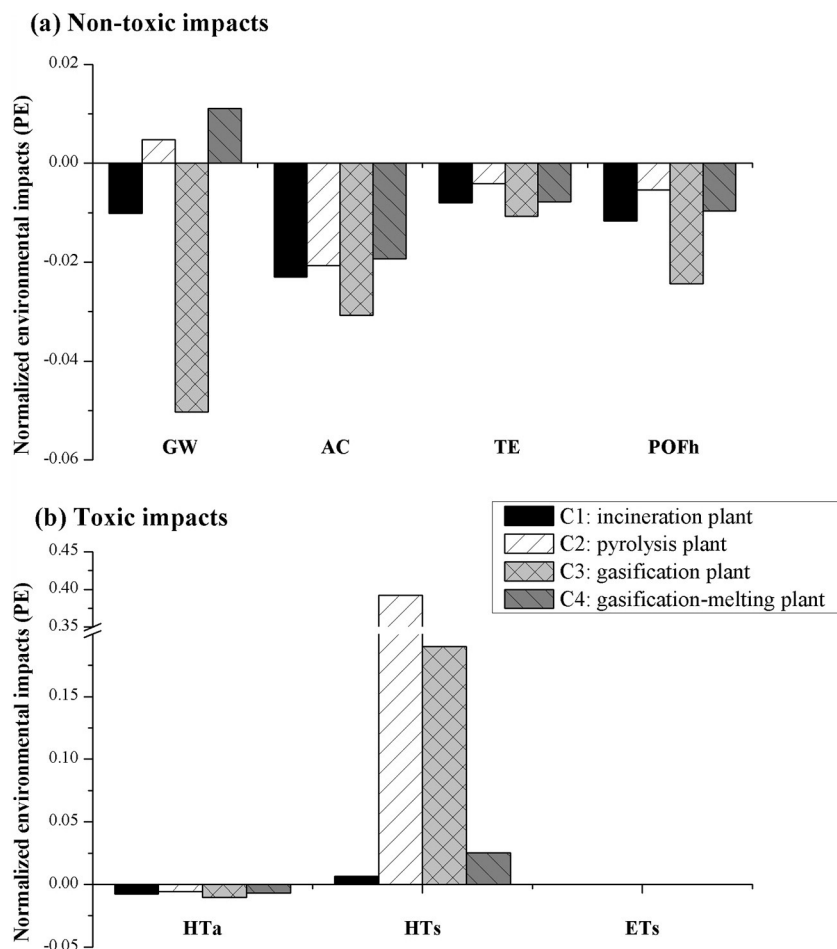


Fig. 4. Environmental impacts of different systems based on case studies of the selected commercial WtE plants: (a) non-toxic impacts; (b) toxic impacts.

Table 3

Sensitivity analysis by changing of the plant efficiency by ±10%, based on the data from theoretical analysis.

	Environmental impacts change ^a (%)						
	S1	S2	S3	S4	S5	S6	S7
GW	±50.2	±19.2	±24.9	±20.4	±26.9	±110.9	±18.3
AC	±19.2	±23.5	±17.8	±18.4	±20.8	±12.7	±14.0
TE	±9.8	±12.1	±12.2	±11.9	±15.5	±23.9	±34.6
POFh	±14.6	±17.8	±665.5	±480.2	±24.5	±22.0	±32.2
HTa	±2.8	±3.6	±2.0	±1.9	±4.1	±11.9	±6.4
HTs	±0.4	±0.3	±0.2	±0.2	±0.3	±0.4	±0.3
ETs	±0.1	±0.1	±0.1	±0.1	±0.1	±0.2	±0.1

^a Results represent a percentage increase or decrease of the environmental impacts in the base case scenarios.

The reduced emissions by pyrolysis and gasification can in fact be ascribed to, on one hand, a lower amount of flue gas as a consequence of the lower excess air required for syngas combustion; on the other hand, the limited NO_x generation as a result of the homogeneous gas-gas reaction (Consonni and Viganò, 2012). It shows also a further reduction of emissions from gasification systems using gas turbine/CC and internal combustion engine (S6, S7), because purifying the syngas allows the removal of a part of acid gases; and, the syngas volume is much

smaller to limit the total flue gas. Conversely the direct emissions from pyrolysis systems (S3, S4) tend to increase due to char and tar combustion.

All systems contribute positive impacts to toxic categories including HTa, HTs and ETs. Fig. 2 reveals that HTs and HTa are the highest burden categories, being 1–2 orders of magnitude more significant than non-toxic impacts. Direct emissions and ash management are the main contributors. The avoided emissions are insignificant, which is opposite to that of non-toxic impacts. The toxic impacts are decisively due to heavy metals, PCDD/Fs and PM emissions for their relatively high equivalent factors. Ash management takes a crucial effect to HTs and ETs, since heavy metals contained in the ash is liable to be transferred into the soil after landfill, or released during the solidification/stabilization process of the APC residues.

Consequently, it could be concluded from the theoretical analysis that compared with incineration, both pyrolysis and gasification own the potential to have a better environmental performance due to two-fold benefits: the reduced process emissions as well as a substantial increase in the amount of energy recovered. However, the important input energy demand, for example waste pre-treatment, syngas cleaning and endothermic pyrolysis reaction, may on the other hand become additional burdens especially regarding GW. This is also one reason for an inferior performance from pyrolysis systems in comparison

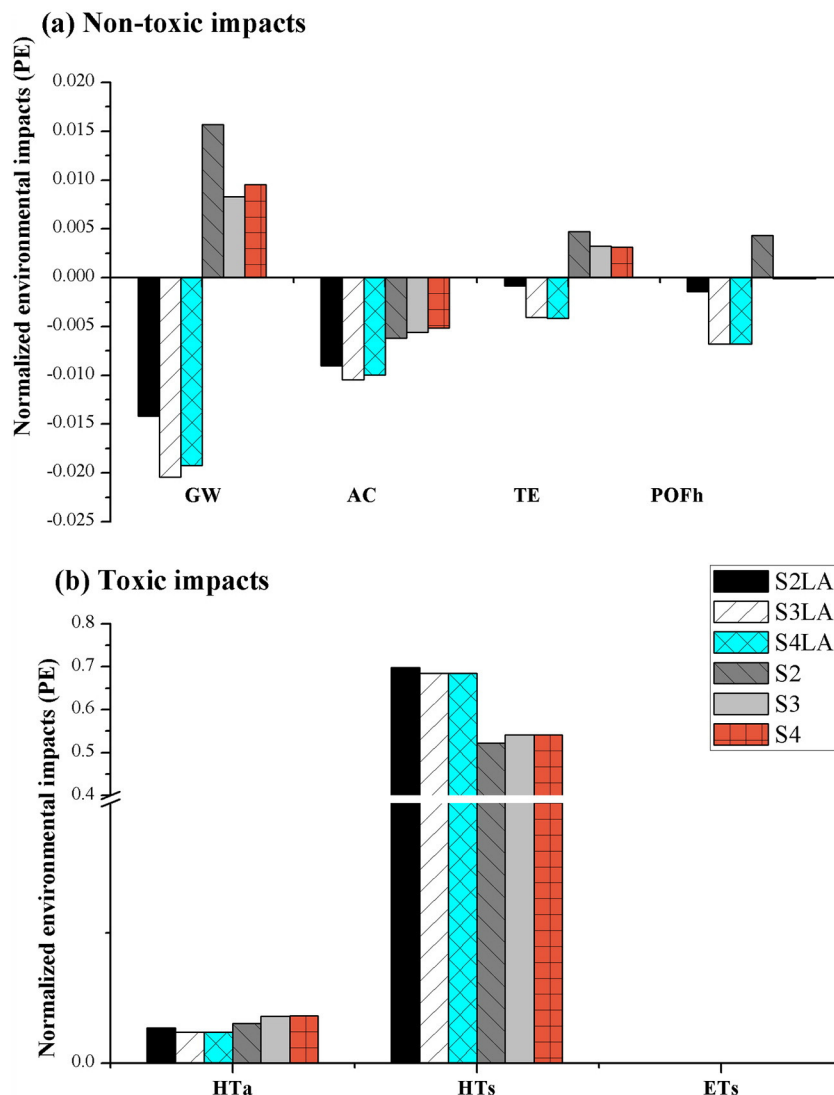


Fig. 5. Sensitivity analysis by alternative utilization of the pyrolysis char, based on the data from theoretical analysis. Corner mark “LA” stands for land application as soil amendment.

to gasification. Overall, gasification equipped with gas turbine (S6) is observed to be the most environmentally preferable system.

3.2. Case studies for commercial operation WtE plants

Fig. 4 summarizes the environmental impacts from four large-scale commercial operation WtE plants, where all impacts experience a significant drop compared with the theoretical analysis. The benefit is mainly due to the reduction in the process direct emissions, revealing that plants based on all the technologies in connection with a steam boiler can comfortably meet the required emission limits. The environmental sustainability of each plant in descending order is: gasification > incineration > (pyrolysis, gasification-melting); while it is difficult to figure out the relative superiority between pyrolysis and gasification-melting. It reveals that the modern incineration could fulfill an environmentally sound technology, i.e., better than pyrolysis and gasification-melting plants at present. The emission factors reported in Table 2 indicate that the actual emissions from the reference incineration and pyrolysis/gasification plants are quite similar due to the technological performance of the modern flue gas cleaning devices (fabric filters, desulfurization, NO_x abatement, activated carbon injection, etc.). The improved performance of incineration could also be attributed to the use of the more efficient combined heat and power (CHP) cycle, which has achieved an additional 6% of heat production. On the other hand, gasification reaches the best performance among the four plants. This fact again verifies the positive role of syngas cleaning, which allows the gas clean enough to employ higher steam data (540 °C, 121 bar compared with 400 °C, 40 bar in conventional waste boiler) for an increased electricity efficiency (27% net compared with 24% in incineration). Additionally, this gasification plant shows further advantage by an abundance of heat production (61%), significantly larger than in the incineration plant (6%). Those together have resulted in a significant environmental saving from the avoided heat and electricity production in the gasification plant.

Contrarily, pyrolysis and gasification-melting plants show an inferior performance. The increased environmental burdens are either due to a high amount of auxiliary fuel used, or a low amount of net energy recovered. Particularly, gasification-melting plant shows an important internal parasitic energy demand reaching 24% of the total energy production, mainly due to the use of O₂-rich air for ash melting.

An obvious reduction in HTs and ETs is achieved in the incineration and gasification-melting plants. The offset impacts are mainly attributed to the recycling of the bottom ash, slag and metals owing to two-aspect benefits: the reduced amount of ash to be treated, which is the main cause of solid heavy metals leaching; and, the avoided manufacture of road construction materials and metals from their virgin materials.

3.3. Sensitivity analysis

A sensitivity analysis has been carried out to identify key process parameters as well as to seek for potential improvements. The evaluation is based on the data from the theoretical analysis considering two variations: changing of the plant efficiency, and alternative utilization of the pyrolysis char as soil amendment.

A ±10% variation of the plant efficiency for each system is conducted. Results in Table 3 show an up to ±665% variation in the environmental impacts, of which non-toxic impacts appear of remarkable relevance. The variation is primarily related to the amount of energy recovered as it could replace the associated emissions from the burning of fossil fuels. The results confirm a crucial role of the energy recovery efficiency in determining the total sustainability of a WtE plant.

For pyrolysis systems (S2–S4), the sensitivity analysis considers also the case where the char is used as soil amendment. In such case, the pyrolysis char is considered to have two additional merits (Harder and Forton, 2007; Roberts et al., 2009): substitution of fertilizer (N, P and K) and carbon sequestration. Key assumptions and calculations are

presented in Table S10. Fig. 5 indicates that this assumption has exhibited an obvious reduction on the majority of impacts except for HTs and ETs. The benefit is dominantly attributed to the reduced airborne emissions from char combustion, together with a small portion of avoided emissions from fertilizer substitution and carbon sequestration. However, a non-negligible increase of the HTs and ETs loadings are observed due to the increased heavy metals to soil, which should be controlled effectively apart from the associated potential benefits of land application.

4. Discussions

Pyrolysis and gasification have been applied to waste treatment since 1970s, however their commercial application does not achieve widespread so far (Panepinto et al., 2015). One of the main impediments is the heterogeneity of MSW, i.e., inconstant on size and highly variable on composition, which could not easily run stable. Despite this challenge, after years of practical experience, the main technical difficulties seem to be solved and innovative plants started to be operated (Panepinto et al., 2015).

The theoretical analysis of this study shows that using pyrolysis/gasification to supply a gas turbine/CC may achieve higher energy efficiencies and lower emissions than the current incineration. However, its application has not yet overcome many obstacles. For example, the state-of-the-art syngas purification technologies do not achieve the required quality standards. Also running gas turbines require complex maintenance. These reasons have in fact caused a very limited application of the gas turbine/CC in pyrolysis/gasification-based WtE plants (Panepinto et al., 2015); while the most common configuration today is to burn the syngas in a steam boiler, namely, “two-step oxidation” (Consonni and Viganò, 2012).

In recent years, development of the pyrolysis/gasification-based WtE technologies has become a focus of attention, stimulated by the search for more efficient energy recovery and environmentally sustainable waste management. However, case studies results based on the current large-scale commercial plants reveal that the modern incineration could fulfill an environmentally sound technology, which performs better than the selected pyrolysis and gasification-melting plants. To be commercially successful, the pyrolysis/gasification-based WtE must develop the whole process chain (pre-treatment, thermal conversion, products utilization, residues management). Those potential areas of development could include:

1. Boost the plant efficiency. The superior performance of the Lahti gasification plant attains at its effective syngas cleaning, which facilitates increasing the steam parameters while avoiding the corrosion problem. It could serve as a demonstration for designing the next generation of WtE configuration. The overall energy efficiency could also be increased by the utilization of the CHP system, or syngas co-incineration in a higher efficiency power station.
2. Use of selected waste streams. Pyrolysis and gasification plants tend to require very careful feedstock pre-treatment. To be more effective, solutions could be the use of SRF, refuse derived fuel (RDF), or residuals from mechanical biological treatment (MBT) systems, which are more homogenous than the raw MSW.
3. Efficient residues management. Recycling materials from WtE solid residues, particularly metals and bottom ash, may result in two main benefits: a decrease in waste landfill; and, a reduction in the consumption of virgin raw materials. Pyrolysis plant could also consider the use of char in land application. The specific properties of bottom ash/char, in particular the leaching behaviour, should be carefully considered to ensure that the residues would not cause adverse environmental impacts.

Long-term potential areas of development could also attain at (Engineers, 2004):

1. Syngas purification and use in higher energy efficiency equipment such as a dedicated gas turbine/CC.
2. Further processing of syngas to be used as chemical feedstock, liquid fuels, etc.

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Appendix A. Supplementary data

Supplementary data to this article (detailed process description, data acquisition and calculation, inventory analysis, and the sensitivity analysis used in the LCA) are available in the online version, at <https://doi.org/10.1016/j.scitotenv.2018.01.151>.

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Review

Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management

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ABSTRACT

The role of smart technologies can become very important and useful to solve the main population issues nowadays and provide foundations for a sustainable future. A smart approach is an opportunity for knowledge integration, necessary to solve crucial problems of contemporary societies. Today, the main challenge is to reduce the effects of global warming and ensure a balanced economic development of society. The close collaboration of all involved engineering professions is mandatory to achieve interdisciplinary synergies and can bridge challenging engineering tasks. Intense research efforts should be directed towards balanced resource utilization, efficient energy conversion technologies, integration of renewable energy systems, effective approaches to enable circular economy framework, effective process integration as well as other issues important to the population. This review editorial is primarily focused on the contributions presented at the 3rd International Conference on Smart and Sustainable Technologies held in Split, Croatia, in 2018 (SpliTech2018). The SpliTech2018 conference was a multidisciplinary event with research topics related to the main conference tracks, i.e. Smart City/Environment, Energy, Engineering Modelling and e-Health. The strategic focus of the conference was to help solve crucial issues of our times, mainly related to the sustainability and smart utilisation of limited and valuable resources. This contribution brings new ideas and discusses present issues as well as challenges that should lead towards a sustainable future based on the application of the smart technologies. The herein addressed papers bring together latest research progress into four main topic areas: (i) Green Buildings, Energy Use and Consumption, (ii) Solar Energy Utilisation, (iii) Efficiency and Waste Elimination, (iv) Smart Cities and Internet of Things. The main results of this introduction review article include a discussion of different concepts and technologies that bring further development on a broad range of topics focused on efficiency improvement, smart and sustainable resource management, cleaner production concepts and on the discussion of the various actions which would lead towards a sustainable future.

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Contents

1. Introduction	566
1.1. The call for sustainability	566
1.2. The energy sector	566
1.3. Review methodology	569
2. Green Buildings, Energy Use and Consumption	570
3. Solar energy utilisation	573

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4. Efficiency and Waste Elimination
 5. Smart cities and the Internet of Things
 6. Concluding remarks
 Acknowledgments
 References
 Online reference

1. Introduction

1.1. The call for sustainability

Global greenhouse gas emissions are continuously growing on a global scale, Fig. 1 (Pbl.nl, 2018), where climate change issues are ever more present, causing severe impacts to the population (Xu et al., 2019a). Dominant emissions are ones related to CO₂ and 2018 was a record year of some sort since CO₂ emissions increased by about 2.7%, while in 2017 the increase was 1.6% (Globalcarbonproject, 2018). This recent trend in CO₂ emissions is obviously concerning (Fig. 2), especially when knowing that the CO₂ level was almost stable (IEA, 2017) in the period from 2015 to 2017. The present CO₂ level is more than 411 ppm (co2.earth, 2019), while for instance, it was below 400 ppm just five years ago. The more severe GHG is methane (CH₄), since it is almost 30 times more potent as a heat-trapping gas when compared to CO₂, (sciencedaily, 2014). Relatively large quantities of the CH₄ are being trapped in the ice sheets that are gradually released in the atmosphere by melting of the ice sheets due to climate change issues. The Paris climate agreement in 2016 by UNFCCC (United Nations b, 2018) was an important step for addressing this problem since policy makers showed a willingness to gather global efforts to combat climate change issues and to limit warming below 2 °C. It is more than clear that present actions are not sufficient and that resolute and timely actions are needed on a global scale to be able to achieve this goal and hence to reduce the harmful impacts of anthropogenic activities on the environment, (Wang et al., 2019a). In this line of approach, it is the necessity for sustainable development, which leads to the integration of efficient approaches that are based on the multidisciplinary knowledge, (Baleta et al., 2019).

Besides concerning the rise of CO₂ emissions, there is also a constant rise of other harmful pollutants such as N₂O emissions, CH₄ emissions, due to livestock, rice production, natural gas and oil production, synthetic fertilisers etc.

The general impact of population on the environment is obviously a complex one: problems related to plastic waste have become more severe lately, since there is strong evidence of their

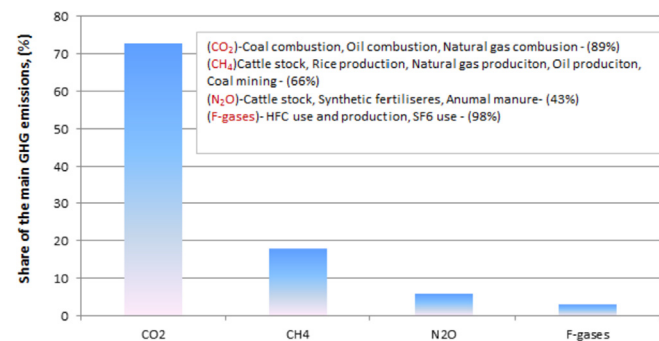


Fig. 1. Global greenhouse gas emissions, (Pbl.nl, 2018).

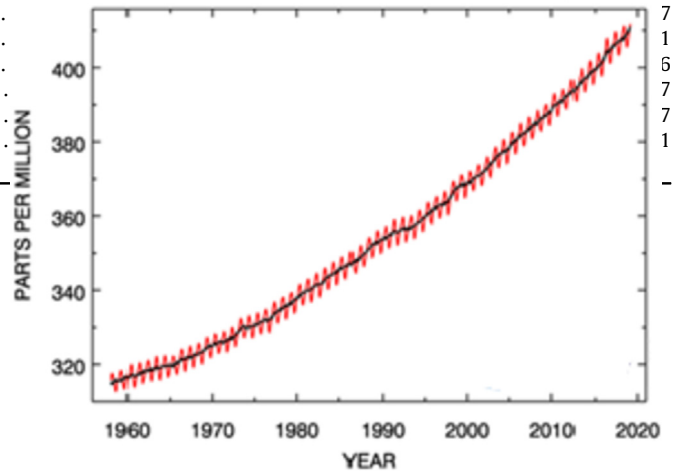


Fig. 2. CO₂ emission trend, (Noaa, 2019)

long-term unfavourable impacts on sensitive ecosystems, which is already monitored in the form of micro-plastic polluted oceans, with direct impact on the human food chain, Fig. 3 (Prata et al., 2019). In the case of the EU region, plastic waste is quite a serious issue, since the yearly quantity produced ranges from 10 kg per person to over 40 kg per person, with an EU average of about 31 kg per person, (Weforum, 2018). The main region which is critical with respect to the plastic waste issue is North Pacific, Fig. 3. Timely, targeted and efficient efforts are needed to prevent further plastic pollution (Ferreira, et al., 2019)

The major challenge related to the issue of plastics could become truly pressing by 2030 when China plans to ban the import of plastic waste, as China has been importing about 45% of the world's overall plastic waste since 1992 (cbc.ca, 2018). Joint efforts are needed, both technological and social; countries need to be able to adopt and shift from a "plastic based society", i.e. drastic changes in habits and perception would be required, (Nielsen et al., 2019).

Plastic pollution is one of the greatest challenges related to waste issues, but one of the major issues is the food waste problem (as well as food lost in production processes), which becomes increasingly emphasized by the general rise of the population that is mainly concentrated in cities. According to data from 2015, the annual global quantity of food waste ranges from about 95 to 115 kg/consumer in developed countries (data with excluded quantity of food waste from production processes), while 6–11 kg/consumer is expected to be waste annually in less developed parts of the world (Weforum, 2015), Fig. 4.

Food waste has a significant impact on sustainability and environment being currently accountable for more than 3 Gt/y of CO₂ emissions. It is estimated that about 28% of the world's agriculture area is already "utilized" for the production of wasted food. Once more, as it is being the case with plastic pollution, one of the mandatory goals is to raise public awareness, regarding food waste issue (Ellison et al., 2019) and to ensure technological advances to support and enable a food waste reduction (Principato et al., 2019).

1.2. The energy sector

Coming to the energy sector, present electricity production globally is still based to a large extent on fossil fuels, i.e. by more than 50% (Fig. 5 data based on IEA electricity information), mainly coal and natural gas. One of the main issues with existing fossil fuels energy systems is their conversion efficiency, which is relatively low, with a high rate of wasted thermal energy.

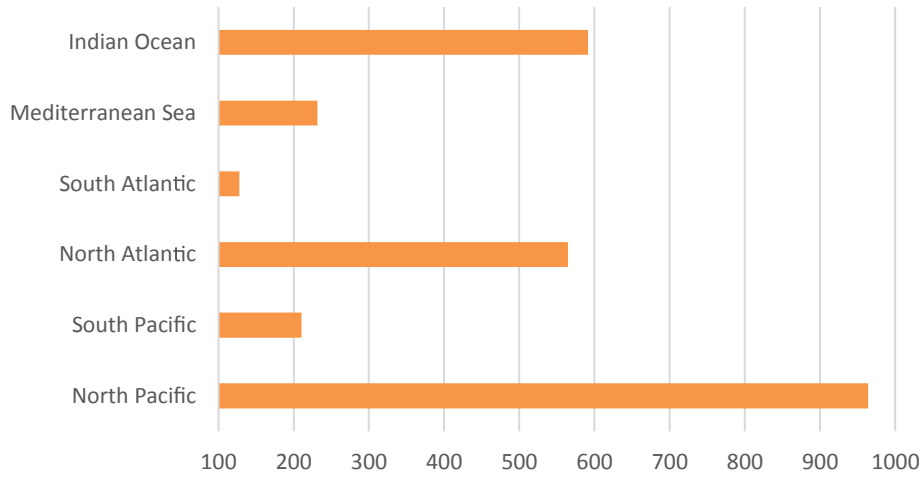


Fig. 3. Global distribution of plastic waste in World's Oceans in thousands of tons, (Weforum, 2018).

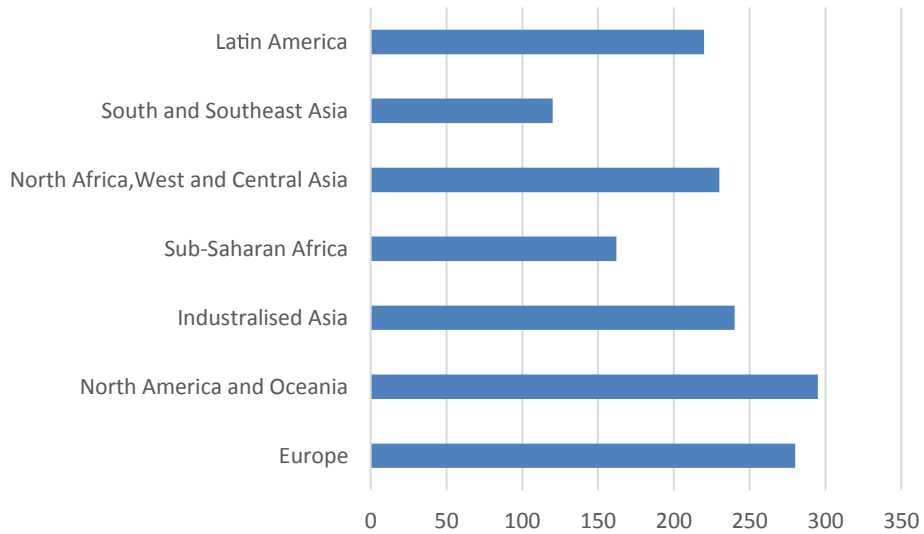


Fig. 4. Food losses and food waste per countries in kg/y, (Weforum, 2015).

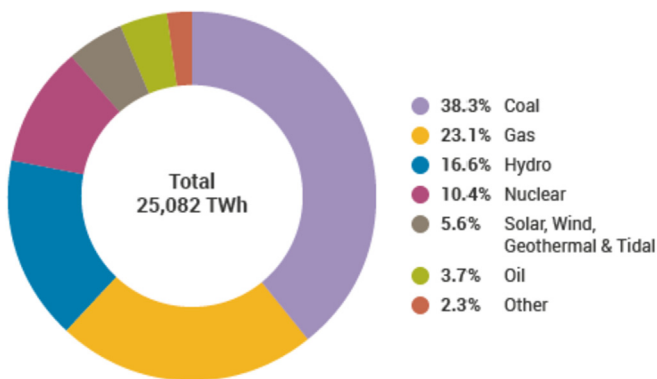


Fig. 5. Global electricity production from sources in 2016 (World-nuclear, 2019),

For coal-based power plants, it is reasonable to expect average energy conversion efficiency from 35% to 45%, the latter value for state-of-the-art plants, while for natural gas the efficiency can go up to 60% for combined cycle plants (worldenergy, 2014). Consequently, the operation of current fossil fuels based technologies is

followed with a high rate of released waste heat, about 60%–70% on average, and which by large is not properly utilised. The novel, i.e. more efficient energy concepts are necessary to provide more efficient utilisation of released waste heat, especially in industrial applications, (Brückner et al., 2015). The magnitude of total rejected energy is caused due to the limitations of the electricity generation technologies and the transmission and distribution of electricity (Flowcharts, 2019). Besides the development of cleaner transportation systems, (such as electric driven vehicles or even novel alternative transportation systems), more efficient engineering solutions are needed in the case of fossil-based engines with internal combustion, which one can reasonably expect that will continue to dominate the automotive market in the close future. The global picture regarding transportation is starting to change, especially in terms of globally sold electric cars, albeit at a slow pace, Fig. 6, (Reuters, 2018). China is planning to produce more than 600,000 electric buses by 2020, (sierraclub, 2018), so expected rise in the number of electric vehicles is almost exponential one.

Some countries have announced their will to ban diesel vehicles, especially equipped with older than Euro 4 norm diesel engine versions, (Reuters, 2018) and this decision already influenced the declined sales of diesel cars.

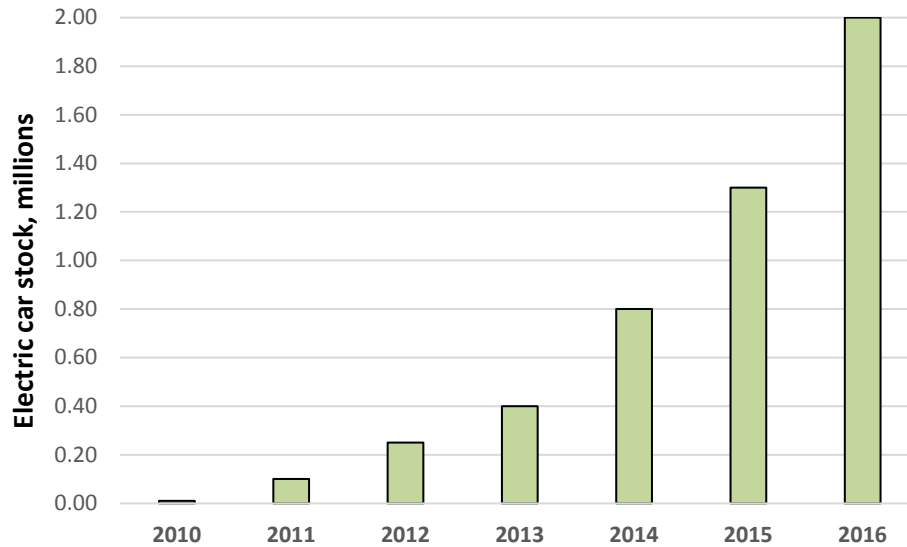


Fig. 6. Global sales of electric cars (Reuters, 2018).

Present renewable energy technologies offer a response to fossil options, albeit with limitations, primarily due to the still low energy conversion efficiency and the non-dispatch-ability of power generation. In the last decade, the market is dominated by photovoltaics (PV) and wind generators, which show a strong increase, while the capacities of big hydroelectric plants are rising at modest rates, as their potential has been utilised for decades now, especially in developed economies, Fig. 7. The overall contribution of the newly installed capacities in PVs and wind was 84% in 2018 (55% PVs and 29% wind), (Ren21, 2018).

The dominant problem with PV technologies is still the relatively high overall investment and their limited efficiency, although both have improved considerably in the last ten years. Nowadays, market available solar photovoltaic technologies are mainly silicon-based (about 95% of the market) with an energy conversion efficiency that usually ranges from 12% to 17% (Fraunhofer, 2019). The main current progress related to the development of new PV technologies is mainly expected in the area of organic and hybrid (organic-inorganic) Perovskite PVs, (Torabi et al., 2019), while other

PV technologies are still in the early stage research, i.e. not close to the market implementation. Electricity production from the existing wind generation technologies can ensure an average efficiency from about 35% to 45%, with an average wind capacity factor of 20%–40% (windeurope, 2018), depending from the specific type of wind farm (offshore or onshore). The main present issues with wind generation technologies are their relatively high overall investment cost, which is a major issue for widespread implementation in less developed economies, where transmission grids also need to be developed, and, like in all renewables, the problem of intermittency (Boemi et al., 2013). To enable the efficient utilisation of renewable energy technologies, the key feature besides technological advances of the technologies as such is to ensure sufficient transnational energy connectivity, i.e. transmission grids, and to do this along with the development of novel and more efficient energy storage technologies. It is in this context that the EU has recently announced a new energy connectivity strategy with the main emphasis being on how to efficiently ensure energy connectivity between the EU and Asia, (Eeas.europa, 2019). The

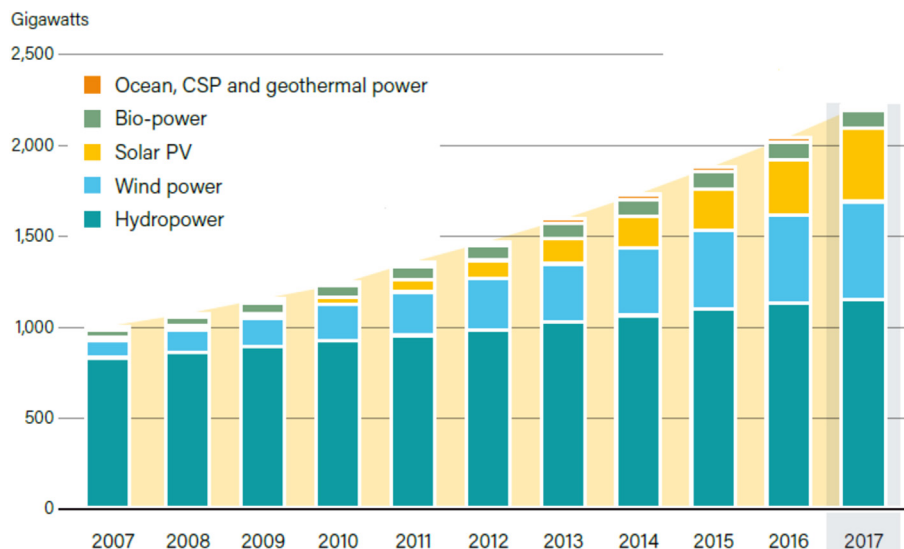


Fig. 7. Comparison of global renewable energy capacities (Ren21, 2018).

main EU energy connectivity target is to have an interconnection capacity of at least 15% between EU member countries, (Ec.europa, 2018). Global energy interconnection will remain one of the critical features to enable efficient penetration of renewables. Overall, solar PV and wind generation technologies are intensively progressing and will have a major role in the ongoing energy transition, (Irena, 2019). In this line of approach, the main goal of the energy transition is to ensure a safe and feasible pathway to shift from fossil-based economies to carbon-free economies, (Lee et al., 2018).

Further advances of existing energy storage technologies (flywheel, battery and thermal storage in general) are needed and especially in the case of lithium batteries, (Zhu et al., 2019). High demands are expected in global cumulative energy storage capacities, Fig. 8, considering the targeted shift to becoming a decarbonised society (i.e. to enable efficient intermittency of solar and wind technologies and to reduce transmission and distribution costs). According to the projections, approximately more than 900 GW of energy storage capacities will be needed by 2040, (About, 2018).

The main goals of novel or advanced existing energy storage technologies are to enable a reasonable duration (above 20 y, with significantly reduced degradation), acceptable unit cost and safety. It is interesting to note that, according to projections, only about 7% of assumed battery demands should be dedicated to stationary storage, while the unit prices of lithium and cobalt batteries will be affected due to the growing market of electric vehicles. On the other hand, the global rise in battery capacities will cause more intense environmental issues associated with battery technologies, (Tian et al., 2017), mainly in terms of usage of limited natural resources, photochemical pollution and acidification, the rise of CO₂ emissions, water pollution, ecotoxicity and recycling issues. The main challenges related to energy storage technologies will be directed to the overall improvement of their environmental suitability and cleaner production processes in general.

The rapid development of information technologies (IT) in recent years enabled a wide range of possibilities for a smart approach in various engineering applications such as the Smart City concept (O'Dwyer et al., 2019) and the implementation of Internet of Things (IoT) technologies (Srinidhi et al., 2019), which have recently become a hot topic in the research community. Based on a SCOPUS analysis, there is a significant rise in the number of research papers in the entioned topics, Fig. 9. In general, the sustainable aspect related to smart technologies is not sufficiently addressed by the research community concerning the individual research topics such as Smart City or IoT, Fig. 9.

The rapid urbanisation, with more than 50% of the global population already living in cities a figure that is expected to exceed 70% by 2050 (esa, 2014), intensifies all these problems, as the present infrastructure will not be able to bear the population pressure, especially when attempting to reach a sustainable

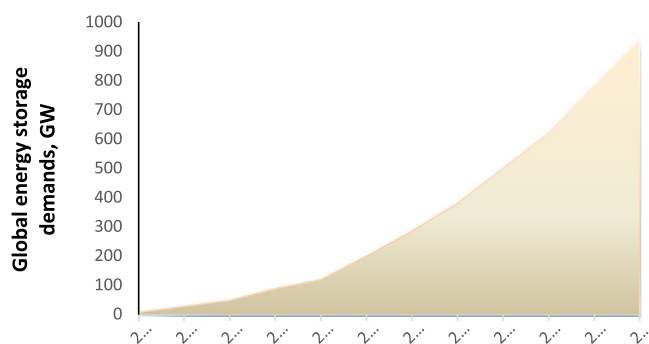


Fig. 8. Projection of global energy storage demands (About, 2018).

adaptation to novel circumstances. With the fast development of IT technologies, the Smart City concept could be a solution for cities, however coupled with the efficient application of IoT technologies. The fast development and implementation of smart technologies for various applications (Makate, 2019) is certainly opening new ways towards sustainability. In the long run it can cause environmental impacts that are still not sufficiently investigated. There is a steady, global rise in electronic waste, Fig. 10 (estimations are from 2017 to 2021) and the concerning fact is that only about 20% of globally produced electronic waste is being recycled (Collections, 2017). According to the latest projections the quantity of the electronic waste in 2050 would reach more than 120 million tonnes, (weforum, 2019). With the rapid development in the implementation of IoT technologies and smart concepts in general, and if no preventive actions are taken, this could cause serious sustainability issues and the demand arises for a smart and efficient electronic waste management (Ilankoon et al., 2018).

Benefits related to the implementation of smart technologies certainly exist and could be helpful to ensure further technological development, (Ismagilova et al., 2019). The cleaner aspect and general investigation of specific technological impacts on sustainability caused by the application of smart technologies need to be carefully checked to enable a balanced and sustainable progress of smart technologies.

1.3. Review methodology

Taking all these issues and challenges addressed into account, it becomes evident that major efforts in the research community should be focused, but not limited, on the following research topics;

- Further development of existing renewable energy technologies to become more economically viable, coupled with research of alternative and novel renewable-based energy technologies,
- Integration of renewable energy technologies in industrial applications as well as in buildings,
- Development of efficient energy storage technologies,
- More efficient utilisation of waste heat,
- Efficiency improvement of existing fossil-based energy conversion technologies,
- Development of cleaner transportation options especially in urban environments,
- Further progress in the efficient application of the circular economy concept and effective dealing with the plastic waste issues and efficient recycling technologies,
- Strategies to solve food-waste and electronic waste issues,
- Implementation of smart technologies as well as IoT technologies and investigation of their general impact on sustainability.

The main objective of this review editorial is to present and discuss the latest research findings and novelties in the field of smart technologies focused on efficiency improvement and effective utilisation of resources. It is serving as an introduction to the Virtual Special Issue (VSI) of JCLEPRO devoted to the 3rd International Conference on Smart and Sustainable Technologies (SpliTech2018) held on 26–29 June 2018 in Split, Croatia at the University of Split. A general methodology review will be elaborated and presented in the following sections.

The review conducted in this introduction editorial was focused on selected papers from the international conference SpliTech2018 and structurally divided into four main thematic areas (Green Buildings, Energy use and Consumption, Solar Energy Utilization, Efficiency and Waste Utilization and Smart Cities and Internet of Things). Besides the addressed selected and accepted VSI papers, each chapter has a brief introduction to the specific thematic areas,

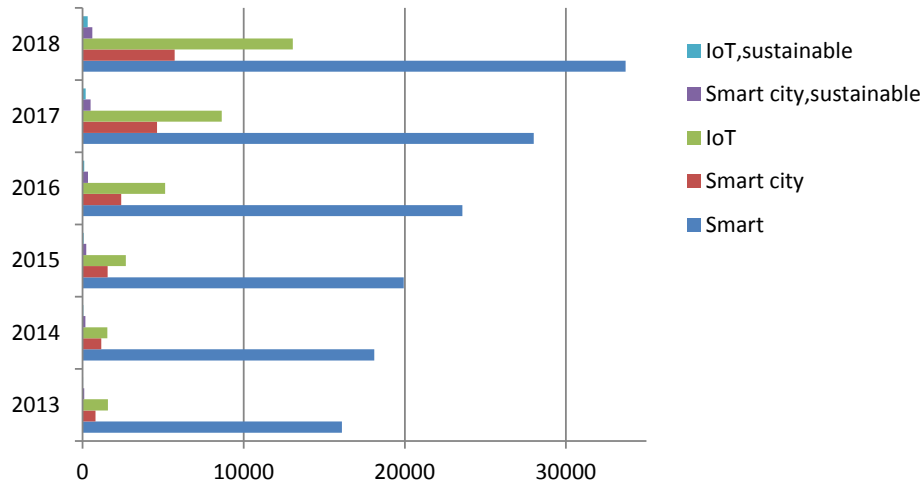


Fig. 9. Number of published papers in Scopus (Scopus, 2019), based on specific targeted keywords.

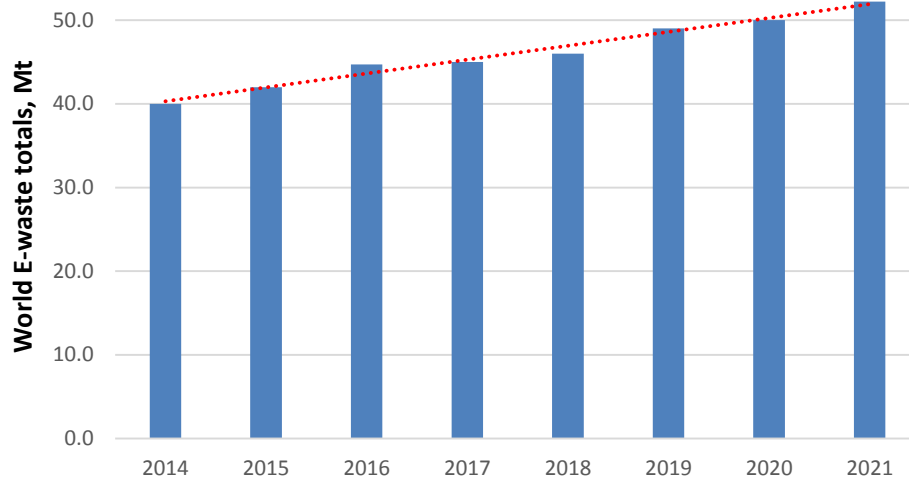


Fig. 10. Global rise of electronic waste, (Collections, 2017)

with the main current issues addressed in the field, together with relevant and latest references. Other contributions from the field have also been addressed as an addition to the selected Spli-Tech2018 papers published in JCLEPRO.

2. Green Buildings, Energy Use and Consumption

Buildings are responsible for about 40% (eia.gov, 2018) of the overall end-use energy consumption and have a higher share when compared to other global end-use energy sectors (industry and transportation), Fig. 11. The residential building sector usually consumes more energy than the commercial sector. Most of the energy demands in the residential sector are related to space heating and hot water preparation, while it is primarily HVAC systems and lighting in the commercial sector.

Buildings are identified as severe pollutants with a share of CO₂ emissions ranging from 30% to 40%, (Xilong et al., ' 2015), depending on the specific economy. Besides CO₂ emissions, buildings are also responsible for other impacts on the environment, mostly air and water-based pollution caused by cement plants, (Raffetti et al., ' 2019). According to the projections of heating, cooling and hot water preparation demands, a rising trend is expected and mainly in the residential sector, (Urge-Vorsatz et al.,

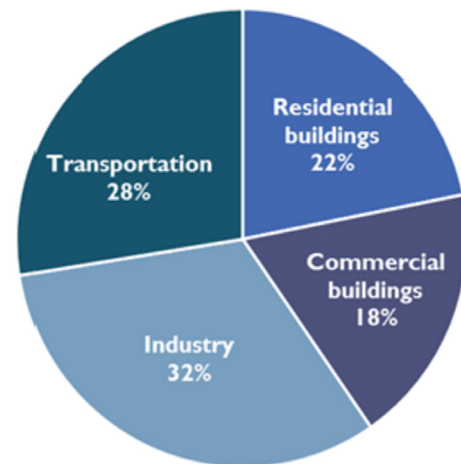


Fig. 11. Total energy consumption by end use for buildings with respect to other energy consumption sectors, (Bcapcodes, 2017)

2015), Fig. 12. The residential sector will be especially affected with a significant rise in cooling demands due to global warming issues in upcoming years, (Jakubcionis and Carlsson, 2017).

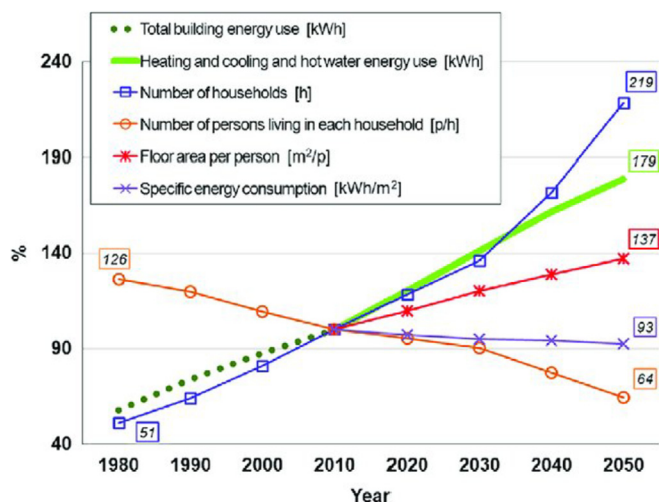


Fig. 12. Heating and cooling trends in buildings (Ürge-Vorsatz et al., 2015).

The introduction of the Nearly Zero Energy Buildings (NZEB) concept (Harkouss et al., 2018) could be a proper response to restraining energy consumption in buildings concerning the previously addressed future projections. According to the Energy Performance of Buildings Directive (EPBD), all new buildings in the EU will need to be NZEB by the end of 2020, (Ec.europa, 2019). The previous goal is challenging and will require significant research efforts to bring novel technological solutions that will help countries to adapt to the new building standards and implementation strategies in reasonable time, (Asaee et al., 2019). One of the major issues related to NZEB or passive buildings is related to air-quality (Poppendieck et al., 2015) concerning the general airtightness of high-performance buildings, (Feijó-Muñoz et al., 2019). Effective ventilation strategies strongly depend on the specific climate circumstances as well as general building characteristics. More research efforts are needed to analyse effective ventilation strategies for high-performance buildings in different climates, (Grigoropoulos et al., 2017). The building envelope performance is a critical feature to reach the expected NZEB standard and to reduce overall heating/cooling demands. Novel strategies are needed to discover cost-optimal solutions in different climates, i.e. to enable the optimal design of NZEB buildings for various types of buildings, (Sankelo et al., 2019). From the previous aspect, the development and consideration of novel building envelope materials should be further provided to discover effective and economically viable solutions, (Huang et al., 2019a). An important aspect in the general NZEB building design is to ensure the efficient implementation of renewable energy technologies through different hybrid energy solutions, (Nizetić and Čoko, 2014). The residential sector in cities and densely populated areas (condominium building facilities) is demanding and challenging to reach the high penetration of renewables due to physical limitations, so efficient technologies followed by proper supportive policies are necessary to reach NZEB target, (McElroy and Rosenow, 2019).

The use of highly efficient renewable energy systems, smartly integrated into urban buildings, can significantly contribute towards net positive energy buildings, which should be the mainstay of 21st-century prosumers, blurring the line between 20th century energy consumers and producers (Baljit et al., 2016). This new role, however, should be coupled with new, ambivalent, smart electricity distribution grids and smart metering systems, (Shukla et al., 2019). In general, the encouragement of Energy efficiency measures in buildings is a valuable opportunity for economies, both to generally

reduce energy demands and help to generate green-related jobs, (Alreshidi, 2018). Present energy efficiency measures in buildings are primarily focused on constructional building elements (building envelope, openings, thermal bridges issue) as a logical path to reduce general building energy demands, but not limited to other important technological solutions in buildings that needs to be explored. The following sections of this review editorial are related to the latest advancements within this specific thematic topical area.

Automatization in district heating systems (Guelpa et al., 2019) is very important since it enables sensible improvement in energy efficiency and in general efficient automatization is nowadays one of the main goals in different energy-related sectors. In the conducted study (Lazarevic et al., 2019), a novel mathematical model was proposed and followed by a developed numerical simulation model using LabVIEW. The developed simulation model enabled accurate and precise monitoring of the heat substation operation. The main advantage of the developed model is in its possibility to be applied on actual heating systems with the possibility to enable efficient control strategies, i.e. to enable further optimization of the overall system performance (model can be used for fault detection and diagnosis of heat substations based on real data). The development of Efficient building energy modelling (BEM) tools is valuable (Farzaneh et al., 2019), since there is a gap between measured and predicted energy demands in buildings, Fig. 13. Mentioned gap depends on the age of the specific building facility, i.e. from the building standards, (Yan et al., 2015). Occupant impact, i.e. behaviour is the most demanding feature that significantly contributes to the mentioned gap between the designed (predicted) and measures building energy performance. Occupant monitoring and then the development of novel models, incorporated in the building simulation tools, are still challenging research tasks with considerable space for improvement, (Mun et al., 2019).

As already addressed, an essential aspect in buildings is indoor air quality as well as the reach of proper thermal comfort conditions, which become emphasised especially in the case of nearly zero energy buildings NZEB (Liu et al., 2019). A review related to the indoor air quality, with respect to human health and productivity, was obtained in (Mujan et al., 2019) with reported latest research findings addressed in the existing literature. The previously mentioned study addressed different influential factors that can be

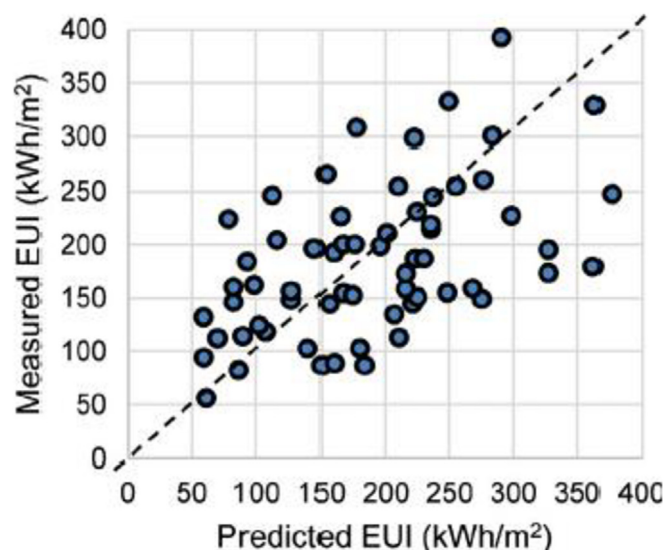


Fig. 13. Gap between measured and predicted building energy demands, (Yan et al., 2015).

measured and controlled, and that affect indoor air quality, i.e. finally human productivity. Different challenges were discussed, as well as further necessary research efforts to ensure minimum requirements and a healthy environment in buildings. General ventilation approaches regarding NZEB buildings were discussed in (Medved et al., 2019) where major driver for the future development of ventilation systems would be through assumed building thermal mass utilization in different periods of the year. With the involvement of novel constructional materials in buildings and different coatings, different indoor emission sources are being enabled, and that can have harmful effects on human health in closed building environments. Risk exposure to different indoor aerosols was reported in (Koivisto et al., 2019), where all influential parameters related to specific indoor emissions were detected and discussed systematically.

The preparation of domestic hot water (DHW) requires noticeable energy demands together with space heating, Fig. 14. With respect to the general energy efficiency targets in building stocks, an important feature is to investigate the opportunities that can lead to the energy efficiency improvement of DHW systems (Dahash et al., 2019). Besides space heating demands, water heating demands play a significant role in the case of residential building facilities. More efficient utilization, as well as the development of novel hot water preparation systems (Lyu et al., 2019), should be delivered in the future research efforts.

Experimental, i.e. field investigation on multifamily buildings was reported in (Tomasz et al., 2019) and focused on effective and low-cost methods to reduce heat consumption in present domestic hot water systems. Based on the conducted field study (long term measurements), and depending from the type of specific building facilities, the detected share of heat losses in the overall heat consumption ranged from about 56% to 70%, and associated with the DHW preparation systems, Fig. 15.

With the proposal of specific measures in DHW preparation systems, the calculated energy savings ranged from 6% to almost 50%, depending on the specific group of objects and assumed energy efficiency measures. According to the results of the previously addressed latest research study, potential for energy savings in DHW systems is obvious and actions should be directed in a systematic and policy-based manner for the encouragement of energy efficiency measures in DHW systems.

An efficient building envelope is a critical feature towards NZEB and high-performance buildings, however, besides the convective building envelope, novel and innovative solutions are needed to be able to reach the NZEB standard as already addressed. The integration of vegetation in architectural buildings, as green walls, represents an approach that can bring specific benefits to the effective temperature balance of the walls. An experimental study

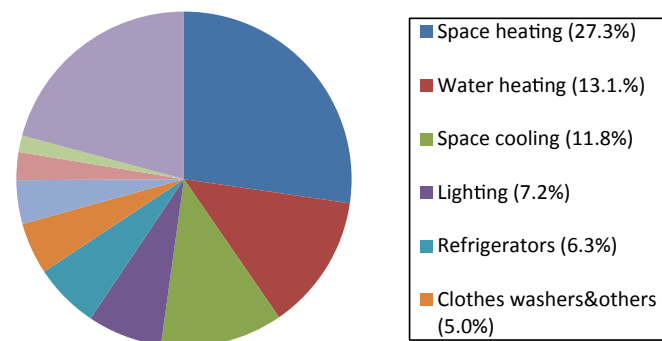


Fig. 14. Average structure of residential building energy use for USA in 2015, (needtoknow, 2019).

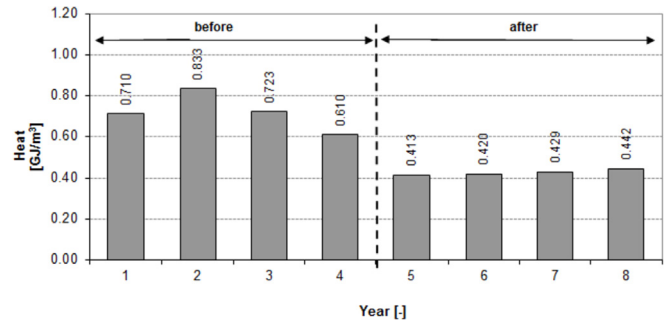


Fig. 15. Comparison of DHW heating demands before and after application of energy efficiency measures (Tomasz et al., 2019).

with assumed green walls was conducted for Belgrade climate conditions, together with theoretical analysis, (Sudimac et al., 2019). The application of vegetation (Fig. 16) was associated with the reduction of external surface wall temperatures ranging from 0.5 °C to 14 °C, depending on the specific period of the year.

According to the authors, the main potential of green walls is the enabled passive cooling of the building walls and future investigations should be intensified in that direction. A novel nano-composite phase-change material for potential application in buildings was elaborated in (Putra et al., 2019). Beeswax/multi-walled carbon nanotubes were considered, and experimental results proved that the thermal conductivity of the novel material was increased to factor 2 with proved high heat storage capability. Massive application of wooden materials in the case of multi-storey building facilities was analysed by (Bruno et al., 2019). The design requirements were discussed in the previous study to reach the NZEB standard in Mediterranean climate conditions. The structural safety of wooden elements was also analysed with a precise provided layout of cross laminated timber panels. The concept of novel super insulating panels/systems, based on silica aerogels, was elaborated in (Ibrahim et al., 2019) with potential for building application. The proposed novel building thermal insulation system was experimentally tested and based on the measured data the U-value was significantly reduced (from 0.66 W/m²K to 0.33 W/m²K) and the novel material showed reasonable resistance to wall moisture risks.



Fig. 16. A segment of green wall examined in (Sudimac et al., 2019).

The effect of thermal bridges is noticeable in the case of new buildings due to strict imposed regulations related to the general performance of the building envelope and due to specific building design, (Danza et al., 2018). An analysis of different thermal bridge scenarios was obtained in (Theodosiou et al., 2019), where the detected portion of heat flows due to thermal bridges, was more than 25% in the case of the analysed advanced cladding systems. The cause for the relatively high impact of thermal bridges is due to the overlook of basic energy efficiency parameters. The study revealed that the oversimplification of regulations and finally underestimation of thermal insulation protection is most influential. The impact of brackets in double skin façades were found to be crucial due to intense heat flows, Fig. 17, so thermal brakes within the bracket body are suggested.

To enable an efficient improvement of advanced façade systems, an integrated approach is required, with imposed innovated technical characteristics that are beyond existing building codes, (Papadopoulos, 2016). Aerogel-enhanced blankets were analysed in (Berardi and Ákos, 2019) as a potential technology to reduce thermal bridging effects in building applications. Laboratory investigations revealed that the considered silica Aerogel-enhanced blanket could be an effective solution for the reduction of heat losses caused by thermal bridges. The economic aspect was not addressed in the previous study which is a critical feature, and that needs to be further discussed. Novel mathematical tools were elaborated in (Sferra et al., 2019) for the efficient detection of thermal bridges in buildings. The novel developed multiscale data analysis method (Iterative Filtering- IF) allows efficient detection and optimisation of thermal bridges. A few case studies were discussed where the developed mathematical tool was applied for the detection and analysis of thermal bridges. The thermal behaviours of the five patented slab front (slab-façade) concepts were discussed in (Bienvenido-Huertas et al., 2018). The gained results showed that linear thermal transmittance could be significantly reduced for the analysed cases. It was also detected that with the

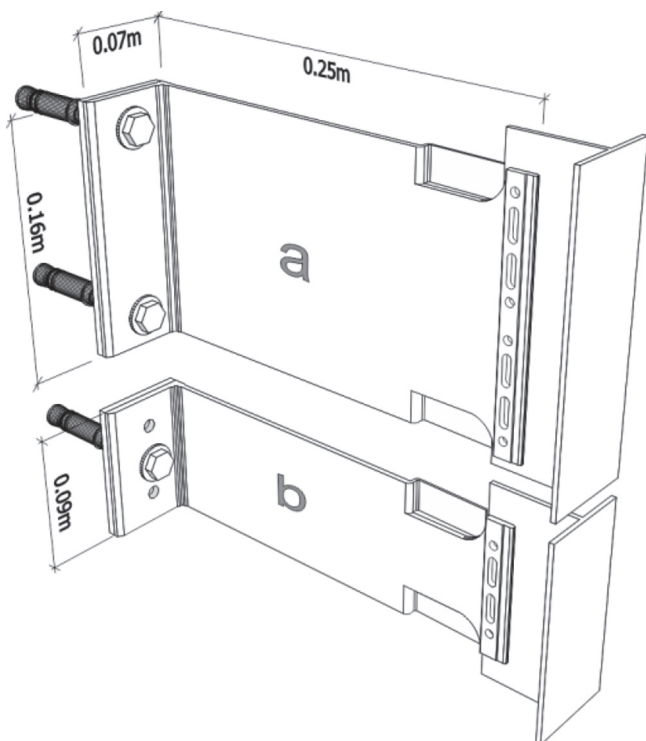


Fig. 17. Examined bracket geometry (Theodosiou et al., 2019).

examined patented solutions, it was possible to reduce heating demands by more than 18% and cooling demands by almost 3.0%.

The thread that runs through the conclusions of recent papers linked with the herein considered thematic area is that there is a bi-directional relationship between the political, regulatory and socioeconomic developments and general progress is evident in the field of building systems and materials, (Pezeshki et al., 2019). The ever-stricter regulation acts as the driving forces for the development of effective insulating materials (Tetty et al., 2019), airtight buildings (Tanyer et al., 2018) and smart façades (Juaristi et al., 2018). It is also important address the importance of Micro-CHP, high performance HVAC systems, smart-grids and predictive BACS systems (Building Automation and Control Systems). It is the availability of these building elements and materials that enable the implementation of ambitious and innovative designs towards efficient and high-performance buildings (Nizetić et al., 2017a). The main progress in this field should be directed towards a more efficient and economically viable integration of existing renewable energy technologies in buildings and more efficient demands side management. Buildings should become energy producers and the opportunity to reach a balanced energy infrastructure in cities that are continuously developing, becoming more demanding from an infrastructure point of view. Progress could only be made with the close collaboration of all engineering disciplines that are involved in the general building sector.

3. Solar energy utilisation

Solar energy utilisation is nowadays focused on electricity production from photovoltaic (PV) technologies (Schmidt et al., 2018) or heat production from various solar-thermal systems (Sakhaei and Valipour, 2019). There are also integrated photovoltaic-thermal PV/T systems (Jia et al., 2019), that are capable of producing both thermal energy output as well as electricity, however, currently less market attractive due to a relatively high overall investment cost. The global growth of installed PV capacities reached more than 100 GW in 2018, where the dominant market leader has been China with 47% of overall installed PV capacities in 2018 and the largest producer of PVs, Fig. 18, (Genentech Media, 2018).

The main technical barriers of market available PV technologies were already addressed in the introduction section. There are significant research efforts to enable more efficient and novel PV technologies such as perovskite (Torabi et al., 2019), organic (Senthil and Yuvaraj, 2019), or ones with the assumed application of nano-technologies (Brekke et al., 2018), such as nanopillar solar

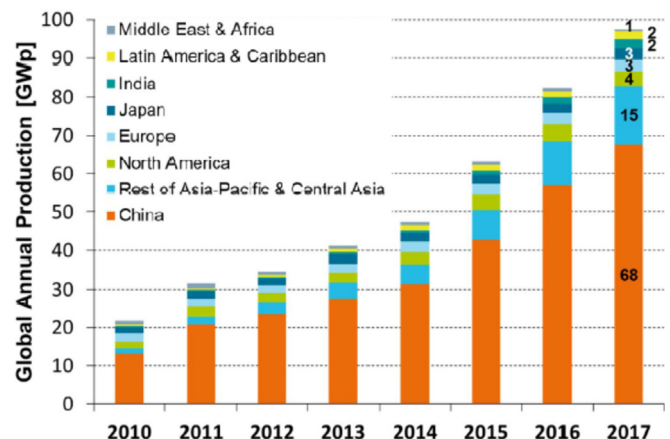


Fig. 18. Global annual production of PVs (Fraunhofer, 2019).

cells (Youngjo et al., 2017). The previously mentioned novel PV technologies are still not ready for an expected wide market application, due to present technical shortcomings and unfavourable economic viability. Among the most promising ones are Perovskite PV technologies (in metal halide variant). According to the latest research findings, they could reach a relatively high energy conversion efficiency (over 20%), with LCOE (Levelized Cost of Electricity) ranging from 4.93 to 7.90 USD cents/kW, (Song et al., 2017). However, they are still open technical issues regarding the stability of Perovskite PV cells long term (i.e. their lifetime), the applicability of technology for large scale PV systems and environmental impacts due to the use of organic solvents. Discussion on all current technological issues related to Perovskite PV technologies can be found in (Djurišić et al., 2017). If those technical deficiencies are solved in the near future, Perovskite PV cells become the cheapest PV power generation technology on the market.

Other present research efforts are more focused on the development of existing market available PV technologies (silicon-based PVs) or associated systems and components (further simplification of production processes, reduction of material waste, efficiency increase, etc.). There are also other technical issues related to widely available silicon-based PV technologies, such as efficiency degradation due to elevated operating temperatures (Grubišić-Cabo et al., 2016) or accumulated dust and its general impact on electricity production (Cen et al., 2018). Moreover, in some countries, there are also legislative issues, which discourage a wider implementation of PVs, (Talavera et al., 2016). Besides all the previously mentioned issues, silicon-based PV technologies have stable growth on an annual basis and are becoming a dominant renewable energy electricity source.

The development of hybrid energy systems could be an effective solution for the integration of various market available renewable energy technologies based on the utilisation of solar energy. Recent research findings are focused on the investigation of different hybrid energy options for residential applications (Bartolucci et al., 2019a), or other applications. An energy management strategy for the improvement of the control strategy in the case of hybrid renewable energy systems for residential applications was elaborated in (Bartolucci et al., 2019b). The novel control strategy allowed correlation between real-time field data and historical consumption data, which enabled a reduction in the energy to unbalance as well as operational costs. The increased implementation of electric vehicles in urban environments requires the investigation of different scenarios where hybrid energy systems could play an important role. A framework for the optimal planning of renewables with actual electric loads was analysed in (Bagheri et al., 2019) to reach low-carbon communities. The main results of the obtained study are reflected through the development of effective policies for the integration of hybrid and renewable based energy systems in urban environments. The electrification of Sub-Saharan Africa with the application of PV/hybrid mini-grids was elaborated in (Moner-Girona et al., 2018). Based on the conducted review, it was found that mini-grids represent an effective option for the development of viable business models. The main issue is detected a quality gap between existing business models and ones related to the effective implementation of PV/hybrid projects. The investigation of energy mix (photovoltaic-wind-diesel hybrid system) was addressed in (Ferrari et al., 2018) for the case of remote off-grid applications in Italy. The gained results revealed that it is possible to achieve economic and environmental benefits with the proper optimisation of the hybrid energy system for remote consumers.

The integration of electric vehicles (EV) was addressed in (Coffman et al., 2017) with respect to residential PV systems. The study revealed that EV subsidies need to be considered on a

regional level and that the implementation of EVs is a rather costly option for the reduction of CO₂ emissions in Hawaii case. A policy review related to solar PV systems as well as an economic analysis of On-grid PV systems was addressed in (Hassan et al., 2019a) for residential facilities in the Philippines. The obtained analysis showed that the most attractive one was a 100 kW PV system with a cost-benefit ratio of 4.17 and a simple payback period of about 4.0 y. The current policy related to PV systems in the Philippines could be improved with the introduction of the additional supporting mechanisms were discussed in the same study.

The efficiency improvement of market available PV systems and their components leads to higher installed PV capacities on a global scale. The efficiency increase of PV systems could be reached with proper maximum power point (MPPT) strategies and different control approaches that have been intensively investigated in recent years, (Mohapatra et al., 2017). A new algorithm related to a novel bio-inspired optimisation method, named memetic salp swarm algorithm (MSSA) was proposed in (Yang et al., 2019a). The developed MSSA is primarily applicable for the efficient tracking of maximum power point for photovoltaics. Four different cases were studied for Hong Kong climate conditions. The gained response from the MPPT system was compared with eight different MPPT algorithms (incremental conductance, genetic algorithm, particle swarm optimisation, etc.). The gained results showed that the proposed MSSA algorithm is more effective when compared to other MPPT strategies (the system can produce more electricity with less emphasised power fluctuations). Future research work will be focused on the application of the proposed algorithm on real PV panels, i.e., to check its suitability in realistic circumstances. A novel maximum power tracking (MPPT) algorithm for PVs was proposed and elaborated in (Grgić et al., 2019). The main difference in the proposed approach, when compared to conventional ones, is that it does not require a PV array current measurement, and excludes oscillation around the MPPT (which is often used in standard MPPT approaches). A simulation model was developed to determine the impact of the different operating conditions on the overall system performance. The model was applied to various possible operating conditions, and the results showed to be approximately 7% more efficient when compared to other MPPT control approaches (with respect to nominal power). A wind-driven optimization algorithm for PVs operating under non-uniform solar conditions was discussed in (Abdalla et al., 2019). The Wind-Driven Optimization algorithm was applied, and results showed that the applied approach ensured a more effective optimisation tool when compared to the other convectional MPPT optimisation strategies (such as particle swarm optimisation, differential evolution, harmony search algorithm, etc.). A novel three-layer voltage/var control strategy (VVC) for the coordination of VVC devices in the case of PV clusters was addressed in (Li et al., 2019a,b). The proposed control strategy enables the monitoring of voltage deviations as well as system voltage stability. A central approach was applied on two layers, and the model showed to be an effective tool for the control of the PV cluster. Voltage was provided in the safe range which can improve the complete voltage stability of PV cluster in general.

A critical practical feature associated with the application of PV systems is the effect of the accumulated dust and its impact on PV panel performance (Gürtürk et al., 2018). Different cleaning approaches were widely analysed and discussed in recent research studies as efficient approaches to replace expensive labour based cleaning that also consumes relatively large water quantities. A novel concept of cleaning robots for PV panels was presented in (Shibo et al., 2019). The proposed autonomous robot solution, Fig. 19, can clean PV panels in an effective manner and an experimental approach was conducted to detect real performance, while

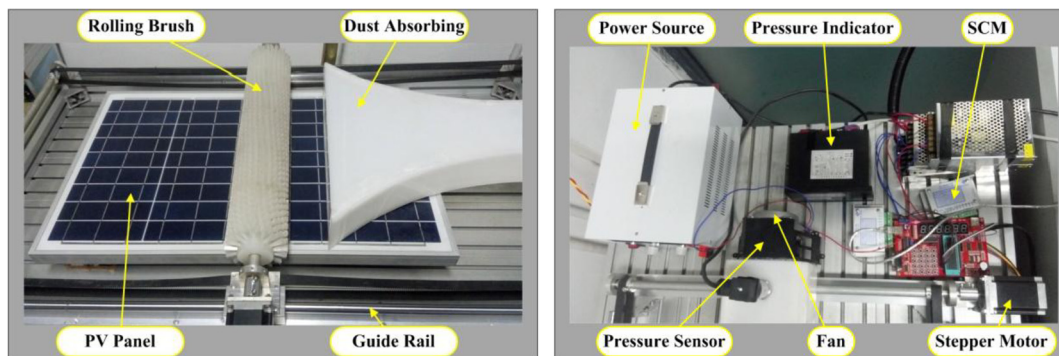


Fig. 19. Experimental setup of cleaning robot with signal collecting module (Shibo et al., 2019)

CFD model was also developed to optimise structural parameters. Influential parameters regarding system performance were analysed and discussed with defined optimal values related to the inlet width and height, outlet width and height and necking radius.

An experimental approach focused to the cleaning of large solar PV plants in desert climates was reported in (Al-Housani et al., 2019). Autonomous drone cleaning was considered with microfiber based-cloth wipers, and the results showed efficiency improvement due to the provided cleaning from 3.1% to 7.7%, depending on the specific period of the year. Automated, robotic dry-cleaning of PV panels was discussed in (Parrott et al., 2018) for Saudi Arabian climate conditions. A silicon rubber brush was applied as a cleaning strategy, and the study generally revealed that robotic cleaning reduced unfavourable dust effects and increased PV panel power output. The main advantage of the proposed cleaning approach is its low cost and excluded damage of PV panel front surface. A novel portable robot solution design for the cleaning of photovoltaic systems was presented in (Al Baloushi et al., 2018), targeted for applications in desert areas. Based on the field results, the cleaning system was able to ensure an increase in PV system efficiency with a reduced quantity of wasted water (and less labour cost). Water free and automated cleaning solution for PVs was proposed in (Deb and Brahmhatt, 2018). The technical specifications of the automated cleaning system were reported together with a conducted review related to soiling prevention methods.

Photovoltaic-thermal (PV/T) systems, Fig. 20 are attractive from a technical point of view since they can produce both electricity and thermal output from available solar irradiation. The PV/T systems

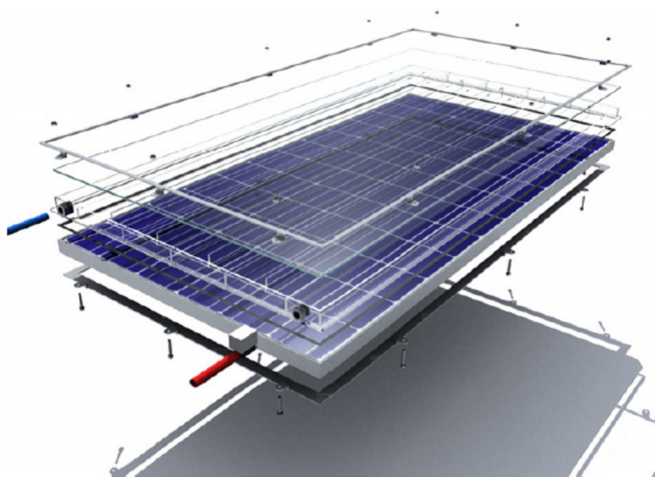


Fig. 20. Example of specific PV/T design (Rosa Clot et al., 2011),

are combined with a sort of thermal energy storage to improve overall system efficiency. PV/T systems are especially interesting for potential integration in hybrid energy systems regarding different applications. As already addressed, a critical feature of the PV/T systems is their high initial unit costs and further development of photovoltaic-thermal (PV/T) systems is necessary to improve overall system efficiency and reduce unit costs, (Jia et al., 2019). From the previous point of view, different PV/T configurations have been recently investigated and mainly focused on the techno-economic aspect.

A comparison of PV/T systems was analyzed and discussed in (Gagliano et al., 2019) in the case when PV/T systems were compared with the PV plant with an incorporated solar thermal storage (PV + ST). The study was conducted for different geographical locations in the EU region (Catania, Split and Freiburg). The energy analysis was focused on residential buildings and conducted using the TRNSYS simulation tool. Different scenarios are being simulated, together with addressed economic aspect. The results revealed that overall the PV/T plant could produce more total energy when compared to a single PV system for all the considered locations. A PV/T plant can gain higher total energy production when compared to the best PV + ST configuration. It was also possible to achieve a reduction in primary energy consumption with the application of the PV/T plant. The economic analysis showed that the PV/T configuration is economically viable, but only for the locations of Catania and Freiburg, while for the location of Split, the cheap energy cost affects the overall economy. However, the conclusion is that the PV/T configuration is a generally more effective solution when compared to the examined PV + ST configuration for the analysed geographical locations. An experimental study of a hybrid PV/T system (attached water cooling system on the backside surface of PV panel) was discussed in (Salem Ahmed et al., 2019) for Egyptian climate conditions. The average efficiency of the PV panel was higher for about 8% when compared to the non-cooled PV panel, while the maximal overall system efficiency ranged from 68% to 74%. A micro PV/T system was proposed for operation in moderate climates with a provided experimental study in the location of Pataras, Greece (Bigorajski and Chwieduk, 2019). A simulation model was developed, and the energy performance of the system was checked. The system was only tested in December and January, so one of the main open issues is the potential overheating issue in summer months (and which was not tested). A modular PV/T façade technology was compared with flat integrated collector storage (ICS) in (Smyth et al., 2019). Hybrid PV/T façade technology can be used for space heating, hot water preparation and electricity generation. The proposed hybrid technology is suitable for building retrofit applications. The experimental results revealed that the thermal

efficiency was higher in the case of the ICS technology in the amount of 5%–10% when compared with the hybrid technology. When the produced electricity from the hybrid PV/T system was included, then the overall system efficiencies were equal. An energy, exergy and economic analysis of two sides serpentine flow based PV/T systems with the application of phase change materials (PCM) were elaborated in (Hossain et al., 2019a). According to the experimental results, the maximal thermal efficiency of the examined system almost reached 88%, while the maximal electric efficiency was around 12% (efficiency of single PV panel was about 7%). An economic analysis was also conducted to examine the feasibility of the proposed PV/T-PCM system. A hybrid PV/T system with Nano fluid as working fluid (water-based Multi Walls Carbon Nano Tubes) was elaborated in a reported study (Abdallah et al., 2019). The addition of nano-particles caused the improvement of thermal properties and electrical efficiency of the hybrid PV/T system. The highest overall system efficiency reached about 83% with a nano-particle volume concentration of 0.0075%. The average efficiency of the system was over 61% with an average reduction in the operating temperature of the system of about 10 °C.

As previously mentioned, one of the critical issues related to the practical application of PVs is the present efficiency degradation due to elevated operating temperatures. Different cooling strategies for PVs have been investigated in recent years that can either be passive (Nizetić et al., 2017b) or active one (Nizetić et al., 2018a,b). The main target of the examined cooling methods was related to the efficiency improvement of existing PV systems in different applications (building integrated PVs-BIPB, concentration PVs – CPV, etc.). A novel thermal management system for concentrated PV systems (CPV) was presented and elaborated in (Manikandana et al., 2019). The proposed cooling concept for the CPV system assumes the application of phase change materials (PCM), applied on the backside surface of the PV panel, Fig. 21. A numerical simulation model was developed using COMSOL Multiphysics software. The gained results showed that it is possible to reduce the operating temperature of the PV panel by more than

20 °C, with an increase of over 20% in PV panel output (when compared to non-cooled PV panel). The thickness of the PCM layer was found to be a critical feature for system performance. An economic aspect of the proposed concept was not discussed in the study, and an experimental approach is needed to determine the economic viability of the proposed cooling configuration.

In the case of concentrating CPV energy conversion technologies, the main technical barrier is the fact that incoming energy being dissipated as heat in an amount about 60% and different cooling strategies were investigated to make CPV systems more economically viable. A passively cooled hybrid thermoelectric generator-concentrator for CPV systems was addressed in (Rodrigo et al., 2019). The modelling for a CPV system with thermoelectric cooling was obtained from a performance and economic point of view. Optimal solutions were analysed to ensure the cost reduction of the considered CPV system through efficiency improvement. A sensitivity analysis of the main influential parameters was done to detect the trade-off between efficiency and cost reduction. The gained results are very useful as a guideline for the development of novel and more efficient CPV prototypes.

A transmissive microfluidic active cooling system for CPV application was proposed and discussed in (Islam et al., 2019). Configuration consisted of several parallel micro-channels attached on the CPV module. Total transmittance of the CPV was reduced for about 5%, which caused a reduction of the peak cell temperature. Economic aspect was not addressed and which should be a step further. General performance analysis of passive radiative cooling methods for PVs was elaborated in (Li et al., 2019a,b). It was found that with an elective spectral, passive radiative and combined cooling, an increase in energy conversion efficiency could be achieved from 0.98% to 4.55%. The passive cooling potential was analysed for different regions in China where it was found that the efficiency improvement ranged from 2% to 2.5%, depending from the specific geographical location. LCOE analysis was also obtained to explore the economic viability of the proposed concepts. The proposed design allowed total transmittance reduction for the CPV modules by 5.2%. The addition of active cooling micro-channels turned out to be an effective design solution. The application of a microchannel heat sink with nanofluid as coolant was reported in (Radwan and Ahmed, 2018) for CPV applications. A three-dimensional model was developed and validated with experimental data for Egyptian climate conditions. It was found that the increase of the nanoparticle volume fraction ratio significantly reduces the cell operating temperature and improves cell efficiency. The reduction in maximal solar cell temperature ranged from 3 °C to 8 °C when compared with water. However, the economic aspect of the proposed solution was not discussed as it was the case in other studies. An investigation of pork-fat as a novel PCM material for PV-PCM cooling was elaborated in (Nizetić et al., 2018a,b). The study revealed that pork fat could be a viable PCM material regarding thermal properties and a simulation study was conducted for two cities in Turkey through the developed numerical model. The main issue is the long-term stability of the pork fat physical properties. Since pork fat has significantly lower unit costs when compared to other conventionally applied PCM materials, investigations towards that direction are worthwhile. The application of aluminium fins as a passive cooling strategy for silicon-based PV panels was reported in (Grubišić-Cabo et al., 2018). The experimental study was conducted on two 50 W Si-poly PV panels and the gained results showed the techno-economic potential of the cooling technique. Proposed cooling technique needs to be further experimentally tested on larger PV panels to get credible conclusions. Interesting work related to unconventional passive cooling approaches for PVs based on sub-bandgap absorption and imperfect thermal radiation was addressed in (Sun et al., 2017). The

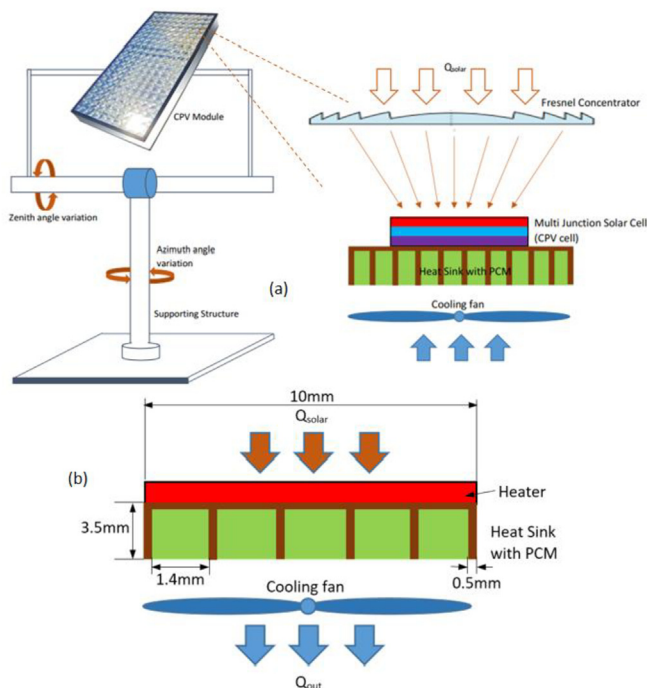


Fig. 21. Sketch of novel thermal management concept for CPV systems (Manikandana et al., 2019).

main idea of the study deals with the elimination of parasitic absorption with the redesign of the PV panel optical properties and improvement of thermal emission with radiative cooling. Based on the proposed actions and conducted simulations, it was concluded that the reduction in PV panel operating temperature could reach up to 10 °C. Passive self-cooling has potential but needs to be further explored by conducted experimental approach.

This section briefly addresses and overview of the latest research findings related to solar energy utilization. From a research perspective, the focus of research activity is the further consideration of potential applications of current market available PV technologies through CPV, BIPV and PV/T systems. Some innovative solutions have been discussed where there are still technical deficiencies that need to be solved in order to ensure economically viable solutions suitable for the market application. The integration of present PV technologies is critical in hybrid energy systems, especially for residential application in buildings; more techno-economic studies are therefore needed to discover effective and viable solutions for the targeted applications. Significant research efforts are also directed towards the efficiency improvement of convectional PV systems, mainly to address advances in control and regulation approaches via innovative technical solutions related to the efficient cleaning of PV panels in demanding environments. Cooling techniques for PV panels have also been extensively investigated for efficiency improvement, where the most attractive ones are passive cooling strategies. Lately, radiative cooling approaches for PVs have been intensively investigated, and a potential exists for efficiency improvement with the introduced redesign of optical properties. Therefore, more research should be provided in the near future related to the development of radiative cooling techniques for PVs. Economic and environmental aspects related to cooling technologies for PV panels are not sufficiently addressed, i.e. the research studies were mostly focused on performance improvement. Novel PV technologies are still in their mature stage and still not widely applicable to the market. The most promising ones are Perovskite PV technologies, which are currently in the focus of the research community. The herein addressed recent research studies demonstrated that further developments in the field are needed to ensure more efficient solar energy utilization.

4. Efficiency and Waste Elimination

In an engineering approach, one should eventually comply with the two laws of thermodynamics: Maximizing the efficiency and minimising entropy on the one hand and reducing the use of resources, as the world is a closed system, where mass flows present the ultimate strain for urban biospheres. Efficiency improvement of existing market available technologies, systems, processes or specific components has become a necessity to be able to reach general sustainability goals for different cases, i.e. engineering applications.

Research studies based on the Scopus research database (Scopus, 2019), revealed a considerable rise in research papers focused on efficiency, 149,533 published papers in 2016 specifically to 175,072 published papers in 2018. A significant interest of the research community is related to energy efficiency topic with 38,402 published papers in 2016 and 47,064 published papers in 2018. The research topics are mainly related to energy efficiency in buildings, transport, industry or efficiency analyses for different technologies, processes and products. Efficiency improvement for various engineering applications and efficient waste elimination management are crucial population problems, so an overview of recent advancements will be provided in the continuation of this review paper. Since the herein addressed topic area of efficiency is wide, the herein presented overview is limited to specific

engineering issues and applications in general.

According to projections, freshwater availability will be a critical issue in the upcoming decades for different regions of the world. It is estimated that by 2050, about 40% of the global world population will be affected by severe water shortage, especially in parts of Africa and Asia, (Oecdobserver, 2012). The estimated increase in global water demands by 2050 would be about 55%, mainly due to industrial needs (manufacturing) in the amount of 400% and due to electricity generation (with included domestic use) reaching about 270%, (Oecdobserver, 2012). There is a high demand for the development of highly efficient freshwater generation systems and technologies, especially ones with assumed seawater desalination. An investigation of the operating parameters regarding freshwater generator capacities and system performances was discussed in (Yuksel et al., 2019). An energy and exergy analysis was applied together with the provided parametric study. The Taguchi method was used to maximise freshwater production and minimise exergy destruction rates in the main system components (condenser and evaporator). The results revealed specific operating conditions that can lead to the improvement of overall system efficiency. A novel biomass-based integrated system was proposed in (Safari and Dincer, 2019) capable of multi-generation, with assumed freshwater generation. The overall efficiency of the proposed systems is about 63% with a freshwater generation of 0.94 kg/s. The main fuel for the multi-generation system is biogas produced from digestion processes. The system is promising, however, requests further investigation of the economic suitability. The effect of saline water mediums (such as pure saline water, still water and saturated sand) on freshwater productivity of modified and convectional solar still was addressed in (Hassan et al., 2019b). A performance analysis related to freshwater productivity was obtained for different periods of the year. According to the results, the maximal efficiency of daily freshwater generation ranged from 13.8% (winter) to 15.3% (summer) for a wire mesh and sand saline water modified system. It was also detected that the produced freshwater cost is reduced with the application of sand and wire mesh. Advanced and highly-efficient solar steam generation systems for enhanced water evaporation was proposed and addressed in (Miao et al., 2019).

A membrane distillation device was developed with carbon Nanotube and qualitative filter paper with aerogel blankets included. The thermal conversion efficiency of the system was about 84.6% and the examined solution turned out to be effective for seawater desalination. However, its economic aspect should be further investigated. The techno-economic evaluation of linear Fresnel reflector plants with integrated membrane distillation systems was discussed in (Soomro and Kim, 2018). The conducted analysis revealed that the considered analysed distillation system was able to achieve evaporation efficiency up to 50%, with an average freshwater generation of almost 32,000 L/d. The LCOE was found to be 0.34 ¢/kWh, with a specific water production cost of \$0.425/m³. The proposed system showed reasonable performance with low unit production costs. Based on the latest existing addressed research findings, significant efforts are focused on investigations related to efficient freshwater generation systems based on the utilization of renewable energy sources.

The role of hydrogen in energy transition is considered to be important in specific applications with respect to the assumed mix of energy technologies. Further improvement of the economic viability of hydrogen-based technologies is necessary. The application of hydrogen is intensively and widely investigated from many aspects (Parra et al., 2019), where one of the main challenges in the field is related to hydrogen production methods with respect to their suitability and efficiency in the long term. A comprehensive review of large scale clean hydrogen production methods was

provided by (El-Emam et al., 2019a). Recent progress in hydrogen production methods was presented and discussed with the focus being on techno-economic aspects. According to findings, it is necessary to ensure lower electricity prices from nuclear or geothermal sources to be able to compete with fossil-based hydrogen production when large scale hydrogen production is considered. Solar or wind-based technologies are highly sensitive and can strongly affect hydrogen production costs. Hydrogen fuel production from renewable biomass carbohydrates was thoroughly addressed in (Sharma, 2019) for different types of catalysis. The study stressed that cell-free synthetic pathway biotransformation showed to be the most suitable economic potential for hydrogen production regarding the considered application. Open issues related to biotransformation based hydrogen production is costly infrastructure, distribution and storage issues. Different challenges related to solar-based photocatalytic water splitting hydrogen production methods were discussed in (Guo et al., 2019). The study was mainly dealing with energy and mass flow perspective. The study revealed that several factors have important impact on the hydrogen generation efficiency such as the general design of a sunlight receiver system and general mass transfer in the system. The potential application of hydrogen is in the case of fuel cell hybrid electric vehicles (Yue et al., 2019), but there are still open issues related to the degradation of PEM (Proton Exchange Membrane) fuel cells and generally high production cost when compared to other market available vehicle technologies. It can be concluded that investigations in the field of hydrogen technologies are progressing in many technical aspects and assumed applications. Further research efforts are necessary for this field to ensure the preconditions for an economically viable hydrogen-economy and solve the main technical barriers related to storage, safety and efficient hydrogen production methods and infrastructure.

Retrofit approaches in specific individual processes and especially industrial applications are valuable to achieve targeted reduction in energy consumption and improve the economic and environmental suitability of different technologies or processes, (Liew et al., 2014). The implementation of the Pinch Methodology (PM) is an important and valuable tool in order to provide more efficient energy systems or components and improve sustainability in general. A new direction has thoroughly been discussed and primarily focused on the implementation and general importance of the PM (Klemeš et al., 2018) for various applications. A detailed analysis of possible approaches that could be used for the retrofitting of existing heat exchanger networks (HENs) was elaborated in (Čuček et al., 2019). Retrofitting approaches were discussed as well as optimisation approaches that can be divided into deterministic and stochastic, Fig. 22. Based on the conducted analysis, different future challenges were detected, identified and discussed such; as the development of more efficient software tools, efficient combination of process modifications, efficient application of a process integration methodology, real-time optimisation, etc. The conclusion of the study is directed to the necessity for the development of hybrid approaches combined with more efficient software tools.

A novel framework for circular integration of processes, industries and economies was discussed in (Walmsley et al., 2019). The framework was developed based on the insights from the industrial sites and processes integration. Air and marine transport were analysed to demonstrate the efficiency and importance of the proposed approach. A heat integration method (multiple heat exchange interfaces) was discussed in (Bütün et al., 2018) as a combination of mixed integer programming and Heat Integration. The proposed novel method was applied in two specific industrial case studies, where the apparent benefit of the developed approach was proved since according to the obtained analysis, it was possible to

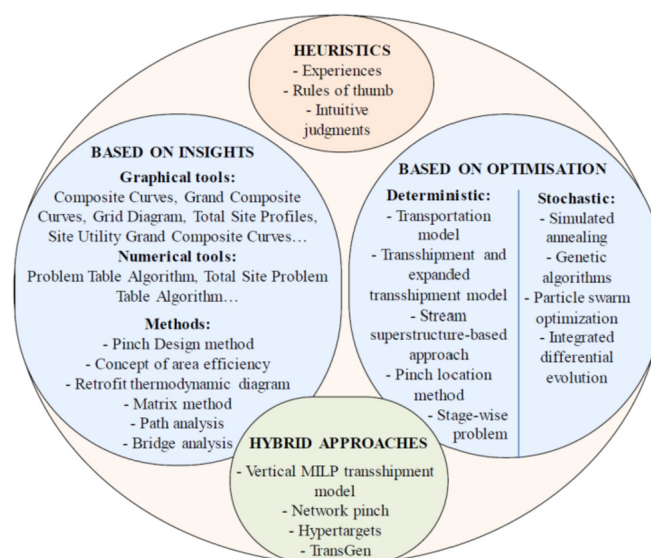


Fig. 22. Sketch of possible approaches for retrofitting existing processes and Total Sites (Čuček et al., 2019).

reduce the total cost of the system by 45% in the first case study. In the second case study, the heat load distribution was reduced by 78% as results of optimal selection. The developed methodology can help during retrofit processes as an effective tool. The integration of industrial parks as an opportunity for the reduction of total annual costs for retrofit was discussed in (Zhang et al., 2018) for the case of industrial parks run by natural gas. A total site analysis was provided for the considered case with deterministic global optimisation. The results showed that with energy retrofit, it is possible to ensure the payback time in less than two months, for specific measures, with a reduction of hot utility by 30.5%. The Time Super Targeting (TST) methodology was proposed and discussed in (Boldyryev et al., 2017) to discover optimal solutions in the retrofit process. A few case studies were addressed and analysed to demonstrate the effectiveness of the proposed methodology. Process Integration methodologies as well as also Total Site approaches are being intensively investigated as useful methodologies that can ensure the reduction of cost and harmful impacts on the environment. According to the latest research outcomes, there is still space for improvement with respect to the different possible case studies, with the main future challenges focused on the development of efficient hybrid approaches, followed by advanced software solutions that should enable highly-efficient optimisation in real-time.

The efficiency of load forecasting methods is a crucial feature to ensure efficient demand response management (Mohammad Rozali et al., 2016) and to be able to efficiently integrate renewable energy technologies in various applications. An analysis of several regression tools for the forecasting of urban electric loads was discussed in (Johannesen et al., 2019). The regression approach was obtained on a continuous time basis, with a vertical time axis approach while considering meteorological circumstances. The proposed approach turned out to be effective for short term prediction (30 min), with the application of random forest regression tools. For long-term prediction, other regression tools can provide better results. The proposed regression methodology can also be useful for the prediction of energy output from intermittent renewable energy sources. A simplified but flexible forecasting method for the short-term forecasting of heat load was proposed by (Nigitz and Göllés, 2019). The method is based on linear regression where the heat load is correlated with ambient temperature for each hour of the day. Method found to be efficient for the regulation

of hybrid energy systems based on renewables. The impact of stochastic forecast errors associated with renewable generation as well as load demands on general micro-grid operations was addressed in (Chen et al., 2019). The novel models for the determination of stochastic forecasting errors concerning the operational stability and state of charge were proposed.

Specific impacts related to the service lifetime of the units was also addressed and discussed. A novel and smart energy management algorithm was developed for the load forecasting of island power systems in (Chapaloglou et al., 2019). The developed model is interesting since it integrates load forecasting methodology (pattern recognition) with a custom and optimal scheduling algorithm for the power. With the application of the developed forecasting algorithm, it was possible to ensure a more efficient penetration of renewables into the grid. A detailed review related to the application of forecasting models in renewable energy power systems was provided in (Ahmed and Khalid, 2019). The review was obtained for different applications such as optimal over system dispatches, energy market policies, generation scheduling, etc. Based on the conducted review, one of the main challenges is to determine optimal and precise forecast models with respect to the economy of the system and specific planning aspects. A real-time energy management system for a smart community micro-grid was elaborated in (Yan et al., 2019), with an assumed battery swapping and application of renewables. The proposed approach turned out to be efficient for energy scheduling and suitable for real-time applications. The overall economy of the considered renewable energy system could be improved. Considering the previously addressed latest research findings, it can be concluded that progress in efficient load forecasting exists, however, more case studies should be addressed and new advancements are generally necessary to provide more flexible and efficient load forecasting methods.

Besides the already previously addressed importance of globally installed PV capacities, wind capacities also play an important role in energy transition with a constant rise in installed units (Solar Power Europe, 2018). Investigations related to the improvement of existing wind turbine technologies are mandatory to improve their economic aspect and general market suitability from some other aspects (environmental and safety). The wind share effect on the aerodynamic performance, as well as electricity production, was analysed in (Ghazale et al., 2019) for the case of horizontal axis wind turbines. Blades were designed using the blade element momentum theory (BEM) together with a calculation of aerodynamic coefficients along the blade length. Based on the obtained results, it was found that the wind share effect does not have a significant effect on the aerodynamic coefficients in the root region (most changes occurred at 20%–80% of blade length, where wind turbine coefficient was generally reduced). The proposed analytical method increased the accuracy of the BEM method. A novel design of a deflector integrated cross axis wind turbine was reported in (Chong et al., 2019). The performance analysis of the specific design was carried out through simulations, and the concept showed reasonable potential in practical terms since it allows more efficient operation in circumstances of low winds, or highly turbulent wind flow conditions.

The investigation of vertical wind generators has become more intense in recent years due to their specific advantages when compared to horizontal turbines. However, existing technology still needs to be improved, especially in the blade design and novel materials to become more resistant to fatigue issues. Performance analysis of a Savonius vertical axis wind turbine was elaborated in (Manganhar et al., 2019), where the turbine was coupled with wind accelerating and guiding the rotor house. It was found that the introduced rotor house causes improvement regarding rotor

coefficient with a factor of 1.74. The impact of oil temperature on the efficiency of the wind turbine gearbox system was reported in (Sequeira et al., 2019), where different oils were tested. The oil temperatures were measured for different loads as well as their effect on active power production. It was found that mineral oils are better for wind turbines than synthetic oils and the correlation was found between oil degradation and oil temperature. A concept of a small wind turbine equipped with flexible blades (morphing blades) was investigated in (MacPhee and Beyene, 2019) as an effective engineering design to increase the flexibility of existing turbines, with respect to variable operating conditions. The experimental results revealed that a flexible blade design enables more power output than the rigid ones, with an increase in the power coefficient by over 32% and operational range by over 34% for the considered cases. The previously addressed recent research studies prove that there are different technical possibilities for the improvement of existing wind generation technologies.

The energy efficiency improvement of the industrial sector is very important along with the building and transportation sector since some branches of the industry have high energy demands with significant impacts on the environment. An efficient production route analysis, with respect to the lowest energy consumption, was addressed in (Unver and Ozlem, 2019). AMPL software was used to simulate production efficiency and to analyse the specific process in the production route, Fig. 23. According to the conducted analysis, it was possible to achieve energy efficiency savings in the amount of 65% per unit production, with a proper correction of the production routes. The conducted analysis revealed that it was possible to achieve energy efficiency savings in the production process without direct investment in the production process.

Application of the neural networks together with the neuro fuzzy inference system was addressed in (Kaab et al., 2019). Approach was used to predict life cycle environmental impacts as well as energy output for the case of the sugarcane production. Results showed that largest impact on the sugarcane production have electricity consumption, machinery, biocides and stem cuttings. A routing strategy based on an improved A-star algorithm was proposed and discussed in (Balaji et al., 2019) for a case when the deployment of a receiver station was guided together with a ground support team, in circumstances when a suspended base robot was used in transmission line inspections for industrial applications. The proposed algorithm was tested in one segment of the transmission line in the State of Missouri (USA). The reported results revealed that a noticeable improvement in performance was achieved when compared to traditionally used inspection methods. Improvements were achieved in economic aspects, with reduced costs of about 8%, and also in environmental aspects, with a reduction of over 20% (when the proposed algorithm is compared to ad-hoc routing algorithms). An analysis directed to comprehending knowledge related to the energy intensity change in China's food industry was presented in (Xie and Lin, 2019). A comprehensive decomposition method was used to analyse energy intensity variations. The highest impact on the reduction of energy intensity has technological progress (reduction of about 70%) and improvement of energy efficiency (18.4%) and governmental policies. More investment in the research and development of novel technological solutions in the food industry is needed and coupled together with effective and strict governmental regulations during the planning stage. A novel simulation tool was developed and presented in (Gadaleta et al., 2019), suitable for the optimisation of industrial robot energy consumption. The proposed solution allowed automatic computation of the energy-optimal motion parameters and enabled an energy consumption reduction. A simulation approach was tested on an industrial robot and the

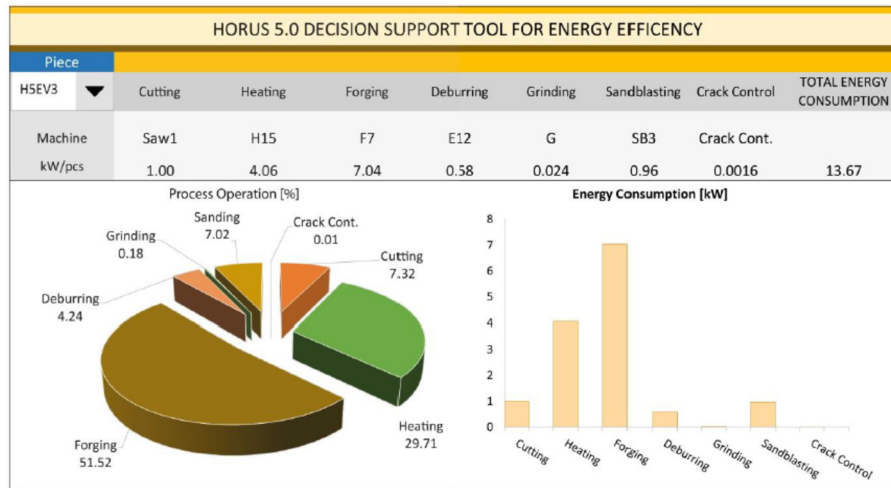


Fig. 23. Screenshot of used simulation software (Unver et al., 2019).

effectiveness of the method was proven. The economic aspect of the proposed approach was not addressed. A lean energy-saving concept was proposed in (Cai et al., 2019b) as a tool for the improvement of energy efficiency and reduction of harmful emissions from the manufacturing industry. The novel concept was applied to an industry case study and showed to be an effective tool to enable a sustainable manufacturing industry. A detailed study related to the cement industry was obtained in (Kermeli et al., 2019) and mainly focused on strategies for possible improvements regarding energy efficiency and reduction of greenhouse gas emissions (through the implementation of integrated assessment models). The importance of retrofitting was discussed as well as the issue associated with the reduction of the clinker to cement ration. Different energy scenarios were simulated with respect to the estimated energy intensity in the cement industry and released an amount of GHG emissions.

The efficiency of various technologies, processes components in energy systems is an important research topic with significant impact on sustainability and utilization of the limited resources. Selected latest advancements are briefly addressed; however, a more detailed review is needed in this rather wide research field. An investigation of gear ratio effects on exhaust emissions as well as fuel consumption was elaborated and discussed in (Umut Karagolan et al., 2019). A specific parallel hybrid construction was analysed that was equipped with a combustion engine and electric motor. Five different gear ratios were analysed through a developed simulation model using Matlab® software (version 9.4). The analysis provided the best combination of gear ratios that caused lower fuel consumption as well as reduction of CO₂, CO, NO_x and HC emissions. The highest achieved reduction in fuel consumption was about 17% with around 9% reduction in CO₂ emissions. Performance differences (fuel consumption as well as specific emissions), between hybrid and conventional vehicles, were addressed in (Huang et al., 2019b). The main idea of the research was to check fuel consumption in realistic circumstances when compared to the laboratory results. The field results revealed that both hybrid and conventional vehicles had considerably higher fuel consumptions than in the laboratory results. It was also found that pollutant emissions were lower with respect to regulation standards, but hybrid vehicles had higher CO emissions and no reduction in HE emissions compared to emissions from conventional vehicles (according to authors, a possible cause could be frequent stop and start of hybrid vehicles). An analysis of internal combustion and electric motorcycles was elaborated in

(Weber de Assis Brasil et al., 2019) with the main emphasis is on the comparison of their energy performances. The dynamometric results showed that electric motorcycles are more energy efficient when compared to internal combustion motorcycles. The analysis was conducted for the Brazilian market, and it was found that battery impacts on the environment should be better investigated to get the overall aspect related to electric motorcycles. Future transportation systems will be organised as a mix of different transportation technologies with the associated economic and environmental impacts. In (Rocco et al., 2018), a hybrid approach (input-output analysis) was proposed as an evaluation framework to analyse the impact of transportation technologies with LCA (Life-cycle assessment) evaluation framework. The analysis of LCA and wheel to wheel approaches were compared, and considerable differences exist when the two mentioned frameworks are applied. It was also found that the impact of infrastructure and vehicle production facilities have significantly reduced CO₂ emissions. An energy efficiency analysis of a wet compressor system was obtained in (Abhay et al., 2019). A parametric study was conducted considering different influential parameters (air relative humidity, overspray percentage of water droplets, droplet diameter, etc.) to check the overall performance of the compressor system and its impact on system efficiency. It was found that the examined wet compression can cause an increase in the system's energy efficiency; if a small droplet diameter is ensured, together with larger overspray's in circumstances of lower compression speeds. They emphasized that the general control over the droplet dimensions and compression speed will be critical features from a practical point of view. An improvement of steam turbine stage efficiency was analysed in (Shibata et al., 2019) with an enabled control of the rotor shroud leakage flow. Based on the conducted CFD analysis, it was found that the stage efficiency could be improved from 0.2% to 0.7% with the proposed swirl breaker since it reduces mixing losses and improves incidence angles. Evaluation of flow losses and their impact on the performance of organic Rankine cycles was discussed in (Sun et al., 2019) with R245fa as the working fluid. It was found that the flow losses for the considered case can cause irreversibility in the evaporator and condenser. Flow losses ranged from 14% to 37%, with a maximal 17% decrease in thermal efficiency. From the addressed research papers, it is clear that there is a broad spectrum of possibilities for efficiency improvements in different engineering technologies to enable the more efficient use of existing technologies, systems and processes in general.

Waste issues have become a critical population feature with a necessity for effective approach circular economy framework, i.e. to achieve a desired zero-waste society (Türkeli et al., 2018). The main critical features related to waste issues have already been addressed in the introductory section with the emphasis being on plastic waste issues, food-waste, electronic waste and their unfavourable long-term impacts on the environment. The second major issue related to the waste issue is related to the energy consumption as well environmental impacts associated with the recycle systems for municipal solid waste, (Nabavi-Pelesaraei et al., 2017). Efficient waste management strategies and firm actions are needed for the proper implementation of the circular economy concept (Sabki et al., 2019). Waste should be apprehended as a valuable resource, where different possibilities for waste utilisation (recycling options) should be explored more intensively. The investigation of different waste potentials and recovery technologies for different processes is mandatory to ensure the desired sustainable goals.

The application of abundant residue in heat and electricity sustainable production processes, with an enabled production of the digested substrate (fertiliser) was reported in (Bedoic et al., 2019). The chemical characterisation of residue grass was obtained with a laboratory batch of mono and co-digestion tests. The gained results showed that reasonable digestive parameters could be achieved, with a low amount of impurities (which means that biogas from residue grass could be a viable option). A conducted life cycle analysis showed that residual grass is perspective for electricity and heat production when compared to maize silage. Synthesised ionic liquids were analysed in (Ullah et al., 2019) to examine how the extraction of specific but useful chemicals from sustainable rice husk waste and that affects the general properties of two ionic liquids. An ultraviolet technique, magnetic resonance as well as thermogravimetric analysis and high-performance liquid chromatography was applied to investigate the properties of the ionic liquids. The silica was successfully isolated from the examined biomass which could finally lead to the more efficient utilisation of rice husk in different industrial applications. The recycling possibility of phosphorus from incinerated fly ash (or sewage sludge) with the addition of biomass was reported (Zhao et al., 2019). The experimental results revealed that phosphorus bioavailability is improved with the proposed addition of biomass fuel.

The development of novel recycling possibilities should be followed by the promotion of sustainable consumption and production. Waste generation is significantly affected by recycling behaviour, which can vary from the type of specific economy. Waste management behaviour issues were addressed in (Minelgaité and Liobikienė, 2019) for the EU region. The study stressed the general lack of knowledge amongst the EU population to understand the relationship between waste reduction and resource efficiency. The education of the population is mandatory to increase individual awareness and understand the contribution of individuals to the global waste problem. Recycling has a key role in smart waste management and different recycling possibilities have been investigated in recent years and some of them are addressed in Table 1. Based on the provided overview, the latest research findings are clearly focused on recycling and significant efforts are being made to solve issues with different kind of waste (plastic waste, electronic waste, polymer waste, etc.), where the main goal was to turn them into useful resources (materials) for different potential engineering applications (novel constructional materials, regeneration of valuable metals, hydrogen production, etc.).

A brief review of recent research findings in this section indicates that efficiency is still a crucial and challenging research task, since recent progress in that widespread field is clearly visible and directed explicitly to the efficiency analysis of systems, individual components or processes (freshwater generation systems, BEM

systems, renewable energy technologies, industrial retrofit, etc.). The efficiency of transportation systems is progressing well, different techniques and approaches are being investigated towards the reduction of harmful pollutants into the environment caused by the utilisation of existing market available vehicle technologies. However, the focus should be directed towards the development of future transportation systems as an expected mix of transportation technologies (novel clean transport technologies with efficient utilization of renewables). Efficiency in industrial applications is also progressing where further development of Process Integration methodologies and Total Site approaches is needed through mainly advanced software solutions and hybrid approaches. More research efforts should also be directed towards the development of efficient demand response management strategies and general load forecasting methods as an important precondition for the efficient integration of renewable energy technologies in various applications. Waste management is mainly directed towards the investigation of novel recycling possibilities, which is visible from a wide number of recently conducted research studies. The investigation of the environmental suitability of novel recycled materials as well as analysis of economic aspects is missing in the majority of conducted studies and future research work should be addressed regarding these raised issues.

5. Smart cities and the Internet of Things

Connecting anything to the Internet regardless of its size is the main concept of the Internet of Things (IoT), where regular objects interact with their surroundings, and can be remotely supervised by users (Atzori et al., 2010). The IoT concept is applicable to various areas, such as agriculture, industry, healthcare, smart cities, security, nano-grids, etc. The global market share in recent years of IoT technologies with subsectors is presented in Fig. 24, with projections for 2020 regarding the expected market size, Fig. 25. Possibilities for technological developments through smart technologies are extensive, but critical approaches also need to be addressed to enable the sustainable and gradual implementation of IoT technologies (i.e. to investigate environmental impacts of smart technologies).

Specific technological solutions based on IoT technologies are challenging and futuristic in some aspects (gesture control armband, smart farming, smart eye, etc.), but some solutions are already close to the wide market applications. With such applicability, the number of Internet-connected devices is rapidly increasing and could reach more than 34 milliards by 2025 according to response predictions, which means a significant rise in IoT infrastructure.

Without a doubt, the economic impact of IoT markets will be significant, especially when compared to saturated markets such as smartphones, (Al-Turjman, 2019). In the near future, the overcome of several technical issues related to the application of IoT technologies should be bridged such as power consumption, energy efficiency, connectivity, processing power, device to device (D2D) communication, infrastructure and many more (Asghari et al., 2019). These issues are amplified in densely populated areas such as smart cities that would host most of the IoT devices, and perform data collection through sensors, supplying information that will aid in distributing various resources in a more efficient manner (Zedadra et al., 2019). Smart cities would demand great infrastructure due to unprecedented data that needs to be generated (Gharaibeh et al., 2017), representing a big market, especially for advertising companies. The data related to connected devices can reveal the hidden patterns in user habits that are not normally captured by browsing the Internet after it is processed through techniques, such as Big data (Ang et al., 2017).

Table 1
Overview of the latest selected investigated recycling possibilities for various applications.

Reference	Recycling waste	Application/Remarks
Singh et al. (2019a)	Ployethylene gloves	Hydrophobic coating application
Zhao et al. (2019)	Waste biomass	Phospor recovery from fly ash from the industrial sewage sludge.
Seghar et al. (2019)	Natural rubber industry waste	Investigation of the physical properties after extrusion process
Singh et al. (2019b)	Coal bottom ash	Concrete aggregates blended with metakaolin
Mir and Pandey (2019)	Waste plastic	Hydrogen production
Hossain et al. (2019b)	Demolished bricks, fly ash and rice husk ash	Production of green building bricks
Luhar and Luhar (2019)	Electronic waste	Application in constructional industry
Park and Kim (2019)	Waste printed circute boards	Extraction of metals
Wang et al. (2019b)	Sapphire kerf waste	Purification application
Kale and Gorade (2019)	Medical cotton waste	Production of self reinforced composites
Yang et al. (2019b)	Lithium-ion batteries	Graphite regeneration
Siddique et al. (2019)	Ceramics waste	Concrete production
Ebin et al. (2019)	Household battrie waste	Extraction of valuable metals
Okan et al. (2019)	Waste ploymer	Different application
Saccani et al. (2019)	Carbon fiber/epoxy composite waste	Production of composites
De la colina martinez et al. (2019)	Electronic waste	Concrete production

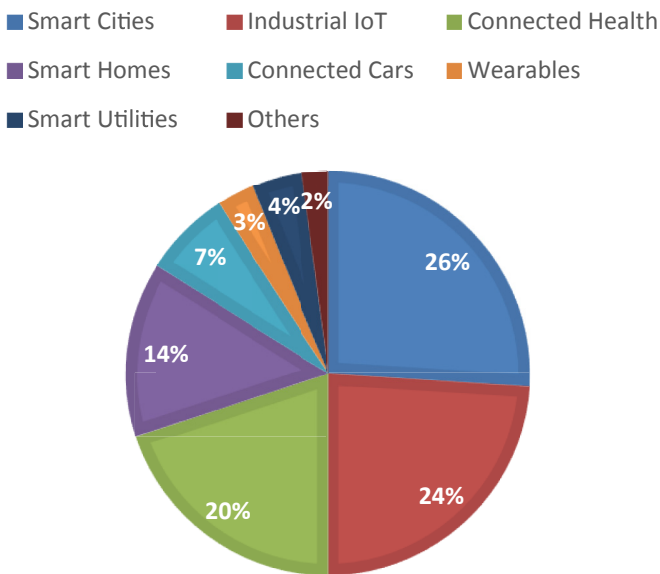


Fig. 24. IoT technologies for different applications (Forbes, 2017)

It is foreseen that smart cities will not only hold most of the IoT devices but also most of their users and applications, solving several issues related to modern cities, Fig. 26. The main idea of the smart city concept is to provide more efficient services (better organisation) in cities, to improve safety, enable a general quality of the environment in cites for work and living. Smart transportation systems could increase user comfort, security, reduce traffic jams by providing drivers real-time data regarding traffic reports, rerouting traffic and adjusting speed limits based on this information (Neto et al., 2018).

Moreover, drivers will no longer search for vacant parking spots because of smart parking solutions that enable them to visualise this information in real-time through their smartphones (Lin et al., 2017). Waste management could become more effective due to available techniques, giving cities a cleaner look (Pardini et al., 2019a, b). Security, safety and privacy will also play a huge role with modern cities possessing various CCTV cameras that can identify potentially hazardous situations in real-time, as well as the perpetrators. The users will gain in security and safety but the trade off their privacy. Device management will also be a challenge because it will be impossible for people to individually manage every device, so could certainly rise, which means that IoT devices

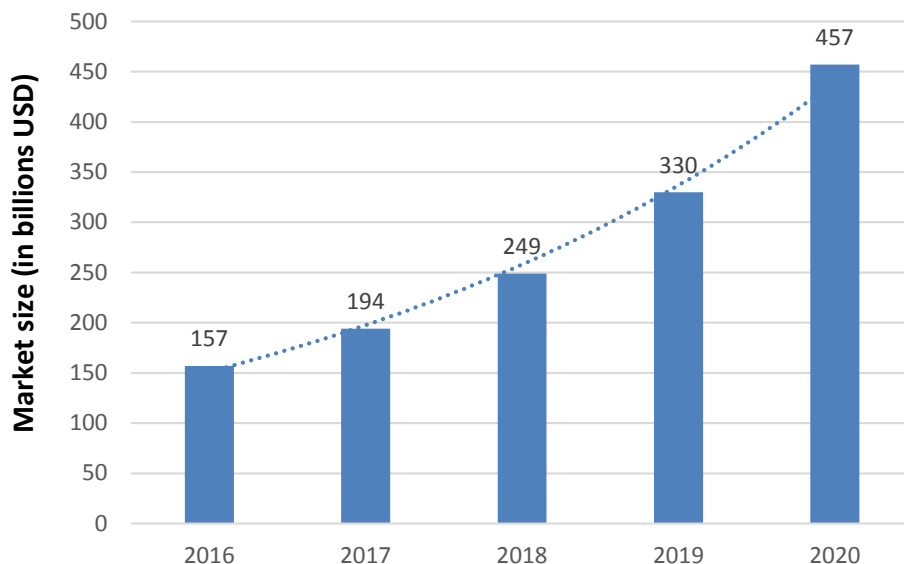


Fig. 25. Market size of the IoT technologies, (Forbes, 2017).

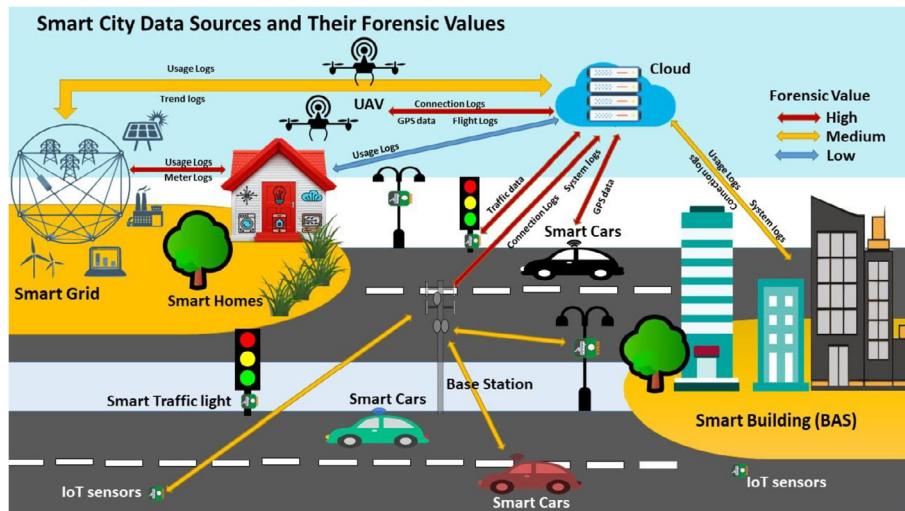


Fig. 26. A sketch of the Smart city concept (Elsevier, 2019)

must be energy efficient or self-sustainable to reduce their impact (Deakin and Reid, 2018). With the rise of IoT applications, a rise in specific resources for electronic equipment could be expected and a general increase in e-waste. With the increased data traffic representing such a big issue, pre-processing the data sent by devices might be vital, (Tang et al., 2018). These data are going to be transmitted wirelessly where various options are available and can range from traditional cellular networks to specific IoT methods, such as LoRa, SigFox, NB-IoT, 5G, etc. (Oliveira et al., 2019). For data consulting with an IoT user (human, applications or devices), it must be stored in an IoT Middleware platform that needs to be secure, robust and which allows third-party applications to be built on top of it (da Cruz et al., 2018a). An exhaustive performance evaluation should be made to determine the scalability of the chosen middleware solution in scenarios with various concurrent users. While pre-processing, data mostly focuses on minimum, maximum and average values whereas post-processing is generally based on more sophisticated techniques, such as big data or even artificial intelligence where the context of transmitted data could change its interpretation (da Cruz et al., 2018b). A brief review of the latest research results from this progressing thematic are provided in the continuation in this review paper and directed towards specific applications and issues (smart grids, smart city, smart transport, smart waste management, smart agriculture, etc.).

One major issue is related to the distribution and transmission efficiency of smart data which is usually obtained through optical networks, Fig. 27, i.e. efficiency of smart grids. A strategy aiming to improve network agility and automatization was proposed in (Xu et al., 2019b) and based on software-defined networks and function visualisation. Novel routing applications have been developed using the OpenFlow protocol. The proposed solution turned out to be effective and feasible on a semi-practical platform demonstration.

Bi-directional energy flows between the smart grid, and wind energy prosumers were incorporated into a developed model. Presented results proved further contribution to the development of stochastic energy management models for the efficient integration of renewables in smart grids. A review article related to energy metering in smart grids was provided by (Danielly et al., 2019). The main challenges related to smart metering were discussed to ensure fully functional and security-aware smart grids, Fig. 28. A detailed description of the main smart meter functionalities was provided and discussed in relation to the general

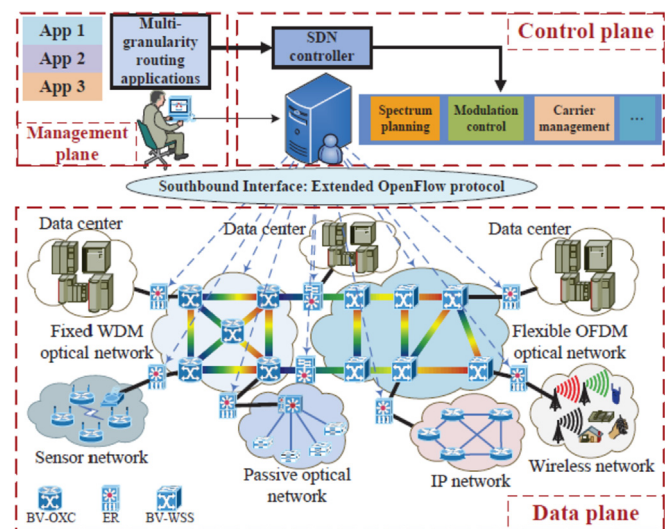


Fig. 27. Software architecture for multi granular inter-DC optical networks (Xu et al., 2019b).

technical capabilities of smart meter market available technologies. The main step towards further development and more efficient utilisation of smart meters will be through the application of the IoT concept (more efficient sensing and measurement). The implementation of smart sensing through IoT technologies could lead to the automatization of energy measurement, i.e. more efficient response and real-time decisions. One of the major challenges is to develop novel and smart detection systems by the gradual development of IoT structures in smart homes.

The development of a smart and sophisticated control and data acquisition system for optimisation, control and monitoring of drinking water systems was reported in (Mkireb et al., 2019). The developed smart demand response approach turned out to be an efficient solution in an examined real case study in France. The proposed system showed flexibility underwater demand uncertainties and would be useful to check the effectiveness of the developed model for other case studies in different countries. The literature review focused on automated approaches for disease vector mosquitoes, monitoring was reported in (Santos et al., 2019).

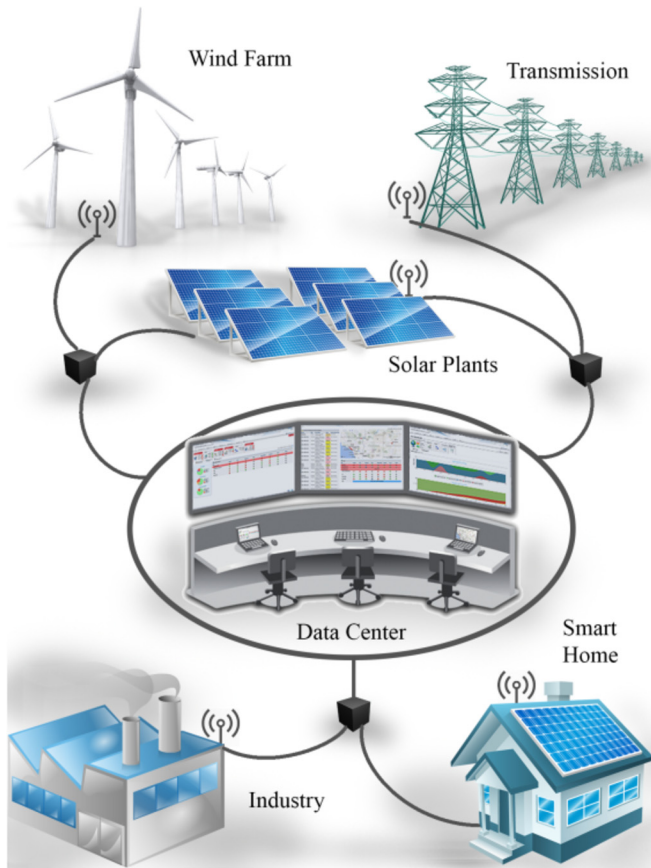


Fig. 28. Smart grid perspective (Danielly et al., 2019).

The main research outcome was directed towards the identification of further research opportunities in that specific area considering new data processing as well as the application of transmission emerging technologies. In order to ensure the further progress of monitoring approaches, the new technologies are needed with an emphasis on Machine Learning, Big Data and Internet of Things. The application of optical sensors was also addressed as a key feature in insect-borne disease surveillance. A smart grid framework for the stochastic wind energy management was discussed in (Hussain et al., 2019). A bi-directional model was applied between smart cities and wind energy prosumers. The developed model was found to be an effective tool for non-linear stochastic price modelling, i.e. an energy management modelling strategy suitable for the smart city concept. A novel lightweight context-aware IoT service architecture was proposed in (Prasad et al., 2019), i.e. the LISA approach to support IoT push services in a more efficient manner. The main concept of the LISA approach is to formulate a user model that would resolve local decision making while using agents and web service paradigms. For the model, a performance analysis of an IoT tourist guide system was analysed as a case study. The simulation results revealed that the LISA could reasonably reduce information distributed to the users with a selection of the most relevant among them. The proposed method can be further optimised with fine tuning (user-specific settings) and the improvement of the query processing time as well as query generation time. Smart control algorithms were addressed in (Pallonetto et al., 2019) for demand response approaches in the residential sector. A simulation model was developed to analyse smart demand response strategies concerning different electricity tariffs and thermal comfort conditions. According to the case study obtained for typical residential facilities

in Ireland, the possibility to reduce electricity costs was proved as well as reduction of the utility generation costs and carbon emissions. The optimisation of a smart energy network system for Canadian communities was discussed in (Ghorab, 2019) to minimise energy costs and reduce GHG emissions. The study was conducted on twenty Canadian buildings with an enabled exchange of thermal energy and electricity. The optimization model provided possibilities for a reduction in electricity costs and GHG emissions, where the integration of PV systems (with enabled battery storage) lead to the highest reduction in GHG emissions. The importance of smart grid optimization was demonstrated since it was possible to improve both economic and environmental aspects. A comprehensive review focused on demand response modelling, and smart algorithms were delivered in (Vázquez-Canteli et al., 2019). The conducted review directed that the majority of published papers are focused on single-agent systems and stationary environments. The need for education on multi-agent systems should be provided in the next step. Further challenges and possible research directions were also examined in the mentioned paper.

Smart mobility (transportation) in smart city concepts represents a significant challenge to enable a smart and efficient journey. The application of Big Data technologies can help to ensure efficient management of vehicles that are treated as nodes in the network. An Ant colony optimisation (ACO) approach was applied in (Lakshmanprabu et al., 2019) for the routing of vehicular networks. Based on the obtained simulations, it was concluded that it is possible to achieve a significant reduction in the node count rise (Hadoop framework case). The future development of the proposed approach should be directed towards the hybridisation of ACO algorithms, with some metaheuristic algorithms. Two-hybrid adaptive bandwidth and power algorithms (HABPA) with Delay-tolerant Streaming Algorithms (DSA) were proposed by (Hassan et al., 2019c) to enable a more sustainable smart city platform. The experimental approach considered an analysis of the performance metrics, power drain, battery lifetime, delay, etc. According to the experimental results, it was possible to optimise the power drain and battery lifetime (about 37%). The main contribution of the proposed HABPA approach for media streaming through an IoT-based smart city is the battery lifetime extension which is more than important from a sustainability point of view. Excessive application of electric vehicles, followed by the necessary development of infrastructure, will have a significant impact on electricity generation structure. The previously mentioned problem was discussed in (Taljegard et al., 2019) as a case study for Scandinavian-German market circumstances. The electricity generation capacities by 2050 were addressed where a cost-minimisation investment model was applied together with an electricity dispatch model. The analysis showed the importance of careful transportation system planning with respect to the development of renewable energy capacities. A gamified survey approach was considered in (Lara et al., 2019) to investigate how the population value electric vehicle (EV) charging services, i.e. how willing they are to pay for EVS charging services (goal was to provide insights on willingness). An evaluation approach was applied through a conventional questionnaire combined with a game-based questionnaire. The main goal was to solve the issue related to data collection regarding EVs, since data are usually unavailable or difficult to reach from the existing EV-related datasets (general nature of available data). The gamified questionnaire showed to be more efficient when compared to text-only questionnaires and have increased design complexity as well. The proposed approach showed to be especially efficient for cases when it was difficult to extract real-world data. It was also found that EV owners are ready to pay less if the state charge is high and users are generally ready to pay higher prices if the

electricity price is known. In any case, the developed and demonstrated approach contributed to a better understanding of influential parameters for EV owners related to payment willingness, for EV charging, and insight will help to develop an efficient and innovative sustainable business model. The social impact of future autonomous vehicles was discussed in (Marletto, 2019). Specific social-technological impacts were discussed in future terms such as the integration of suppliers to ensure components for automated vehicles, a collaboration between the leaders and managers of transportation systems, the impact of innovators, etc. Autonomous vehicle transportation systems will cause specific social impacts on society and they need to be further investigated. New challenges and possibilities for the development of smart grids were discussed in (Monteiro et al., 2019) with respect to vehicle electrification. Issues related to current electrical power grids were discussed and the general necessity for a more flexible adaptation in dynamic environments. Further progress in the development of power electronic systems was also found to be a critical feature towards efficient smart grids in transportation systems. More intense research work is needed in the field of smart transportation systems.

The implementation of smart and IoT technologies in the field of security has become significantly interesting for different surveillance purposes (e-health, smart homes, management systems, etc.). A novel framework for the efficient emergency management of critical events and incidents was proposed in (Manar et al., 2019) for smart cities. The proposed framework uses text mining, text classification, named entity recognition and stemming techniques. The data are automatically collected from social media and processed to generate intelligence reports. The results were collected from Arabic tweeter with an achieved classification accuracy of more than 96%. The developed approach turned out to be a more efficient tool in emergency situations through better coordination and planning of specific rescue situations and protocols. Issues related to the application of IoT technologies for healthcare purposes were addressed in (Panchatcharam and Vivekanandan, 2019). The application of IoT technologies towards smart healthcare services was discussed; current issues such as the main benefit related to the application of smart technologies through improvement of healthcare administration. The concept of a novel cost-effective smart home sensor was reported in (Davidson et al., 2019) as a useful technical gadget to improve home security. A smart home sensor has the task to inform the user via an Android application in the case when doors are opened in home environments (or office applications). The potential application of the developed sensor was discussed and its technical issues that need to be solved, such as interference with other radio frequency devices. The possible application of IoT technologies in real stores or marketplaces was addressed in (Chojnacki and Rykowski, 2019) for behaviour control and monitoring of activities (but also for other applications in stores such as HVAC control, etc.). The implementation of IoT technologies could lead to the development of different market tools to enable more efficient business in the considered applications. Fog computing has the potential for different applications and services since it can enable cost reduction and increase effectiveness in general. The implementation of fog computing in the analysis of surveillance videos in smart cities was discussed in (Nasir et al., 2019). The novel and efficient framework was proposed and based on fog computing. The proposed approach showed good potential for cloud solutions with effectiveness for IoT supported smart cities. The monitoring of different defence activities for staff with the application of IoT technologies was reported in (Bhatia and Sood, 2018). Daily activities, social engagement and other aspects that can represent a threat to national security have been collected via IoT based data collection systems. The developed approach

could be a useful tool to analyse the behaviour of defence personnel and to detect potential risks from a safety point of view.

Smart agriculture has become an emerging field where IoT technologies could be implemented in an effective way and help make agriculture more sustainable and economically viable. A comprehensive review related to the application of IoT technologies for precise agriculture was provided by (Khanna and Kaur, 2019). Future research directions have been discussed for the improvement of IoT technologies and present critical issues linked with the efficient application of IoT technologies in agriculture. A smart agriculture monitoring system for the detection of soil temperature and moisture was presented in (Mekala and Viswanathan, 2019). The proposed cloud-based solution can ensure the efficient monitoring of specific crop comfort levels and could be an accurate and effective decision tool for farmers with a reported accuracy of 94%. A case study for a solar pumping system monitored via the application of IoT technologies was reported in (Sirisamphanwong et al., 2019) for Thai smart farming. Specific technical IoT based smart solutions were discussed that were based on real application and gained experiences and contributed to the concept of smart farming. Results of the study could be useful for other similar applications. IoT technologies can also be used for smart irrigation in agricultural purposes, which can contribute to environmental sustainability. A concept of a smart water management approach for an efficient water irrigation system in agriculture was reported in (Kamiński et al., 2019). The specific architecture of the proposed management system was discussed, and the major concern is found to be in the necessity to redesign some components in the system to enable high stability followed with less computing time. An analysis focused on the effective application of IoT technologies in the case of cotton farming was reported in (Khan et al., 2019). The study focused on the architecture design of different IoT solutions with the application of cotton farming (cultivation, irrigation, harvesting, etc.). An IoT based framework was proposed, and it could lead to smart farming for the considered case.

Further, development directions of IoT technologies for smart agriculture were discussed in (Lakhwani et al., 2019). Different benefits linked with the application of IoT technologies in agriculture were discussed, i.e. the already investigated technical applications and potential for improvements. The possible prediction of strawberry disease with the application of IoT technologies for smart farming was reported in (Kim et al., 2018). A cloud-based technology was elaborated for the collection and analysis of data and prediction of possible scenarios in strawberry farming.

IoT devices were applied together with the development of an IoT-Hub network. The developed smart monitoring system proved to be efficient as a prediction tool for the control of disease occurrence in strawberry farming. A smart system for bicarbonate control in irrigation processes was reported in (Cambra et al., 2018) to enable precision farming. The developed smart solution enabled the control of pH nutrient levels in hydroponic agriculture. An auto-calibrated pH sensor was used connected to a wireless node and enabled a web monitoring interface that can be reached with a computer or smartphone. The concept proved to be efficient for the considered purpose, i.e. effective technical approach for smart control of nutrients during the irrigation process.

Smart waste management could be further advanced and upgraded with the implementation of IoT technologies. The smart waste management concept in future smart cities was discussed in (Marques et al., 2019) from a long-term perspective. The necessity for intelligent services and their development in future smart cities were discussed as well as the importance of IoT technologies. Waste management was addressed via a case study regarding a specific concept, i.e. technical solution that can handle 3902 garbage bins in

a simultaneous manner. The proposed garbage bins can separate organic and recyclable waste. The concept of a smart waste management system capable of separating different types of waste was proposed in (Kansara et al., 2019). A specific smart bin prototype can alert garbage collector services when the bin is filled to 80%. The strategy for efficient collection of filled bins is also developed to save fuel for garbage trucks and to reduce the harmful impacts on the environment. The garbage truck is assumed to have a robotic arm for the segregation of different types of waste. The literature review focused on the implementation of IoT technologies with respect to the smart waste management approach was provided in (Pardini et al., 2019a, b). Current smart based efficient strategies for waste management were discussed focused on the urban environments. An IoT based model was developed to provide a comparative analysis and detect technical issues that need to be solved to enable more efficient smart waste management. A smart trash monitoring and segregation system were presented in (Dhyani and Patel, 2019) using emerging technology. An effective approach related to the proper management of municipal waste through different stages was discussed and followed by the utilisation of IoT technologies (smart water detection, smart trash segregation and smart garbage collection). Innovative techniques related to the previous aspect were addressed, which were based on a conducted literature survey. An efficient and smart approach for residential garbage collection under smart city concepts was discussed in (Rossit et al., 2019). A case study of a mid-sized Argentinian city was analysed with examined garbage bin locations, selection criteria. The main goal was to improve the quality of service and to reduce costs by the smart waste management system. The developed model demonstrated that an effective door-to-door garbage collection system with community bins could be provided. The study (Anagnostopoulos et al., 2018) addressed the issue related to smart waste management regarding bins and trucks with the application of IoT technologies (i.e. sensors and actuators). The focus of the research was on dynamic scheduling in stochastic conditions for different seasons of the year in two years. The problem was solved with a multi-agent system applied for stochastic analysis and turned out to be a quality solution for the considered purpose. A stochastic optimisation framework was developed and discussed in (Jatinkumar Shah et al., 2018) for the smart management of waste in smart cities. The main target of the provided optimisation was to reduce costs and to consider the quality of waste that can be recovered from the collected waste. The developed numerical model can help for the smart planning and collection of waste with the assumed application of acquisition technologies. The model can also monitor the level of recyclables included in each trash bin.

Recent advancements in the application of smart technologies supported by the IoT concept showed that potentials for improvements are high, especially within the smart city framework.

Different smart technical solutions are discussed in various applications, with the main focus being on enabling efficient and cost-effective smart technologies on the market. It was also noticed that the studies did not address the environmental impacts of specific IoT technologies, i.e. sustainability in general. Future research directions should be focused on the environmental and economic evaluation of smart technologies. Investigations of novel technical solutions should be enabled to integrate existing sensor technologies into useful products for the population. Final benefit of the smart technologies should lead to cost-reduction, improved quality of service and contribution to environmental protection.

6. Concluding remarks

The world is rapidly progressing through the 21st century and is

turning into a more challenging and complex system, especially from the sustainability point of the view. The rapid growth of population, along with the urbanisation and the development of more than 30 mega-cities by 2020, is at the same time the result and the driving force of socioeconomic and technological changes, as we are moving at an unknown pace, with long-term effects on population and environment. Against this background, the analysis and optimisation of single and partial problems are of course important, and it is a prerequisite, but is not sufficient, as interdisciplinary knowledge is needed, to achieve the sustainability goals which are a 'sine qua non' to ensure the population's survival into the 22nd century. This review paper was focused on recent advancements in the wider spread field of smart technologies to provide a foundation for the two main axes of sustainability, namely efficient conversion of resources and rational waste management, through the implementation of the smart technologies.

In order to achieve this, review editorial was compiled selected papers that were presented at the 3rd International Conference on Smart and Sustainable Technologies (SplITech2018), held on 26–29 June 2018 in Split (Croatia) at the University of Split. Additionally, an overview of recent research studies was carried out, to highlight the progress in the field and to obtain a deeper insight into current advances on specific topics.

From the findings of the conducted review, specific and useful conclusions can be derived in the fields of energy efficiency, novel energy technologies and the applications of smart and IoT technologies. Recent works in the area of energy thrifty and environmental friendly buildings focus on the implementation of the NZEB concept and the effective integration of renewable energy technologies (RES) in buildings, based on experimental investigations and field case studies. Innovative thermal insulation materials and techniques are widely investigated for the improvement of the building envelope's energy performance, the targeted reduction of thermal bridges and the improvement of thermal comfort conditions. Another critical aspect is the effective demand-side management and the successful integration of different RES technologies into the NZEB concept, to be able to transform buildings from energy users to energy producers. Recent progress in solar energy utilisation is directed towards the further improvement of PV technologies available on the market as well as investigations of novel PV technologies, with Perovskite based technology being the most promising one for the upcoming market application. Efficiency improvement and further development of control strategies for PVs and for management of hybrid energy systems were also discussed.

Further points of interest are silicon-based PV technologies, such as cooling techniques for PVs, cleaning strategies for PVs, more precise regulation techniques for MPPT, etc. All those actions will lead to more feasible silicon-based PV technologies, which is important since they are expected to dominate the market for the coming decade. The application of PV/T technologies can contribute to increased overall efficiencies and utilised roof areas, which is always a commodity in short supply. Still, considerable research efforts are needed to improve the cost-efficiency ratio of PV/T systems. Similarly, research progress is also monitored in the development of CPV systems, where different concepts and ideas were discussed to overcome some present technical barriers and to reduce both the investment and operational cost of CPV technology.

Considering energy efficiency beyond the building sector, research results are discussing case studies for different engineering applications, systems and processes, including renewable energy technologies, freshwater generation systems, fuel cells, steam turbines, compressors, etc. One thing common in all these applications, is the margin for further improvements, especially to improve efficiency in the industrial and transportation sector, both

of which are energy intensive. Yet again, the importance of process integration methodologies was underlined, with further necessary advancements towards more efficient hybrid solutions supported by more efficient software tools.

Waste management is a key issue towards sustainability and a wide research area. The problems of plastic waste, especially of micro-plastics, food waste and electronic waste are in the focus of the research community and are inexorably linked with the stability of the ecosystems. Different recycling possibilities were being intensively investigated to enable smarter use of precious resources and a reduction of waste production. One point that emerges is the need to promote the circularity in the economy, a most promising approach which can ultimately address the resources and waste problems at the same time. However, there is a lot of research work that needs to be done, both on the methodology and its development via successful case studies.

The last thematic area within this VSI was dedicated to the smart city concept and the application of smart technologies supported by IoT technologies. In a sense, the smart city concept provides the framework for the implementation of all the mentioned technologies, yet at the same time, it cannot be considered as the simple summation of their results but is rather their integral. There is a significant growth of studies and research publications addressing the application of smart technologies and their incorporation into products. Recently investigated smart concepts are focused on several topics: smart city's framework, smart metering, smart transportation, security, smart agriculture, smart waste management, etc. Smart technologies are considered as an opportunity for cost reductions, a tool for the improvement of service quality and a way to achieve the reduction of environmental impacts. The way into the future leads probably along two routes. The first is the intensification of research focused on the potential application of smart technologies that can improve life quality, especially in urban areas, from air quality to public transportation for instance. The second is the improvement of the cost-effectiveness of smart technologies, which will provide a boost for their propagation. A finding met in most publications is that more case studies are needed, to demonstrate these factors to convince the public and the stakeholders of the benefits that can be achieved.

Economic growth, improvement of living standards and the development of society, in general, has an environmental cost, which has become apparent that it is leading to a distortion of natural balance. It is anthropogenic activities that cause to a great extent the problem, and it has to be human interventions that will provide solutions. Sustainability is a goal that is not illusionary, but it presupposes a vision, carefully planning of targeted actions and their timely and effective implementation. Novel technologies need to be critically evaluated, to fulfil complex requirements that will enable a balanced and sustainable future. The herein addressed contributions will hopefully help to obtain a better insight and understanding of causative consequences, technological potentials as well as threats regarding specific technologies, processes and products. The topics addressed are truly widespread, and this paper should have served its purpose if it has provided highlights that should act as an impulse and a guide for further and more targeted research by the scientific community.

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Review

Waste Management through Composting: Challenges and Potentials

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Abstract: Composting is the controlled conversion of degradable organic products and wastes into stable products with the aid of microorganisms. Composting is a long-used technology, though it has some shortcomings that have reduced its extensive usage and efficiency. The shortcomings include pathogen detection, low nutrient status, long duration of composting, long mineralization duration, and odor production. These challenges have publicized the use of chemical fertilizers produced through the Haber–Bosch process as an alternative to compost over time. Chemical fertilizers make nutrients readily available to plants, but their disadvantages outweigh their advantages. For example, chemical fertilizers contribute to greenhouse effects, environmental pollution, death of soil organisms and marine inhabitants, ozone layer depletion, and human diseases. These have resulted in farmers reverting to the application of composts as a means of restoring soil fertility. Composting is a fundamental process in agriculture and helps in the recycling of farm wastes. The long duration of composting is a challenge; this is due to the presence of materials that take a longer time to compost, especially during co-composting. This review discusses the proper management of wastes through composting, different composting methods, the factors affecting composting, long-duration composting, the mechanism behind it, the present trends in composting and prospects. The extraction of mono-fertilizers from compost, development of strips to test for the availability of heavy metals and pathogens as well as an odor-trapping technique can go a long way in enhancing composting techniques. The addition of activators to raw materials can help to improve the nutritional quality of compost. This review further recommends that degradable organic material in which composts slowly should be assessed for their ability to mineralize slowly, which could make them advantageous to perennial or biennial crops. Viricides, fungicides, anti-nematodes, and anti-bacterial of plant or organic sources could as well be added to improve compost quality. The enhancement of composting duration will also be useful.

Keywords: composting; organic fertilizer; biodegradability; decomposition; waste management

1. Introduction

Improper waste management is detrimental to human health. Apart from being unsightly, it causes air pollution, affects water bodies when dumped into the water, as well as depletes the ozone layer when burnt, thereby increasing the impact of climate change. Wastes are often improperly managed [1,2] using conventional methods. Wastes are burnt, disposed into oceans, waterways, and dumped by the roadsides [3]. These practices breed insects and pests, release offensive odors, are unsightly and contribute to global warming (during combustion). Organic (degradable) wastes transformation

is either aerobic or anaerobic. When transformed under aerobic conditions, compost is formed [4]. When treated anaerobically, biogas—as well as effluents that can be used as biofertilizers—are formed [5]. Composting is a safe method of waste management. Composting is an aerobic process where complex degradable materials are degraded and transformed by microorganisms into organic and inorganic byproducts [6]. The byproducts contain ‘humic-like’ compounds that differentiate them from those found in native soil, coals, and peats. Composting is a means of transforming different degradable wastes into products that can be used safely and beneficially as biofertilizers and soil amendments [7–9].

The composting process helps to protect underground water from becoming polluted compared to the landfilling method of waste disposal, which could pose a pollution threat to underground water. This is because there is a reduction of the microbes and chemical pollutants during composting. These are the pathogenic microbes present in waste which are harmful to humans. The beneficial microbes absorb chemicals such as POPs and EDRs left in the soil during composting. An elaborate explanation on this is made later in this review. The application of composting increases agricultural productivity and organic matter content of the soil [10], owing to the sufficient nutrient in the composted materials and the presence of plant growth-promoting organisms [11]. This helps to ensure food security to a great extent. Aside usage as fertilizer, compost is useful in bioremediation [12], plant disease control [13], weed control [14], pollution prevention [15], erosion control, landscaping and wetland restoration. Composting also increases soil biodiversity and reduces environmental risks associated with synthetic fertilizer [16]. Composting is started and managed under a controlled environmental condition rather than a process that is natural and uncontrolled [17]. The controlling process differentiates composting from decomposition (a naturally occurring process) [18]. As beneficial as composting is, it takes a longer time to be ready, produces offensive odor, has long mineralization time, may contain some pathogens that can withstand high temperature to some extent, i.e., thermotolerant pathogens and insufficient nutrient content. All these have discouraged farmers from incorporating them as a means of sustainable agriculture. This made the synthetic counterpart (chemical fertilizers), which is readily available, preferred to the organic source, i.e., composting. Compost should be appreciated after the comparison of the advantages and disadvantages of the two sources of nutrients. More information on how to trap odor, a rapid method of pathogen and heavy metal detection will make composting more utilized. Several works have focused majorly on the agronomic evaluation, microbial contamination, and nutrient composition of compost [19–22], leaving out the causes of long duration in composting and prospects to alleviate odor, pathogen and heavy metals. This review evaluates the challenges associated with composting and the prospects which can make composting to ensure sustainable agriculture. Therefore, this review recommends that mono-nutrients could be extracted from compost, rapid methods should be developed to detect pathogens and heavy metals, odor-trapping techniques should be sorted. In addition, the concept of slowly composting organic materials should be well explored to ascertain if they contain specific nutrients and if they could be sustainable in biennial and perennial farming, composts should also be enriched with nutrient-rich activators, antibacterial, antifungal, antiviral and anti-nematode agents.

Although composting has many reported benefits that have been mentioned above, various challenges are posed by this method of waste management, from its effects on climate change to its release of carbon dioxide into the atmosphere and the depletion of oxygen, as well as the production of offensive smells from the release of hydrogen sulfide produced from anaerobic activity. As a result of these health impacts, various regulations have been put in place by different bodies in different countries concerning the use of the method. These limitations show that this method should still be improved to address various concerns mentioned. Two major areas of improvement are the temperature regulation and the control of oxygen flow. These are key to the function of the microbes carrying out the composting process. The various microbes at each stage have the temperature at which they function, so these must be well-monitored, and they need oxygen so that the anaerobes will function less. Increased activity of the anaerobes increases the production of more carbon dioxide

and the release of hydrogen sulfide, which can cause various health issues. If these can be sorted, then opportunities abound for this process to be effective in proper waste management.

2. Wastes: How Are We Affected and How Should We Treat Them?

Waste is any unwanted solid, liquid, or gaseous substance [23]. Poorly managed wastes have adverse effects on humans, animals, plants, and the environment [24]. About 50% of wastes generated is organic [25–27]; thus, the proper management of organic wastes will drastically reduce the volume of pollution arising from improper waste management.

2.1. Effects of Wastes

Wastes affect the environment leading to severe hazardous impact on lives. Humans and animals alike are affected by these adverse effects, which can cause disease outbreak, reduction in life expectancy, and unsafe environment. Some wastes may rot, but those that do not will smell and generate methane gas, which significantly contributes to the greenhouse effect. The environmental and health impacts of wastes will be described subsequently. Wastes pollute the air, water, and soil. Air pollution includes odor, smoke, and dust. When solid wastes are burnt, greenhouse gases such as carbon dioxide and nitrous oxide are released, these lead to ozone layer depletion and greenhouse effect [28]. Hydrogen sulfide and methane are also released into the air. These substances are toxic to human lives.

Another environmental effect of waste is water pollution. It is reported that approximately 1400 people die daily due to water and water-related problems/disease [29]. Wastes that find their way into water bodies such as rivers, streams, and oceans can have a disruptive influence on the water bodies by lowering the pH and causing toxicity to the aquatic inhabitants and humans that use the water. Some of these pollutants are less soluble in water and are highly lipophilic [30]. Reports have shown the presence of toxic metals [31–33] in water bodies. Water polluted with wastes from a location could serve as receiving water in another place. Soil pollution, too can result from improper waste management. Wastes dumped indiscriminately are unfriendly to the sight, breeding disease vectors. Metals from iron, radioactive wastes, etc. are toxic to soil organisms and plants, thereby reducing crop productivity [34].

Human diseases result from improperly treated wastes that harbor disease vectors. Mosquitoes breed in stagnant water bodies, in blocked drainages, in tires that collect rainwater, in empty food cans, plastics, etc. The refuse workers as well face some hazards which include tissue damage, respiratory infection, injuries from glass, razor blades and syringes, as well as parasite infections caused by skin contact with refuse [2]. Though workers use protective measures such as gloves and nose masks, advanced automated means should be encouraged to prevent refuse workers from casualties associated with waste treatment.

In Australia, Langdon, et al. [35] studied the risk assessment for organic contaminants in composted solid municipal waste. In their study, they were able to categorize the risk levels into low, medium, and high priority, based on the health implications. From this, measures can be put in place on how the individual toxicants from these wastes can be properly and efficiently disposed of. In another study by Gangwar, et al. [36], they studied the impact of electronic waste on human health and reported the release of various toxic metals into the air, as a result, causing air pollution. Other studies have also reported the impact of these wastes on human health and the environment [37–40].

2.2. Classification of Wastes According to Biodegradability

Based on the biodegradability, wastes can be classified into biodegradable, moderately degradable, and non-biodegradable. Aerobic and anaerobic organisms act on biodegradable wastes as a result of speeding up their degradability rate. Some agricultural wastes such as cow dungs, poultry droppings, etc. are examples of biodegradable wastes [28]. While moderately degradable wastes are slowly degrading wastes. They have tough textured components. Examples of such wastes are wood and cardboards [28]. This is discussed extensively in the latter part of this review. Non-Biodegradable

Wastes, on the other hand, cannot be broken down biologically [2]. Examples of non-biodegradable wastes are wastes from mines, mineral materials, polythene bags, leathers, plastics.

2.3. Methods of Waste Disposal

Wastes could be composted or disposed of using conventional methods. Below is the classification of the waste disposal methods comprising of the conventional and composting methods.

2.3.1. Refuse Disposal by Open Dump

This is a refuse disposal method where wastes are dumped indiscriminately in any available space. Waste could be disposed of on the street or the highway. This method of waste disposal should be discouraged. The wastes disposed of through this means to serve as breeding grounds for houseflies and rodents, which are vectors of certain diseases (cholera and Lassa fever). They also cause an offensive odor [2].

2.3.2. Refuse Disposal by Animal Feeding

Domestic animals such as goats, dogs, and sheep are fed with wastes like yam peels, cassava peels, leaves, and leftover foods. The food wastes could be infected and thus, lead to infection of animals directly feeding on the wastes or humans that feed on those animals [41]. Some human diseases have been traced to the consumption of animals that have been previously fed with contaminated feeds [41]. For instance, trichinosis in humans has been traced to the contamination of raw garbage used in feeding animals [41].

2.3.3. Refuse Disposal by River and Ocean Dumping

Wastes containing numerous chemical substances are discharged into water bodies and could render the water toxic to aquatic life as well as humans [3]. There could be biomagnification of toxic wastes in humans, which is transferred from the consumption of animals living in water bodies [42]. Some industries are located close to rivers or oceans for natural discharge of their effluents into the water bodies. They do this in a bid to save the cost of waste disposal. In some developing and underdeveloped countries, houses are built on top of water such that their feces drop directly into water bodies, which eventually carry it away. The water which flows from this source can be receiving water in another location and may serve as a source of water-borne pathogens, which could cause infection for people using the water for various domestic purposes. Such water-borne pathogens include *Vibrio* sp., *Salmonella* sp., and *Shigella* sp. [43].

2.3.4. Refuse Dump by Incineration

This is the process of burning combustible wastes at high temperatures. This method reduces the volume of such wastes by 90%. The leftover from the burning of materials like ashes, glass, and metals are then disposed of in a sanitary landfill [2]. This method only reduces the size of wastes, it is not a total means of waste disposal, and it is also associated with fire disaster and the release of greenhouse gases [44]. Energy can be produced from incineration. This energy is preferable to energy produced from coal. This method could save about 2–2.6 Mt of CO₂ eq per year [45].

2.3.5. Refuse Disposal by Deep-Well Injection

The deep-well injection method involves the deposition of wastes into the subsurface, impermeable rock layers. This method is used for toxic fluid wastes from industries [2]. Wastes such as acidic and caustic chemicals, oil field brine, and radioactive wastes from uranium processing plants are disposed of using this method. Before wastes can be disposed of using this method, the local subsurface geology of the area should be considered to prevent pollution of underground water. The disadvantage associated with this method is that it can lead to groundwater contamination.

2.3.6. Refuse Disposal by Sanitary Landfills

This method of waste disposal involves the use of waste as landfills. This method is also known as controlled tipping [46]. The process is carried out by spreading wastes in thin layers and compressing with a heavy bulldozer when each layer is added. When the refuse is about 3 m high, it is covered by a thin layer of clean soil and compressed again. This process is repeated until the pit is filled [2]. Wastes disposed of through this method could host pathogenic microbes or toxic chemicals that are harmful to the soil and soil organisms, as well as humans (through inhalation of polluted air or consumption of contaminated water). These adverse effects have made this method of waste disposal to be discouraged by the EU members states [47], thereby promoting other methods of waste disposal such as anaerobic waste treatment and incineration with energy recovery [48]. A landfill directive was proposed in 2001 that the EU member state should reduce waste management by landfill to 35% by July 16, 2016, and that landfill is eliminated by 2020 [49].

2.3.7. Refuse Disposal by Composting

Composting can eradicate degradable organic wastes. Degradable organic wastes are otherwise known as biodegradable wastes [41]. Composting is a workable means of transforming various organic wastes into products that can be safely used and beneficially employed as biofertilizers. Recalcitrant substances, polythene bags, and plastics, among others, cannot be composted. Composting is a safe way of managing organic wastes, but it is associated with odor production and release of greenhouse gases (CO₂, SO₂, and NO₂).

The comparison between conventional and composting methods of waste management are further represented in Table 1.

Table 1. Comparison between composting and conventional waste management

Composting	Conventional	References
Composting helps to ensure environmental sustainability, as it helps to hold the soil particles together, thereby preventing erosion. It helps to keep wastes in a controlled environment and recycled to a useful product. They help in the bioremediation of polluted soil. They also increase biodiversity in the soil by attracting different insects, bacteria, fungi, etc. that are beneficial to the crop. They are treated in a controlled environment where they do not stay forever	Conventional waste management methods (open dump, river and ocean dumping, sanitary landfills, and incineration) pollutes the soil, air, and water bodies. They release odors and create bad sights. In addition, they cause contamination of underground water when wastes are buried.	[50–52]
They also help to suppress diseases in plants and enrich the soil	They (animal feeding, incineration, open dump, river and ocean dumping) host pest, pathogens and insects, which have a bad impact on human and animal health	[53]
They help to reduce greenhouse effects by mitigating the production of gases like methane. Though CO ₂ is release during composting, lesser compared to other (combustion) modes of waste management	They contribute majorly to the greenhouse effect. This is as a result of the combustion of wastes	[54,55]
Reduces the volume of wastes drastically	Wastes (open dump, river and ocean dumping,) are usually piled and therefore increasing in volume of wastes	
Recalcitrant substances, such as polythene bags, plastics among others cannot be composted	It (incineration) can treat plastics, polythene bags, etc., though they pose an environmental pollution threat	[56]

3. Fertilizer–Environment Impact: An Overview

Fertilizer is defined as any substance of natural or synthetic origin that is added to soil to supply certain elements crucial for plant growth [57]. Fertilizer is required to be applied to the soil to replace

the nutrients taken up by crop from the land with the primary goal of maximizing productivity and economic returns [58,59].

Fertilizers may be made up of one or more essential nutrients, and this serves as a means of fertilizer classification. The fertilizers that contain only one of the major elements are called single, simple or straight fertilizers. Those that contain two or more of the major elements and trace elements are categorized as mixed or compound fertilizers [60]. Nitrogen, phosphorus, and potassium (NPK) are the major nutrients required by plants. Although micronutrients are also necessary for normal development in plants, higher concentration leads to toxicity. According to Rai, Ashiya, and Rathore [59], chemical fertilizers have been said to be toxic to soil organisms such as earthworms, which are well known to promote soil fertility as a case study. Fertilizers can be grouped into organic or inorganic fertilizer according to their source of production [61]. Organic fertilizer is a fertilizer that is produced from organic substances or materials which could be biofertilizers or composts, e.g., plants and animals remain, while inorganic fertilizer is made from synthetic or inorganic raw materials. The deleterious effect caused by the chemical fertilizers on the environment through chemical toxicity and leaching into the waterways thereby affecting aquatic life directly or indirectly has necessitated the need for safer alternatives. Some alternatives have been proposed such as the use of microorganisms, composting, among others. We try to focus on composting and how it can help in maintaining a safer environment.

3.1. Composting Methods

There are different composting methods, with each method having its advantages and disadvantages. Therefore, the method that best suits the goal of the researcher and the type of material to be composted dictates the composting method to be adopted. Some of the composting methods are enumerated below.

3.1.1. Indian Bangalore Composting

The Indian Bangalore composting method was developed at Bangalore in India [62]. The method is majorly recommended for the composting of night soil and refuse. The composting is carried out by digging trenches or pits about one meter deep where organic residues and night soil are put in alternate layers [62]. The pit is finally covered with a 15–20 cm thick layer of refuse. The materials are left in the pit without turning or watering for three months. During this period, there is a reduction in the volume of the materials, and more night soil and refuse are placed on top in alternate layers and covered with mud or earth to prevent loss of moisture and breeding of flies. This type of composting takes about six to eight months to obtain the finished product [62]. This method is laborious and expensive to support.

3.1.2. Vessel Composting

In-vessel composting refers to any type of composting conducted in an enclosed area such as a container, building, or vessel. In-vessel methods depend on a variety of forced aeration and mechanical turning techniques to enhance the composting process [63]. This method is labor-intensive and expensive.

3.1.3. Windrow Composting

Windrow composting is conducted by placing raw materials in long narrow piles or windrows, which are turned regularly. The mixing of the materials allows aeration into the setup. A typical windrow composting set up should start from 3 feet in height for dense materials like manures and 12 feet high for fluffy materials like leaves [63]. It is difficult, and costly to support, but it is rapid and retains heat.

3.1.4. Vermicomposting

The term refers to the use of earthworms for composting degradable organic matters [64]. Earthworms can degrade practically all kinds of organic matter by feeding on them. They can eat their body weight per day. For example, earthworms that weigh 0.1 kilogram can eat 0.1 kilogram of residue per day. The excreta of the worms—termed “castings”—are rich in nitrate, as well as available forms of phosphorus, potassium, calcium, and magnesium, which improve soil fertility [28]. The existence of earthworms in the soil promotes bacterial and actinomycetes growth.

3.1.5. Static Composting

This is a traditional method of composting where wastes are composted aerobically using passive aeration (little and infrequent turnings or static aerations like perforated poles or pipes). This method is time-consuming, though it is a simple way of composting, which has low operational and capital costs compared to vermicomposting, windrow, vessel, and Indian Bangalore composting. This method simply involves the formation of a pile of raw materials and has a low requirement of labor and equipment. Aeration is based mainly on the passive movement of air through the pile, thereby degrading the organic matter slowly [63].

3.1.6. Sheet Composting

Sheet composting release the benefit of decayed organic material without building a composting pile. In this method, organic matters such as leaves, garden debris, grass clippings, weeds, and vegetative food are thinly spread directly onto the soil as a mulch. The organic materials are then tilled in with a hoe, spade or garden fork and left to decay there, rather than in a heap or container. One or more layers of organic material(s) are spreads over the growing area, watered thoroughly and left to decompose until planting time. More layers of organic materials are placed at the bottom layers decompose thoroughly [62]. The method is cheap and straightforward.

3.1.7. Indian Indore Composting

Indian Indore method involves a mixture of raw materials such as plant residues, animal dung, and urine, earth, wood ash, and water. All organic wastes available on a farm such as weeds, stalks, stems, fallen leaves, pruning, chaff, fodder leftovers are made into a layer about 15-cm-thick until the heap is about one and a half meters high. The heap is cut into vertical slices of about 20–25 kg for the night rest. The bedding is taken to the composting pits and filled layer by layer within a week. Enough quantity of water is sprinkled over the materials in the pit to wet them. Moisturizing of the compost is done only three times throughout the whole period of composting. The moisturizing is done on the fifteenth day after stacking the compost pit, on the next 15 days after the first moisturizing and finally after one month after the first moisturizing. This method is labor-intensive and time-consuming. It is also prone to flies, and pest disturbances and wind can lead to loss of nutrients [62].

3.1.8. Berkley Rapid Composting

This is a fast composting method. Here, materials compost faster if the size is between 0.5–1.5 inches in size. Soft, succulent tissues do not need to be chopped in very small pieces because they decompose rapidly. The harder the tissues, the smaller they need to be chopped to enhance decomposition. Once a pile is started, nothing should be added because it takes a certain length of time for the initial materials to break down, and anything added has to start from the initial breakdown stage—thus lengthening the decomposition time for the whole pile [62].

3.2. Uses of Compost

3.2.1. Increase in Soil Fertility, Crop Yield, Erosion Control, and Soil Amendment

The compound fertilizer form of compost is a welcome idea at present because of the recent campaign against the use of synthetic fertilizers. According to Majbar, et al. [65], compost helps to improve soil fertility and plant yield. Supplement of compost with synthetic fertilizer can be another route of application of compost for plant growth. Literature showed synthetic fertilizer might be more effective than compost in plant growth promotion [66]; therefore, we suggest the combined application of the two in appropriate proportions. Composts also host plant-growth-promoting bacteria, which help to increase soil fertility and plant growth.

Erosion causes the soil to lose its fertility. An appreciable amount of nitrogen, phosphorous, and potassium are lost to erosion. The use of surface-applied organic amendments has been reported to be very successful in combating erosion. Compost increases the water holding capacity, soil structure, and aggregate stability of the soil [63]. This is due to the presence of humus (stable residue resulting from a high degree of organic matter decomposition) that binds to the soil and can be said to act as soil 'glue' holding the soil constituents together [67].

3.2.2. Biocontrol of Diseases, Bioremediation and Safe Waste Management

Compost serves as a biologic control for plant diseases. The microorganisms present in compost use different mechanisms in combating their pathogenic counterparts. These include competition for nutrients, parasitism, predation, antibiotic production, production of lytic, and other extracellular enzymes or compounds [68]. For instance, the control of plant wilt and damping-off diseases was reported to be countered by *Bacillus* sp. in compost [69].

Soil polluted with heavy metals can be remediated with compost. Compost has been useful in degrading chlorinated and non-chlorinated hydrocarbons, wood preserving chemicals, solvents, heavy metals, pesticides, petroleum products, and explosives in soil. Compost can reduce the toxicity of some chemical pollutants by absorbing or degrading such elements [70]. Heavy metals can be made unavailable by precipitation [71], adsorption [72], complexation [73] and redox reactions [74].

Composting is a safe way of managing degradable organic wastes. Wastes that could be dumped into water bodies, roadsides or even burned can be composted. The products from such composted wastes are used for different beneficial purposes [63,75].

3.3. Major Elements in Compost

For compost to be useful, it must have some elements in an optimum quantity which will supply adequate nutrients to plants. Though these elements may not be necessary if the compost is meant for landfills.

3.3.1. Nitrogen

Nitrogen is one of the most important elements for plant growth when there is a deficiency of it plant growth and development is impaired. Nitrogen is a significant constituent of chlorophyll and responsible for the green color in plants. Compost has been reported to contain optimum N content required for plant growth [75]. High accumulation of nitrogen in compost fertilizer is not a common occurrence because due to mineralization, nutrients in compost fertilizer is released gradually. Excess nitrogen in plants because of fertilizer over-application can result in rapid growth, brilliant green color, and a diminished root system. In extreme cases, excess nitrogen can cause the burning of the leaf tissue and the plant's death. Deficiency in nitrogen causes a loss in the green color of leaves, stunted growth, low protein content, and yellow coloration [76].

3.3.2. Phosphorus

Phosphorus is a constituent of the complex nucleic acid structure of plants, which regulates protein synthesis. Phosphorus is, therefore important in plant's cell division generation of new tissue and complex energy transformations in the plant. Adding phosphorus to soil low in phosphorus promotes root growth, winter hardiness, stimulates tillage, and often hastens maturity in plants. Deficiency in phosphorus can lead to stunted growth, poor seed and fruit development, delayed maturity, and there could be a change in the color of the matured leaves to characteristic dark blue to blue-green coloration in plants. Compost has been reported to contain optimum phosphorus concentration necessary for plant growth [75].

3.3.3. Potassium

Potassium is an element necessary for proper plant growth. It increases plant growth, carotene, and chlorophyll contents [77]. It promotes the vigor and color of plants. Potassium is needed for the plant to create sugars. It is also essential because it helps the plant to resist disease and survive adverse weather conditions such as drought and cold. The deficiency of potassium in plants can lead to scorching and browning of tips of older leaves, which progresses to the total leaves with time. Weak stalks could also be associated with potassium deficiency. According to Kammoun, et al. [78], composts are good sources of substantial phosphorus required for plant growth.

3.4. Microbiology of Composting

According to Hafeez, et al. [79], the major component responsible for the biodegradation and conversion process during composting is the resident microbial community. Composting occurs by the activity of a mixed microbial community. Of all the microorganisms that have been said to be present during composting, bacteria and fungi have the highest population [80]. Two different groups of aerobic microorganisms are involved in composting, the first group is the mesophilic organisms, while the second group is the thermophilic organisms. These organisms could be bacteria, actinomycetes, molds, and yeasts, and they dominate different phases of composting. The mesophilic stage, the thermophilic stage, and the second mesophilic stage, which is known as the cooling stage, are the important phases in the composting process. The composting process could start with a mesophilic stage where the temperature lies between 20–40 °C (Figure 1). The thermophilic stage comes in after the mesophilic stage. In the thermophilic stage (40–70 °C), active decomposition takes place compared with the mesophilic stage [79]. During this stage, mesophilic organisms are killed or inactivated and the population and diversity of thermophiles and/or thermotolerant bacteria, actinomycetes, and fungi increase [81]. The second mesophilic stage is also known as the curing phase, comes after the thermophile stage; at this stage, the compost is matured.

Actinomycetes have been observed to have biodegradative activity; they secrete a wide range of extracellular enzymes [82]. They as well have the capacity to metabolize recalcitrant molecules [82]. Some lignocellulose degrading microorganisms are involved in composting. Lignocellulose comprises polysaccharides (cellulose and hemicellulose), phenolic polymer, and lignin [83]. The ability of organisms to degrade organic matter depends on their ability to produce enzymes that are needed to degrade the substrate's components (cellulose, hemicellulose, and lignin). The more complex a substrate is, the more complex the enzyme required to biodegrade the organic matter [84]. Singh and Nain [85] revealed that hundreds of fungi are also capable of degrading lignocellulose. They said that three major types of fungi are known to reside in dead woods containing lignocellulose. They are soft rot fungi, brown rot fungi, and white-rot fungi. These organisms degrade the wood components. Soft rot fungi (*Chaetomium*, *Ceratocystis*, and *Kretzschmaria deusta*) are capable of decomposing cellulose but degrade lignin slowly and incompletely. Therefore, the regulation and control of these microorganisms can help to speed up the rate of composting.

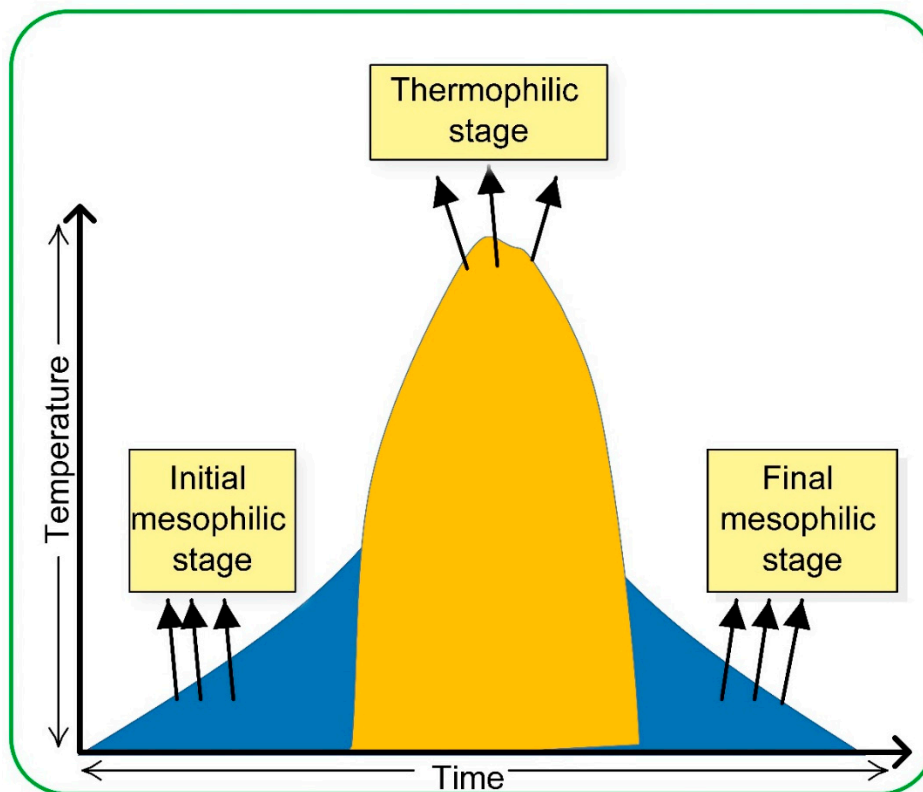


Figure 1. Temperature changes in composting.

3.5. Biochemistry of Composting

Compost is essentially a mineralization process during which an array of aerobic and facultative organisms degrades organic matters to inorganic compounds with a stabilized humic acid or humus as a major end product. The three major fractions of humus are fulvic acid, humin, and humic acid. Humus contains amino acids, purines, pyrimidines, aromatic substances, uronic acids, amino sugars, pentoses, hexoses, sugars, alcohols, methyl sugar, and aliphatic acids. In addition, during composting, CO_2 , NO_3 , SO_4 and PO_4 are released. These are released in gaseous forms in the presence of oxygen (aerobic conditions).

3.6. Insects in Composting

The role of insects in composting cannot be underestimated. They can either be present non-deliberately [86] or inoculated. Different insect species such as the Black Soldier Fly (BSF) [87], Japanese beetles [88], cricket [89], Milichiidae [90], and housefly larvae [91]. Of all these species, BSF is the most popular, due to its ability to degrade a wide range of substrate [92,93]. Insects degenerate large biomolecules of wastes into forms of nutrients that can be used to promote plant growth [93]. It is noteworthy to note that some insect species which have been tagged “problematic” could be of advantage during composting. For instance, stable fly (*S. calcitrans*) well known to induce weight loss, reduce milk production, and cause death in cattle and as well as infect animals and humans [90].

3.7. Factors Affecting Composting

The factors affecting composting include the texture of raw materials, composting temperature, moisture content, pH, oxygen, and C/N ratio.

3.7.1. Temperature and Carbon to Nitrogen (C:N) Ratio

Temperature is an essential factor in composting because it helps to hasten the composting process and eliminate pathogenic organisms that are harmful to soil organisms, plants, animals, and humans [79]. Microorganisms present during the composting process are classified according to the temperature at which they exist. Microorganisms growing at 20–40 °C are classified as mesophilic organisms, while those growing above 40–70 °C are thermophilic bacteria [81]. Mesophilic organisms start the composting process; they break down the readily degradable compounds of the waste. Their metabolism leads to a rapid increase in compost temperature. The volume of the wastes treated sometimes affects the temperature (heat generation); if the volume of waste is low, the high temperature may not be attained. Sometimes the temperature during composting does not rise to 45 °C, but pathogens could die when nutrients present in the composting materials are exhausted and when competitive organism excrete enzymes which are capable of destroying the pathogens.

An ideal C:N of 30 is optimum for a composting process [63,94]. When composting materials are low in C:N, air will fail to penetrate the pile, which results in anaerobic conditions and causes odor production in addition to nitrogen loss in the form of ammonia gas. In addition, if the C/N ratio is too high, the activities of microorganisms will be reduced, and the rate of decomposition will be slow [95].

3.7.2. Oxygen and pH

The presence of oxygen is important during the composting process. When organisms oxidize carbon for energy formation, the oxygen present is used up, and gases are produced. Without adequate oxygen, the composting process will become anaerobic, and gases (methane, carbon dioxide, and ammonia) will be produced, leading to the production of undesirable odors [63].

The pH of the materials that are composted affects the composting rate. Alkaline pH has been reported to be best for composting. When pH is acidic, composting is very slow because the microorganisms are destroyed [96].

3.7.3. Moisture Content, Particle Size, and Raw Material Texture

Moisture is a key factor that supports the metabolic activities of microbes. The moisture content for composting materials should be maintained between 40% to 60% [96]. The presence of moisture in compost was reported to come from either the initial water added or the metabolic water produced by the actions of the microorganism. Excess water leads to a reduction in the diffusion of oxygen, and this, in turn, reduces the metabolic activities of the organisms. Microbial cells fully depend on water for their metabolic activities. Thus the metabolism of organic molecules by microorganisms is only possible when such organic molecules have been dissolved in water. Moisture decreases as the composting process proceeds [81].

Best composting conditions are usually attained when the material's particle size ranges from 1 to 2 inches in diameter [62]. This size brings about a higher surface area, which helps to increase microbial activity as well as the composting process. The rate at which aerobic decomposition takes place increases as the particle size decreases. However, extremely small particles may reduce the oxygen movement within the pile, thereby reducing the composting rate [97]. Besides, tiny particle size encourages moisture retention and reduces airspace thus leading to a decrease in the composting process.

Degradable organic materials with hard texture, high lignin or tough texture generally composts slowly [98]. For instance, hard, textured leaves have a high tendency to compost slower than soft textured leaves. Leaves that have thorns also may take a longer time to compost because of their physical barrier. Leaves with leathery or hard texture may be due to high lignin content.

3.8. Waste Management: Recent Trends, Challenges, and Potentials of Composting

Technological advances have made separation processes easier, driving the methods and materials used in composting through important changes. Many primary separation tools have evolved for

better waste management through composting. The composting process has been improved with the addition of biochar as a co-compost material. This reduces the time of composting, and suggestions have been made that seed germination improves when directly placed in finished compost. The surface area of biochar is reduced by the clogging of the pores. Among the activities affected by the presence of biochar in composting are those of the microbial communities. It increases the presence of some microorganisms [99]. It influences and enhances their efficiency in fast decomposition. Properties such as high stability, high nutrient sorption, porosity, good water holding capacity, low bulk density make biochar useful in composting [100]. Biochar also balances pH and acts as a catalyst in speeding up composting [101]. The control of odor and bioaerosols released during composting will go a long way in improving the efficiency of composting. Odor release can be prevented by improving aeration in compost piles, using oxygen feedback control and aeration process with a switch [102]. The addition of bulking agents such as rice straws, sawdust, wheat straws will remove moisture from the compost pile and increase air porosity [103]. Toxic gases released during composting can as well be trapped using modern bioreactors such as the airbag bioreactors [104] and spray towels [105]. The airbag bioreactors trap and recycle ammonia, thereby increasing the nitrate content of the compost [104].

Techniques such as culture-based and culture-independent methods were used for decades to check the microbial diversity in composting. However, some limitations occur in the use of culture-dependent techniques, which prioritizes the use of culture-independent techniques. This was also found to be limited in community evaluation giving rise to the recent use of molecular methods. Molecular methods make evaluations and characterizations easier and affordable. Different outcomes from these methods have led to questions arising as to the authenticity of these methods [106]. For comprehensive reviews and research on methods in identifying microbial diversity in compost, studies of Awasthi, Sarsaiya, Awasthi, Liu, Zhao, Kumar, and Zhang [55], Yamamoto and Nakai [107], Qiu, et al. [108], Hou, et al. [109] and Ishii and Takii [106].

3.8.1. Long Composting Duration

Agricultural wastes such as leaves, plant part remains, and dead plants occupy a large percentage of wastes produced on the farm. Some of them hold recalcitrant compounds and low nutrients, which make their composting difficult. When such wastes are added in a composting pile, they slow down the composting rate of other materials. The different taxa of plants vary in toughness (sclerophylly) due to quantities and varieties of chemical compounds (e.g., lignin, suberin, cellulose, phenolics, tannins, irritants, and allergens) [110]. High-quality leaves (like nutrient-rich alder leaves) will decompose faster than low-quality leaves (like nutrient-poor conifer needles). High nicotine content in leaves, such as tobacco, also contributes to their elongated composting time [97]. High lignin, cutin, polyphenol, and suberin content in plant wastes elongates the composting time in a composting pile. Lignin are produced by phenylpropanoids (coniferyl, p-Coumaryl and sinapyl alcohols). Lignin is very complex to compost due to its recalcitrant nature. Highly crystalline lignocellulose is more recalcitrant when compared to the amorphous portion of the lignocellulose. Though certain bacteria and fungi (for instance, Basidiomycetes and Actinomycetes, respectively) degrade lignin over time. These species produce complex enzymes. The enzymes they produce include manganese, versatile, laccase, lignin, and dye-decolorizing peroxidase. Actinomycetes are also capable of degrading lignin [111].

Highly phenolic compounds take a longer time to compost due to their complex chemical structure [110]. Two groups of bacteria can degrade phenol. The first group of bacteria (e.g., *Arthrobacter*, *Micrococcus*, *Alcaligenes*, *Acinetobacter*, *Corynebacterium*, and *Staphylococcus*), use phenol as a carbon source while the other group utilizes other forms of carbon as their energy source. *Penicillium*, *Fusarium*, white-rot fungi, and some algae are also capable of degrading phenol.

Co-composting is the addition of materials together during composting. This is done majorly to bring about an optimum C:N, to hasten the composting process and also to improve the fertilizer quality [81,112,113]. While the co-composting, a combination of different materials may hasten or slow down the composting rate. When highly nutritious substrates are added to composts, microorganisms

become more available, and the composting process is hastened. When materials with low nutrients, high cellulose, or high lignin contents are added to a compost pile, the composting process is slowed down.

High C:N in organic materials makes them unsuitable for the microorganism to utilize, making them difficult to compost. Reduction of the C:N of such substrates using activators will be necessary to ensure a hastened composting process. Activators are sources of microorganisms that are expected to degrade the raw materials that are being composted [114]. Examples are sewage, poultry droppings, cow dung, pig dung, goat dung, etc. They are known to have a low C:N ratio, which makes composting them alone very difficult because of the odor problem associated with them [70]. Therefore, co-composting them with degradable materials having a high C:N ratio helps to attain the proper C:N ratio. Furthermore, materials that take longer time to compost can be composted separately to prevent it from slowing down the composting process of other materials. The composts made from such materials could as well be evaluated for their ability to release nutrients over a long period to a biennial or perennial crops.

3.8.2. Low Nutrient and Agronomic Value

The agronomic evaluation of compost is conducted to observe the effect of the composts on the growth of certain plants by assessing the yield of plants cultivated with the compost, and the results observed are used to determine the quality of the compost. Compost has been reported to increase the yield of crops due to the nutrient present in them [115–117]. In a similar manner, there have also been reports of low nutrient status in compost, which did not increase plant growth. It is, therefore very important to evaluate the nutritional value of composts and as well add nutrient-rich substrate to improve its nutritive and agronomic value.

Chemical analysis is conducted on compost to examine the quality and concentration of the elements present in them. According to the Food and Agricultural Organization of the United Nations (FAO, 2001) supported by the work of {Brinton, 2000 #764} Brinton (2000), the standards of nitrogen(N), phosphorous(P) and potassium(K) in organic fertilizer are stated that N content should not be less than 1%, while the P and K content should not be less than 1.5%. In addition, the fertilizer must supply calcium, zinc, copper, and other essential micronutrients in concentrations that range from 0.01%–0.05%.

3.8.3. Detection of Pathogenic Microbes in Composts

The source of the degradable materials and activators (which could be animal dung or sewage) determines the diversity and population of the microorganisms as well as the pathogens that could exist in the compost produced [118]. Pathogenic organisms like *Escherichia coli* and *Salmonella* sp. are present in composts [67,119]. According to Wu, et al. [120], *Thermoactinomyces* was also reported from mushroom compost. *Thermoactinomyces* are thermophiles that can cause “farmer’s lung”; an allergy disease of the respiratory system in agriculture workers. Composts should be properly evaluated for the microbial and chemical constituent to ensure the safety of plants, soil organisms, animals, and humans.

3.8.4. Composting on Persistent Organic Pollutants (POPs) and Endocrine Disruptors (EDRs)

POPs and EDRs are hazardous chemicals that are leftover in soils, water, etc., and are not easily degraded by all means available. They include polycyclic aromatic hydrocarbons (PAHs) (fluoranthene, benzo(b)fluoranthene and benzo(a)pyrene) and nonylphenols (NP) among others. POPs and EDRs affect human health negatively, therefore, the need to take them seriously. Exposure to EDRs is mainly through inhalation, contact, and ingestion of contaminated products, air, water, and soil. Plants absorbed these hazardous chemicals from soils in contact with treated waters [121]. Contaminations from water and soil have been documented in Asia, the United States and Europe [122,123]. Ingesting these plants, therefore, leads to bioaccumulation of EDRs in humans, although quantities absorbed by plants may

be negligible. Finding a means of eradicating these hazardous groups of chemicals has not been easy. Although many methods have been employed in eradicating them no accepted level of success. However, compost methods have shown to be capable of eliminating these threats to human existence. A careful application can improve agricultural and environmental sustainability [124]. The presence of microbes in compost help to absorb POPs therefore bioavailability of these POPs is very critical for their absorption. To cope well, microbes go through various adjustments such as physiological, behavioral, and morphologic to be able to fully absorb (Figure 2).

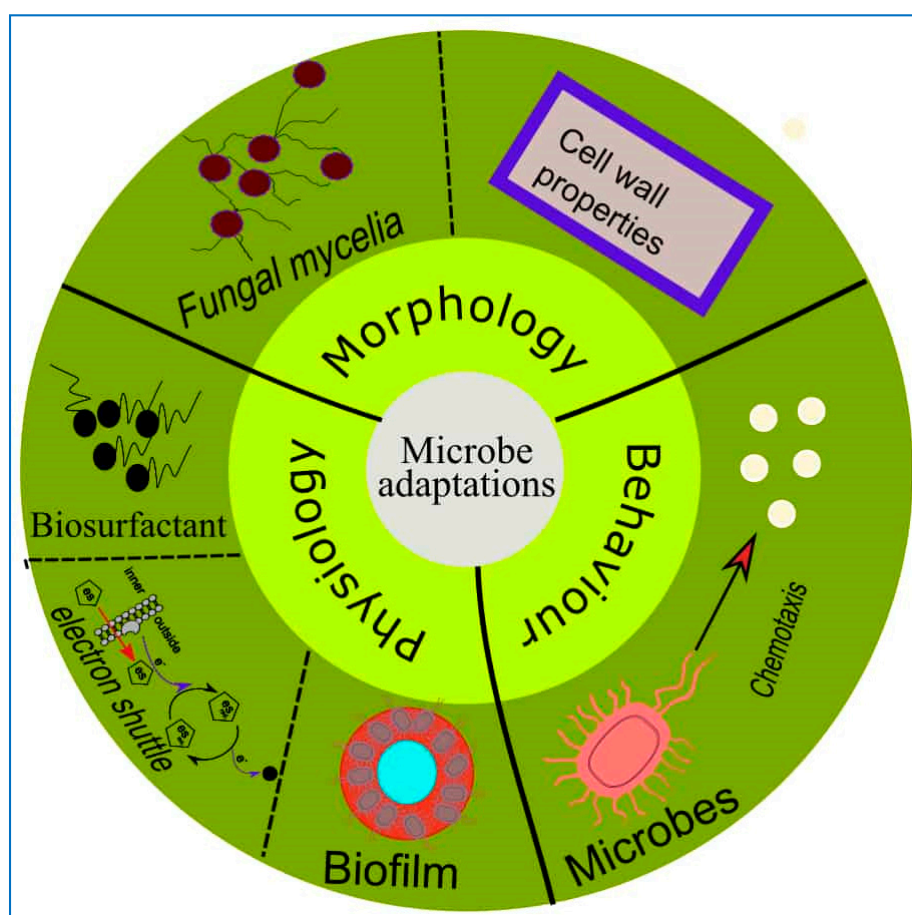


Figure 2. Morphologic, physiological and behavioral adaptations of microbes.

4. Practical Implications and Future Perspectives

In the 1970 s, the aerated static pile system was developed in the United States to control temperature change due to the changing rate of aeration. Instead of the mechanical turning, a fan was used to either blow air into or suck air from it. The two main teams involved in this research were at the United States Department of Agriculture (USDA) facility at Beltsville in Maryland being run by Epstein and at Rutgers University run by Finstein [125,126]. Initially, mixtures of sludge and woodchips were considered, and in 1980, manual on the 'Beltsville aerated-pile method' was produced by the USDA and the United States Environmental Protection Agency (USEPA) [127]. Generally speaking, the system that sucks air was a good one for minimizing odors while the other one gave better control over temperature, thereby enhancing the processing time. The aerated static pile system made available a relatively low-cost controlled composting system that allowed for a range of control strategies [127,128]. This made it possible for researchers to build their controlled systems without relying on large scale commercial plants. Many researchers in the 1980 s and 1990 s used this system to test and validate their ideas. As research continues to evolve, the drive to improve the composting

process started increasing. Two important factors underlie these drives *viz* sanitization (ensuring that the material was safe to use from the point of view of pathogenic microorganisms) and stabilization (controlling the breakdown of the more readily biodegradable components in as controlled and rapid a manner as possible). Although these two factors were the basis of much research from the 1970s however, the ways in which they should be assessed were themselves subject of much research [128]. As of today, there is no common agreement on how to measure them, but, many national standards have incorporated assessment methods and limits in their regulations.

In the last 20 years, many factors have affected the increase of composting plants across the world. In Europe, however, the major forces have been the landfill directive [48], disposal costs, and financial penalties. Based on the amount of organic waste landfilled in 1995, each of the European Union states had to reduce the amount of biodegradable material in the landfill. From this, the only target date left to be met is this year 2020 [129], when it is expected that the amount of biodegradable waste in landfills should be 35% of that produced in 1995. We, therefore, suggest a few ways that composting can be improved upon for a sustainable environment and improved human health.

Insects can be involved in a controlled manner in composting. Some insects such as black soldier field larvae are capable of ingesting and degrading some organic wastes (e.g., catering wastes and manures). Composting using BSF has been documented to reduce the emission of greenhouse gases 47-fold compared to other methods of composting [130]. BSF, due to its ability to degrade a wide range of substrate, could be incorporated into the composting of recalcitrant organic wastes. Some insects, such as pill bugs and centipedes can be utilized in composting if the conditions are right [90]. The utilization of these insects in composting will help to serve as a means of conserving these important species and encourage biodiversity conservation. Perhaps, instead of them being destroyed, they can be captured and utilized in composting processes. Research can be expanded to know if insects can make specific micro or macronutrients available in compost, or they are capable of releasing enzymes that can lyse pathogens.

Besides, the odor is always a general problem in composting. The production of an odor trapping device which can be incorporated in-vessel composting or used in other types of composting methods.

Furthermore, compost majorly consists of mixed nutrients. Therefore, the ability to extract single nutrients (N, P, K, etc.) will tremendously contribute to the good health of the soil. For instance, trace elements are contained in matured compost within an acceptable limit, but when such composts are applied in the soil for bioremediation purposes, some trace elements can be added to the previously contained trace elements in the soil instead of reducing them.

Energy demand for forced aeration in composting piles and reactors is an important element in composting. The introduction of solar energy may help reduce the cost of energy. A solar composting pilot plant is already in use in San Joaquin Valley in California, USA, intending to reduce the total air emissions of the composting facility by replacing diesel generators and optimizing solar energy use to power aeration equipment [131].

Compost process management is another important factor to consider for future improvement. Indicators and sensors that can help in the understanding of the management process are necessary. The possibility of greenhouse gasses being formed during composting urges the need for proper management processes, hence, the need for more knowledge on handling of enzymes, microbial communities, substrates and processing conditions to effectively reduce the emission of methane and nitrous oxide.

For future research, in some areas where research is needed, the background of researchers will generally set their agenda in terms of the perceived importance of research in various particular areas. Albeit, there is a challenge to test at pilot-scale how easily measurable basic parameters can be used as indicators for more complex processes and to aid a proper control of composting operations. To solve this issue, there is a need for sensors that can measure gas phases, thereby reducing the need for time-consuming and tedious steps. This can increase the opportunities for compost plant improvement.

In this era of next-generation sequencing, DNA sequencing has been relatively affordable compared to what it used to be. Research should tap into this opportunity to apply sequencing techniques in enabling a proper and full understanding of the microbial communities and enzyme functions in composting. These enzyme functions include greenhouse gas production, organic waste production, and odor generation.

5. Conclusions and Recommendations

Improper waste management is a common practice which is not safe and can be replaced with safer waste management method such as composting. The world is tending towards improving environmental and human health. As a form of organic fertilizer, composting can play a significant role in achieving this goal. Focus on composting will cause a shift in the use of chemical fertilizer in favor of compost. This shift will invariably promote environmental and human health by reducing the number of toxic chemicals released into the environment. In the present state, a lot of awareness still needs to be done concerning the potentials of this technology for its full acceptance by farmers. Concerning the improvement technologies, some recommendations are hereby suggested to aid its improvement.

Due to the large nutrients contained in composts, it is recommended that mono nutrients should be extracted from composts. Many times, when pre-planting soil analysis is conducted, there may be a deficiency of one nutrient. The extraction of mono fertilizers from the compound fertilizer form of compost will go a long way in preventing the over-application of nutrients that are not needed. In addition, organisms that are capable of degrading complex degradable materials can be made available to farmers as inoculum to hasten slow composting processes. More researches should also be conducted to discover the odor trapping mechanism to solve the problem of air pollution associated with compost production. There should be provision for CO₂ trapping to prevent the release of greenhouse gases from composting.

For many years now, researchers and companies have envisaged the potential of municipal wastes as a source of raw materials. The organic components in the waste are of great interest. Over the past 15 years, we have moved from processing the organic fractions by composting majorly because of its usefulness in crop production to the use of anaerobic digestion, with the ability to provide methane as an energy source. Across Europe, for example, waste companies have moved their investments into anaerobic digestion systems as a result of government incentives made available to them. These government incentives could bring a new development such as integration of bioenergy processes (anaerobic digestion, biochar) to composting, and the byproducts of bioenergy processes could be composted to increase their value, agronomical and environmental benefits.

The ability of compost to improve soil structure and improve nutrient availability by adding to the nutrient already available has been the major factor driving its use in crop production. The nutrient focus has usually been on nitrogen, but we have recognized that mineral phosphate available for plant production is a limited resource, and its availability was reported to decline after 2035. With this in mind, using the phosphorous in compost combined with more effective and efficient use of phosphorous should be able, at the very least, to significantly extend the life of our sources of available mineral phosphate.

Furthermore, to make an effective compost, plant-derived anti-nematode, viricide, bactericide, and fungicide can be added to compost. This will help to encourage solely organic farming by preventing chemical applications. It is advisable to compost slowly degrading materials separately so that the slowly degrading materials will not elongate the composting period of other materials. More research should be conducted to know if materials that take longer time to compost also mineralize gradually. Slowly mineralizing materials could be helpful to biennial and perennial crops, as they serve as a long-term source of nutrients. Further research should be conducted on the potency of this hypothesis. Information on the nutritional content of different slowly composting leaves should be incorporated into research, as this will help in making decisions if they should be incorporated into compost or not. The high wastes from agriculture generated in developing countries (e.g., Nigeria) can

be composted instead of being combusted. Composts should always be assessed for maturity and pathogens before application to the field; this will prevent potential hazards to the environment and other living things.

Finally, more research should be carried out to discover how to enhance the duration of composting. Though the Berkley method was discovered in the past and is still the fastest composting method, the discovery of faster methods will help to sustain the composting process.

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