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Assessing rice production efficiency for food security policy planning in Malaysia: A non-parametric bootstrap data envelopment analysis approach

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ABSTRACT

The 2007–2008 international food crisis triggered national food security policies of several countries worldwide, creating a problematic situation in the global food landscape and led to a drastic shift in the national food security policy (NFSP) approaches undertaken by affected countries. In this context, agricultural policies were reformulated to focus on achieving a certain degree of self-sufficiency while obtaining agricultural efficiency and sustainable agricultural development. This study empirically evaluated Malaysian rice self-sufficiency (RSS) approach, focusing on production efficiency closely related to maximizing production approach and minimizing environmental impact. We utilized non-parametric bootstrap data envelopment analysis (DEA), input- and output specifications to estimate the relative technical efficiency scores of decision-making units (DMUs) by constructing confidence intervals and correcting efficiency estimations. Our finding reveals that the Malaysian RSS policy approach demonstrates a better orientation toward output maximization than resource saving. However, the average annual change of the efficiency scores in both specifications was found to deteriorate during the analyzed period. Based on regional analysis, an improved RSS strategic approach could help the nation attain rice production maximization, minimize the environmental impacts, and obtain production efficiency mainly through modernizing the irrigation systems, efficient agrochemical inputs usage, adopting best agricultural practices, and implementing soil treatments programs.

1. Introduction

The staple food self-sufficiency or autarky approach has risen in the food policy agenda in several countries following the intense price fluctuations during the 2007–2008 international food price crisis (Clapp, 2017). The crisis affected the economic, social, and political aspects of national food security management worldwide, leading to a serious international debate on the relevance of the autarky approach in food security planning. From a political perspective, supporters of food self-sufficiency emphasize reducing the reliance on food imports in response to international price volatility and dynamic changes in international food trade. Thus, the increased pressure on domestic production led to the increased consumption of available domestic resources. In contrast, some economists view the self–sufficiency movement as misguided since it can be costly and risky due to the introduction of trade restrictions, tariffs, and subsidies (Clapp, 2015, 2017). Moreover, the policies required to support the complete autarky approach are inefficient and can result in trade distortion (Naylor and Falcon, 2010).

In response to the 2007–2008 international food crisis, affected nations increased their annual agricultural budgets to bolster food self-sufficiency by introducing more subsidies, such as agricultural aids (fertilizers, pesticide, seed, etc.) and price support scheme. Additionally, these countries also increased their research and development (R&D) activities and allocated more development expenditures for modernizing their agricultural infrastructures. Although there have been promising signs, such as the success of R&D activities to increase production, the self-sufficiency approach, which can be considered a costly policy, has led to economic inefficiency due to inefficient production processes. Moreover, the overuse of resources to increase production levels has resulted in environmental degradation, such as the widespread use of fertilizers and pesticides and the large-scale exploitation of groundwater for irrigation, which results in soil degradation, water scarcity, and biodiversity destruction (Hill and Mustafa, 2011). Hence, countries considering the food self-sufficiency policy approach may face challenges in the long run in terms of reducing the inefficiency associated with this policy, particularly in the context of maintaining a balance between maximizing production, minimizing environmental

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impacts, and achieving production efficiency for sustainable practices.

The current study seeks to empirically examine rice production efficiency in the context of rice self-sufficiency (RSS) policies (production maximization approach). To this end, we examine Malaysia's annual rice production and its National Food Security Policy (NFSP), established to strengthen its RSS in response to the 2007–2008 international food crisis, using the self-sufficiency ratio (SSR) as an indicator of staple food security. Moreover, the emphasis on the designated SSR for the country's staple food security policy has resulted in environmental pressure, especially the rising trend in agrochemicals utilization under the subsidies scheme provided by the Government of Malaysia (GoM) to increase the production can be observed after the 2007–2008 crisis. Therefore, the current study also integrates environmental factors related to production efficiency in the analysis to provide policymakers with useful information regarding production systems to improve existing food policies (Dakpo et al., 2016).

Next, based on the rice production technical efficiency assessment from the previous study, to the best of our knowledge, there is a lack of focus on DEA statistical properties. Therefore, to enhance the reliability of the technical efficiency estimation than the conventional DEA, this study utilizes the DEA bootstrap procedures proposed by Simar and Wilson (1998, 2000) to make statistical inferences about technical efficiency estimations. Additionally, this approach uses the computer-based statistical technique for checking the accuracy of statistical estimates of the replicate samples (Munim, 2020). The main findings of this paper refer to the evaluation of the technical efficiency performance related to maximizing production and minimizing the resources of the Malaysian regions during the analyzed period of the RSS policy implementation.

Specifically, the following sub-section describes the dilemma faced by the Malaysian rice industry, which is the motivation of this study. Section 2 presents literature review regarding the DEA applications in selected agricultural and rural policies. Section 3 defines the model variables and describes the methodology utilized in this study. The appropriate datasets are applied to model the input- and output–oriented bootstrap DEA. Section 4 presents the results regarding the performance of various Malaysian regions. The latter, Section 5 concludes this study and proposes insightful policy recommendations of an improved RSS policy approach.

1.1. Malaysia's paddy and rice industry dilemma

Empowering Malaysia's domestic rice value chain by utilizing RSS approaches under the NFSP or known as 2011–2020 National Agrofood Policy (NAFP) has become a staple food security priority of the country. This is because the GoM sees the need to increase rice production levels using the available resources to a certain degree to ensure food security (MOA, 2011). However, providing special treatment to this sector to protect national food security interests is costly despite the lack of assurance that this approach would lead to increased economic and environmental efficiency. Moreover, the financial costs associated with achieving RSS are high by any standard for the Malaysian paddy and rice sector compared to other countries (WB, 2019), which may lead to economic inefficiency in the agricultural sector. Heavy investments have been allotted to rice development programs, such as extensive subsidization along the rice value chain, infrastructure development, area expansion, and extension programs, since the First Malaysian Plan (MP) in the 1960s, and these investments continue to increase every year (Twelfth MP in 2021). These investments in food security drastically increased when the food crisis hit the international food market, particularly during the 1970s and the 2007–2008 period. Owing to the recent 2007–2008 food crisis, the GoM reformulated NAFP goals to transform the agricultural sector, making it more productive, competitive, and knowledge-intensive by increasing the agrofood industry's efficiency along the food value chain (Bakar et al., 2012).

In line with the 2011–2020 NAFP, Malaysian paddy and rice policy approaches were reviewed with the following aims: achieving a designated rice self-sufficiency level (SSL); ensuring the supply, consistency, and price stability of rice at any given time; increasing farmers' income levels; and facilitating the production of paddy and rice goods (IPB, 2021). The GoM has also been predominantly involved in market intervention along the rice value chain. At the farm level, paddy growers are provided with agricultural input subsidies, subsidized irrigation rates, and guaranteed rice prices at Malaysian Ringgit (MYR) 750 per metric ton. Meanwhile, rice importation is entrusted to BERNAS (a private entity) under the GoM's BERNAS Concession Agreement, which appointed BERNAS as the sole gatekeeper of rice importation. In return, BERNAS is obliged to fulfill the Malaysian paddy and rice industry's requirements: maintaining the national rice stockpile, acting as a buyer of last resort for paddy farmers, managing the Bumiputera Rice Millers Scheme and the distribution of Paddy Price Subsidies to farmers on behalf of the GoM (BERNAS, 2021).

RSS approaches have undergone several changes, mainly in terms of RSS targets, which have been influenced by political factors, thus creating a dilemma for the Malaysian paddy and rice industry. When the NAFP was introduced in 2011, the RSS level was set at 70%. In 2015, Malaysia's MOA revised the RSS level to 100%; however, this target was subsequently decreased to 80%. Thus, the current RSS level is set at 80%, which is a 10% increase from the initial target of 70% (Bee, 2019). However, the process by which RSS targets are set is unclear (WB, 2019). In terms of benefits to paddy growers and consumers, the NAFP meets its targets when paddy growers receive a relatively higher income while consumers are protected from price volatility (Bala et al., 2014). While the intended outcomes fulfill the needs, especially the political and social aspects, the unintended economic and environment consequences indicate inefficiency. For example, a continued reliance on subsidized fertilizer to replenish soil results in soil infertility and water quality degradation. In the long term, an RSS approach may slow down productivity growth.

As an early indicator of staple food security, the RSS approach is crucial for enhancing the competitiveness of the Malaysian paddy and rice industry since the world's rice market is currently controlled by few suppliers and only a small percentage of global production is traded. Consequently, any interruptions in supply can cause price spikes like in the 2007–2008 international food crisis (Clapp, 2017). Moreover, the efficiency of the RSS approach implemented by Malaysia is essential to demonstrate its commitment to achieving the sustainable development goals (SDGs) set out by the United Nations (UN), specifically SDG2 and SDG12, within the context of improving production efficiency, environmental preservation, and sustainable agricultural practices. The RSS assessment in this study could be also beneficial for the food self-sufficiency communities to further discuss the pros and cons regarding this policy approach. Finally, the evaluation of Malaysia's RSS policy based on regional analysis will provide an in-depth insight into the long-term impacts of the self-sufficiency policy approach in terms of production efficiency performance. These insights, in turn, will help policymakers and planners to design an inclusive NFSP based on regional characteristics, i.e., whether regions are focused on resource saving, maximizing production, or both.

2. Literature review

The development of agricultural policies associated with the non-parametric DEA studies was diverse since DEA has been widely recognized as a practical mathematical programming tool used to estimate the technical efficiency and productivity of the Decision-Making Unit (DMU), which are the essential aspects in agricultural policy development. Charnes, Cooper, and Rhodes first demonstrated the DEA application in 1978 (Charnes et al., 1978).

The DEA has advantage of not imposing a priori functional form and allows for multiple output technologies (Badunenko and Mozharovskyi, 2016). In other words, to define the production frontier, it depends on more common assumptions typical of microeconomic production theory (Monchuk et al., 2010). One shortcoming of the non-parametric frontier approach is its properties challenging to make statistical inferences regarding technical efficiency (Simar and Wilson, 1998) than other alternative efficiency estimation approaches such as Stochastic Frontier Analysis (SFA), where this approach can take into account the statistical noise, i.e., weather (Coelli et al., 2005), especially in the agriculture study context. However, a drawback of the stochastic technique is the necessity that the production technology be specified a priori. Imposing a specific functional form for a technology which is, in most circumstances, unknown can be risky since different specifications can lead to different results (Gong and Sickles, 1992). Fortunately, Simar and Wilson (1998, 2000) bootstrapping method provides an alternate way for statistical inference to be implemented when dealing with the non-parametric frontier model in technical efficiency estimation by constructing the confidence intervals.

Next, previous DEA applications in agriculture were frequently applied on a small scale, such as assessing technical efficiency at the farm level. However, in recent years, in line with the data available from many certified sources (i.e., FAOSTAT, FADN, EUROSTAT, etc.), the interests regarding agricultural performance comparisons at the regional and national levels using DEA have shown a rising trend due to its benchmarking capability was helpful for policy planning. Besides, in the agricultural policy development, the estimated production efficiency can give policymakers and planners vital information regarding the characteristics of the production process at the micro and macro level, i.e., at the farm or regional level. Among that, the DEA helps users to evaluate the production efficiency of the particular crops under investigating that can give benefits in terms of whether the policy development related with these crops should provide imperative in minimizing its input(s) or maximizing the output(s), or both. For instance, Toma et al. (2017) conducted a study regarding environmental policy planning related to agricultural efficiency in European (EU) regions using bootstrap DEA. They found that the older EU countries generally show a better agricultural efficiency performance in environmental planning in terms of resource saving and increasing productivity approach. Meanwhile, Coluccia et al. (2020) found that the eco-efficiency assessment of Italian regions using the conventional DEA approach showed a better orientation in saving resources for the southern regions while the northern regions had shown a more excellent orientation in productivity. More prior study examples related to agricultural and rural policies development that involved DEA applications are shown in Table 1. Additionally, if one has panel data, the DEA can calculate indices of total factor productivity (TFP) change, technological change, technical efficiency change, and scale efficiency change (Coelli, 1996), which in turn, it would give policymakers or planners more information regarding the

Table 1
DEA applications in agricultural and rural policy planning.

Author(s)	Study aims and DEA applications	General findings/contributions	Related policies	Countries/ Periods
Coluccia et al. (2020)	This paper aims to study eco-efficiency related to agricultural production of Italian regions using DEA input- and output-oriented.	The southern Italian showed better environmental planning and the northern towards increasing productivity while achieving the eco-efficiency	European Union Common Agricultural Policy (CAP)	Italy (2004–2017)
Henry et al. (2018)	The study assesses environmental efficiency performance associated with nitrogen and phosphorus usage in dairy farms industry across four different regions of Ireland using bootstrap-DEA.	The environmental performance evaluation showed the Northern Ireland has greater nutrient surpluses compared to the three regions in the Republic of Ireland.	European Union Common Agricultural Policy (CAP)	Ireland (2014)
Toma et al. (2017)	The paper estimates the agricultural technical efficiency scores of 26 European countries using bootstrap-DEA.	The majority of EU countries could better rationalize the inputs used to increase production efficiency both in input- and output-oriented. Older EU countries generally are more efficient and have optimized crop production processes in terms of minimizing the resources and maximization of the production.	European Union Common Agricultural Policy (CAP)	EU Countries (1993–2013)
Yang and Zhang (2018)	This study investigates regional eco-efficiency of China using bootstrap DEA, global benchmark technology, directional distance function.	China's eco-efficiency trend was high in eastern and northern areas but low in northwestern areas. The decomposition of productivity growth implied that technical progress plays a vital role in regional eco-efficiency, while the major problem to obtain eco-efficiency is caused by the decrease in management level.	China's Agricultural Policy	China (2003–2014)
Masuda (2016)	The aim of this work is to measure the eco-efficiency of wheat production at the Japanese regional level using DEA and life cycle assessment.	The eco-efficiency can be increased through the mitigation of aquatic eutrophication caused by the excessive use of NPK.	Japan's wheat and barley policies	Japan (1995–2011)
Baris and Podinovski (2015)	The study assesses the efficiency of units that output profiles exhibit specialisation in agriculture using DEA in the different regions of Turkey.	Propose a methodology to overcome poor efficiency discrimination in DEA where units may exhibit specialisation, i.e., a large number of outputs (various outputs) to the production of the main output.	Turkish Agricultural Policy	Turkey (2009)
Ray and Ghose (2014)	The paper evaluates DEA to attain Pareto-Koopmans measures of India states technical efficiency of agricultural production using input- and output specifications after utilizing the modern inputs.	Both input- and output-oriented efficiencies were found to be declined over time. Additionally, the rate of productive utilization of the inputs has dropped. However, there is room for improvement for food production through improved efficiency.	Indian Agricultural Policy	India (1970–2001)
Gerdessen and Pascucci (2013)	This work develops a methodological approach to assess the multidimensional sustainability of a regional agricultural system using DEA for 252 European agricultural regions.	The complexity of sustainability concept regarding social, economic, and environmental indicators evaluated through a combination of multidimensional perspective and DEA.	Rural development policy of EU countries	EU countries (2008)
Monchuk et al. (2010)	The paper examines the determinants of agricultural inefficiency production in China using DEA and semi-parametric bootstrapping.	Heavy industrial externalities such as air and water pollution are associated with the inefficiency of agricultural production. Also, a large rural labor force involved in agriculture tends to be less efficient.	China's Agricultural Policies	China (1999)
Vennesland (2005)	The study examines the efficiency of Norway's rural development support scheme (RDSS) using two-stage DEA.	The RDSS generates less employment related to agriculture and rural business from the given RDSS-budget in stage first analysis. In step two, the author proposed the reallocation of the budget to maximize the job establishments in rural areas.	Rural economic development of Norway	Norway (1988–1995)

agricultural performance that would help in-depth evaluation of the effectiveness of that related policy.

Subsequently, numerous countries allocate their annual budgets for the agricultural sector, mainly in agricultural assistance (i.e., fertilizer, seed, pesticide, etc.) to reduce the production costs as part of their national agricultural policy approach, mainly for the staple food production. The challenges to allocating the optimal proportion of these inputs budgets have become critical tasks during the preparation of the expenditures. Therefore, the DEA can act as a useful tool for policy development to assess these inputs' budgets estimation for the production of the crops such as rice, wheat, maize, and corn. In the end, it can help a nation to achieve the policy's objectives for sustainable agricultural development.

As the concerns regarding sustainability and environmental issues grow, including in the agriculture sector, the designated agricultural policies not merely focus on production efficiency to maximize the output level, but the environmental efficiency associated with the production process has also become a significant concern. In the case of crops production, inefficient agrochemicals usage (i.e., fertilizers, pesticides) particularly can lead to environmental degradation such as the greenhouse gas (GHG) emissions and global warming potential (Blengini and Busto, 2009; Yang et al., 2009; Hokazono et al., 2009; Wang et al., 2010; Sha et al., 2014; Hariz et al., 2019). Additionally, most developed regions tend to focus on reducing environmental impacts and obtaining production efficiency (Monchuk et al., 2010; Vlontzos et al., 2014; Yang and Zhang, 2018; Toma et al., 2017; Henry et al., 2018; Coluccia et al., 2020). In contrast, in most developing regions, increasing the production level is their priority since the food security issues, which in turn, lacks focus in minimizing the environmental impacts and obtaining production efficiency.

Overall, in many agricultural policies development, two essential components of the previous studies have been given imperative; first, to maximize the production while obtaining production efficiency, and second, to obtain production efficiency while minimizing the resources utilized. For these reasons, the non-parametric DEA approach, besides the parametric stochastic frontier approach (SFA), has become an effective tool for efficiency evaluation in the agricultural production process that helps policymakers and planners establish the appropriate agricultural policy based on the regions or countries necessities.

3. Materials and methods

3.1. Dataset

Statistical dataset of Malaysian paddy and rice published by the Ministry of Agricultural and Food Industries of Malaysia (MAFI) and the Department of Agricultural (DOA) was used to estimate the DEA-based technical efficiency scores of Malaysia and its region rice production. Specifically, the relevant official dataset was extracted from the annual report of the MAFI and DOA's annual statistical booklet of crops. This dataset comprised paddy and rice production, physical area, average yield, capital, financial information, etc. Malaysia has thirteen states (regions), eleven in Peninsular Malaysia and two in East Malaysia. In general, the dataset distribution at the national level was based on the profile of cultivation areas: granary and non-granary areas. Most of the granary areas were equipped with modern agricultural infrastructures and had relatively higher planting frequencies. In contrast, most non-granary areas are still underdeveloped and are dependent on traditional irrigation systems and rainfall. Currently, there are ten granary areas across the nation, including four new granary areas established in 2014 and 13 non-granary areas. On average, granaries account for 71% of the overall rice production, while non-granaries account for 29%.

The dataset utilized had a balanced panel data structure based on 130 regional observations from 2009 to 2018, after considering the 2007–2008 international food crisis, which caused Malaysia to bolster its RSS policy approach under the NAFP for the country's food security. We carried out the DEA technical efficiency estimations of rice production related to RSS policy in two aspects; first, the analysis involved every region in the country. Second, we aggregated these regions into five main geographical classifications; northern, central, southern, east coast, and East Malaysia.

Next, our model assumed that the regions were homogenous for rice production in terms of weather, planting season, and cropping method (Ismail and Chan, 2020). The model also assumed that these regions utilized the same production technologies during the research period.

3.2. Input and output definitions

From the available data, we identified the essential inputs and output associated with Malaysian rice production based on previous studies, mainly in agriculture. For the modelling, we utilized four inputs; land, labor, capital and aggregated agrochemical inputs (fertilizer, seed and pesticide), while the output variable was annual rice production. We extracted the dataset regarding land, labor, and rice production from the DOA's annual statistical booklet of crops. Meanwhile, information regarding capital expenditures and agrochemical inputs (fertilizer, seed and pesticide) were extracted from the annual report of Malaysia's Ministry of Agriculture and Food Industries (MAFI) located in its online library (MAFI, 2021).

In particular, land, the first input, represents the planted area devoted to paddy cultivation, including granary and non-granary areas, in hectares (ha). Labor, the second input, refers to the number of working-age farmers involved in planting activities. Capital, the third input, refers to capital expenditures. Previous studies have utilized several definitions of capital such as the book value of machinery and buildings, depreciated value of total assets, and annual capital costs (Baris and Podinovski, 2015). The current study defined capital input as capital expenditures, expressed in Malaysian Ringgit (MYR). They comprise the annual costs of machinery and farming overhead, and are similar to the capital costs definition utilized by Fare et al. (1997), Baris and Podinovski (2015), and Fatah (2017). Finally, aggregated agrochemical inputs, similar approach with Fare et al. (1997) and Mariyono (2018), expressed in MYR because of the variations in measurement unit and quality (Mariyono, 2018), comprises the total Nitrogen, Phosphorus, and Potassium (NPK) fertilizer, seed and pesticide consumed during the cultivation process. In this study, all the monetary values (capital and agrochemicals inputs) were based on MYR 2010 constant price using agricultural price index for rice.

3.3. Non-parametric bootstrap DEA

We performed non-parametric bootstrap DEA, a statistical efficiency evaluation technique to assess Malaysian regional rice production efficiency, following a similar approach utilized by Toma et al. (2017). Subsequently, we conducted geographical analysis through regional classifications to examine technical efficiency estimations differences under the RSS policy approach during the analyzed period (2009–2018).

Our model comprised both input- and output-oriented specifications to estimate the relative efficiency scores of different DMUs. Each DMU refers to a region involved in rice production during 2009–2018. Under this model, we estimated the extent to which a region could minimize its input consumption relative to the best frontier in the first specification and maximize its output compared to the best DMUs in the second specification. Besides, these regions are considered homogeneous; therefore, using the DEA approach was beneficial since it facilitates the multifactor analysis of a homogenous set of DMUs to measure their relative efficiency (Coluccia et al., 2020).

However, due to the statistical basis of DEA estimators (estimated efficiencies), traditional point estimates are insufficient to view DEA as a consistent efficiency estimator due to the sampling distribution property of estimators (Simar, 1992). To overcome this limitation, Efron's (1979) bootstrap methodology is an appropriate instrument to evaluate the sensitivity of the measured efficiency scores relative to the sampling variations of the estimated frontier. Simar and Wilson (1998) introduced a general methodology for non-parametric frontier models based on Efron's (1979) approaches to enhance the reliability of the technical efficiency estimates than conventional DEA procedure. They also stated in a simplified way that bootstrapping is based on the principle of simulating the data-generating process (DGP) repeatedly, typically by resampling and adding the original estimator to each simulated sample to replicate the sampling distribution of the original estimator. Therefore, if stochastic errors exist in the sampling distribution of point estimates, the bootstrap DEA procedure can be performed to construct confidence intervals, which cannot be derived analytically (Toma et al., 2017). The smoothed bootstrap procedure to smooth the sampling distribution as proposed by Simar and Wilson (1998, 2000) that utilized in this study (see also, Bogetoft and Otto 2010; Long et al., 2020) are simplified as below:

Step 1: Calculate the conventional technical efficiency estimation for $\widehat{\theta}^{i}$ of the i^{th} region using the equation below:

$$\widehat{\theta}_i = \min\left\{\theta_i \middle| y_i \leq Y\lambda; \theta_i x_i \geq X\lambda; \sum_{i=1}^{n}\lambda_i = 1; \theta_i > 0; \lambda_i \geq 0, i = 1,\dots,n\right\} \quad (1)$$

Step 2: Apply bootstrap through smooth sampling from $\widehat{\theta}_1, \dots, \widehat{\theta}_n$ to produce a bootstrap replica $\theta_1^*, \dots, \theta_n^*$. This can be done as follows:

i Bootstrap, sample with replacement from $\widehat{\theta}_1, \dots, \widehat{\theta}_n$, to generate the results $\beta_1, \dots, \beta_n$.

ii Simulate standard normal independent random variables $\epsilon_1, \dots, \epsilon_n$.

iii Calculate bias-corrected estimator, $\theta_i = \left\{\beta_i + h\epsilon_i, if \beta_i + h\epsilon_i \leq 1 2 - \beta_i - h\epsilon_i, otherwise\right.$. Note that $\theta_i \leq 1$ and h is the bandwith factor.

iv Next, modify θ_i to attain parameters with asymptotically correct variance, then we estimate the variance $\widehat{\sigma}^2 = \frac{1}{n}\sum_{i=1}^{n}(\widehat{\theta}_i - \widehat{\theta})^2$ and calculate $\theta_i^* = \overline{\beta} + \frac{1}{\sqrt{1+h^2/+\widehat{\sigma}_2}}(\theta_i - \overline{\beta})$ with $\overline{\beta} = \frac{1}{n}\sum_{i=1}^{n}\beta_i$.

Step 3: For $i = 1,\dots, n$; $(x_{i,b}^*, y_{i,b}^*)$ with $x_{i,b}^* = (\widehat{\theta}_i/\theta_i^*)x_i$ and $y_{i,b}^* = y_i$ is a pseudo data set. By taking pseudo data set as a reference, we calculate the new DEA score $\widehat{\theta}_i^*$ for each region using equation 1.

Step 4: Repeat steps (1) to (3) for B times to produce bootstrap estimates of technical efficiency scores $(\widehat{\theta}_i^*, \dots, \widehat{\theta}_n^*)$ where $i = 1,\dots, n$. Then, the bias corrected estimator of $\widehat{\theta}_i$ can be computed as $\theta_i^* = \frac{1}{B}\sum_{b=1}^{B}\widehat{\theta}_i^*$.

Step 5: The confidence interval $(1 - a)$ for the technical efficiency scores of each region can be constructed by obtaining value a_α, b_α, such that Prob $(-a_\alpha \leq \widehat{\theta}_i - \theta_i \leq -b_\alpha) = 1 - \alpha$. Because we do not know the distribution of $(\widehat{\theta}_i - \theta_i)$, we can use the bootstrap values to calculate $\widehat{a}_\alpha$, $\widehat{b}_\alpha$, such that Prob $(-\widehat{a}_\alpha \leq \widehat{\theta}_i^* - \widehat{\theta}_i \leq -\widehat{b}_\alpha) = 1 - \alpha$. Thus, the estimated confidence level of $(1 - a)$ for technical efficiency of i^{th} region is given by $\widehat{\theta}_i + \widehat{b}_\alpha \leq \theta_i \leq \widehat{\theta}_i + \widehat{a}_\alpha$.

In this study, the bias-corrected bootstrap DEA for technical efficiency estimation of each region was set at the 95% confidence interval with 3000 bootstrap replicates. The calculation was conducted using the "Benchmarking" package of the R software.

4. Empirical results and discussion

4.1. Descriptive statistics

We conducted an empirical assessment of the Malaysian paddy and rice industry RSS policy approach by using the established non-parametric bootstrap DEA input- and output-oriented specifications. This assessment provided us a more in-depth view of recent Malaysian rice production efficiency performance after bolstering self-sufficiency policy closely related to minimizing environmental impacts, maximizing production and sustainability development.

In general, the efforts implemented mainly by the GoM to achieve the designated RSS level for the country's staple food security are through maximizing domestic production, especially in terms of continuous agricultural assistance, investment in modern infrastructures, and the rice development program. The efforts have commonly been shown to be a good indicator of the overall increase in Malaysian rice production performance. The observation of the mean paddy production increased from 193,157 MT in 2009 to 203,016 MT in 2018, as shown in Table 2. However, it is an essential task to assess to what extent this policy approach is effective in the rice sustainability development context by evaluating the technical efficiency performance.

4.2. DEA returns-to-scale test

To increase the precision in the DEA estimation of efficiency scores, it is crucial to assume in the DEA production technology specification whether its characteristic is CRS or VRS (Simar and Wilson, 2002). A false assumption about CRS may result in inconsistent efficiency scores, whereas a false assumption about VRS may result in a loss of statistical efficiency (Long et al., 2020). Hence, based on Simar and Wilson (2002) non-parametric statistical test, we employed a test hypotheses (Table 3) for returns-to-scale test of Malaysian regions rice production technology. The Benchmarking package of testing hypothesis returns-to-scale developed by Bogetoft and Otto (2011) was conducted with 3000 interactions. In this test, the null hypothesis of CRS was rejected since the test statistic value is less than critical values at 5% and 1%, respectively. Therefore, the production technology assumption during the research period is VRS.

4.3. Input- and output-oriented model analysis

Subsequently, we performed the bootstrap DEA based on two VRS specifications: the input- and output-oriented specifications. Simar and Wilson (1998) proposed utilizing bootstrapping as a standard practice in any DEA application to improve the reliability of the efficiency estimates. We started with the input–oriented model since this approach has been widely used to address perennial issues in the agricultural sector (Heijman and Schipper, 2010). Under this model, a region is considered as efficient if its relative efficiency score is closer to one, it has optimized its input resources to obtain a fixed output level while minimizing its environmental impact (Madaleno et al., 2016). The region also is deemed has adopted the sustainable agricultural practices (Dalgaard et al., 2001). On the other hand, the output-oriented specification was selected because it is suitable for investigating a region's technical efficiency within the scope of their potential to achieve the maximum level of output, given a combination of fixed inputs. The same principle applies to the output-oriented model, i.e., if the relative efficiency score is near to one or approaching the frontier level, the region is considered to be efficient.

We further discuss Malaysia's RSS approach based on the VRS input-oriented assumption. The input-oriented efficiency scores of the different regions in Malaysia are presented in Table 4. At the national level, the average efficiency score for Malaysia during the 2009–2018 period was about 71.1%, which implies that the current output level can be obtained using 28.9% fewer inputs on average. Meanwhile, the annual average input-oriented efficiency scores of the Malaysian regions varied between a minimum of about 64.6% to a maximum of 75.3% (Fig. 1), which means that most regions experienced increasing or decreasing returns to scale, implying that they can enhance their production efficiency by adjusting their inputs consumption (Toma et al.,

Table 2
Descriptive statistics of annual mean basis.

		Inputs				Outputs
		Land (ha)	Labor (Persons)	Capital (MYR)	Agrochemical Inputs (MYR)	Production (MT)
2009	Mean	51917.54	13248.46	85,907,568	71,628,048	193,157
	Std. Dev.	60401.63	13069.68	99,946,134	83,676,952	242,794
	Median	37,258	8920	61,650,538	48,073,169	133,048
	Min	1974	150	3,266,363	2,728,812	5551
	Max	213,895	38,220	353,930,479	295,683,539	923,666
2010	Mean	52144.92	13248.46	87,176,665	70,477,886	189,602
	Std. Dev.	60314.11	13069.68	100,834,033	81,485,901	219,832
	Median	37,472	8920	62,646,252	50,557,222	147,531
	Min	2156	150	3,604,433	2,908,875	5071
	Max	213,193	38,220	356,419,255	287,639,996	835,630
2011	Mean	52918.46	13248.46	87,102,013	70,537,824	198,348
	Std. Dev.	61366.08	13069.68	101,006,516	81,770,135	232,137
	Median	37,460	8920	61,657,904	49,843,227	144,613
	Min	2016	150	3,318,268	2,682,433	6447
	Max	215,930	38,220	355,413,540	287,310,410	878,430
2012	Mean	52657.31	13248.46	88,414,402	69,439,701	199,953
	Std. Dev.	60692.51	13069.68	101,905,938	80,013,961	228,459
	Median	37,835	8920	63,526,964	49,801,934	142,762
	Min	2126	150	3,569,666	2,798,438	7665
	Max	213,378	38,220	358,272,937	280,867,900	856,245
2013	Mean	51667.62	13248.46	98,432,251	66,896,171	200,281
	Std. Dev.	60619.22	13069.68	115,485,996	78,477,039	236,342
	Median	37,833	8920	72,075,851	48,892,992	145,127
	Min	1986	150	3,783,539	2,566,582	8425
	Max	210,327	38,220	400,695,096	271,813,399	889,167
2014	Mean	52249.15	13248.46	111,249,344	66,936,684	218,845
	Std. Dev.	60041.85	13069.68	127,841,616	76,892,915	271,968
	Median	37,842	8920	80,573,509	48,394,717	150,112
	Min	2070	150	4,407,462	2,647,246	8530
	Max	212,401	38,220	452,246,021	271,631,686	1,036,180
2015	Mean	52427.62	15168.46	109,392,758	66,096,492	210,877
	Std. Dev.	60513.78	16675.25	126,264,928	76,260,467	251,896
	Median	38,114	9855	79,526,706	47,969,598	149,971
	Min	2017	1016	4,208,568	2,538,560	8550
	Max	215,065	58,476	448,743,535	270,676,957	954,974
2016	Mean	52982.31	14994.77	108,329,211	66,059,214	210,739
	Std. Dev.	60681.69	16321.61	124,071,600	75,631,517	266,636
	Median	38,114	9874	77,929,024	47,438,569	148,297
	Min	1705	1016	3,486,094	2,122,127	7578
	Max	214,875	57,002	439,339,851	267,444,050	1,015,000
2017	Mean	52734.46	14898.46	110,389,387	64,910,281	197,732
	Std. Dev.	60237.62	16399.82	126,095,792	74,114,655	247,868
	Median	36,708	9874	76,841,092	45,106,042	146,660
	Min	2040	952	4,270,345	2,506,710	8563
	Max	214,585	57,013	449,192,159	263,677,670	939,308
2018	Mean	53844.62	14875.31	117,333,264	65,924,417	203,016
	Std. Dev.	61797.54	16395.18	134,663,549	75,649,331	252,253
	Median	36,868	9632	80,339,375	45,056,436	133,636
	Min	1896	952	4,131,590	2,317,104	7504
	Max	214,592	56,964	467,619,269	262,253,194	955,662

Table 3
Non-parametric Simar and Wilson (2002) returns-to-scale test.

Hypothesis testing of returns-to-scale		$\hat{S}$	Conclusion
H_0: Production technology is CRS			
H_A: Production technology is VRS			
Test statistic		0.90156**	Reject H_0
Critical value	5%	0.95466	
	1%	0.94217	

** $p < 0.01$.

2017). Moreover, this result indicates that there is room for improvement of the RSS approach performance as the estimated average efficiency scores are yet to reach the efficient frontier level, 1. For instance, the GoM can consider reallocating expenditures related to cultivation inputs assistance based on the actual necessities of the regions (Vennesland, 2005). Currently, under existing policy, the agrochemical inputs distribution approach is based on hectare coverage regardless of whether a region's production is efficient or not. Therefore, the regions can perform soil investigation and propose the appropriate amount of inputs based on soil profiles for attaining optimal production.

Next, as shown in Table 4 and Fig. 2, the most efficient regions in the country during the analyzed period based on the average efficiency scores rank were Pulau Pinang (0.896), followed by Selangor (0.874) and Negeri Sembilan (0.874), which means that these regions were operating at nearly the optimal level and their consumption of inputs to produce the desired fixed output was also nearly optimal. Besides, these results suggest that these three regions were deemed managed their available resources effectively to achieve their desired fixed output level while reducing their environmental impact, and following the resource saving approach (Madaleno et al., 2016). It should be noted also, both Kedah and Perlis regions can be considered have high average efficiency scores with 0.847 and 0.818 scores, respectively. The results of these regions show a good indicator for Malaysian rice production efficiency performance generally at the national level because these regions are vital for the country's rice production since they are the largest and main

Table 4
Descriptive statistics of average input-oriented efficiency scores[a] and geometrical mean change.

Regions	ConventionalTE	Bias-correctedTE	Lower bound	Upper bound	SD	Change (%) 2009–2018
Johor	0.838	0.792	0.747	0.829	0.094	−0.030
Kedah	0.951	0.847	0.731	0.942	0.026	−0.004
Kelantan	0.696	0.662	0.629	0.690	0.052	0.024
Melaka	0.794	0.735	0.678	0.786	0.085	−0.037
Negeri Sembilan	0.984	0.874	0.785	0.972	0.026	−0.006
Pahang	0.549	0.529	0.511	0.544	0.115	−0.049
Perak	0.747	0.710	0.674	0.739	0.086	−0.023
Perlis	0.879	0.818	0.764	0.871	0.097	−0.024
Pulau Pinang	0.956	0.896	0.842	0.949	0.029	−0.002
Selangor	0.932	0.874	0.825	0.923	0.081	−0.016
Terengganu	0.737	0.710	0.683	0.731	0.036	−0.002
Sabah	0.512	0.487	0.460	0.508	0.047	−0.019
Sarawak	0.321	0.305	0.291	0.318	0.024	0.023
MALAYSIA	0.761	0.711	0.663	0.754	0.061	−0.013

[a] The average technical efficiency estimates of Malaysian regions have dropped after bias-corrected (3000 bootstrap replicates at 95% confidence interval). Bias-corrected regions' ranking is almost similar to conventional efficiency estimations except for Pulau Pinang (most efficient). The upper bound almost coincides with the conventional technical efficiency.

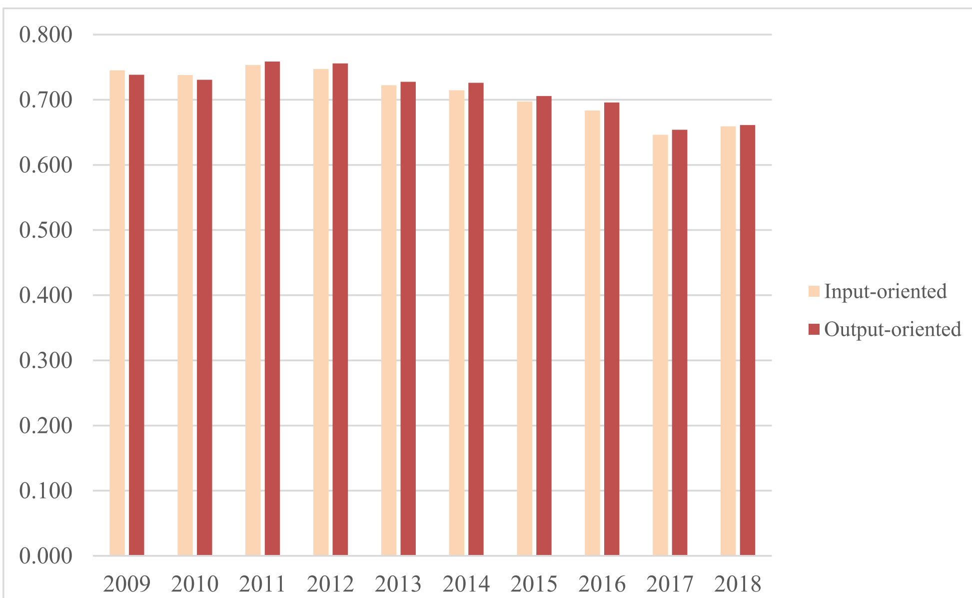

Fig. 1. Comparison between input- and output-oriented average efficiency score of Malaysia, 2009–2018.

rice production areas, contributing almost 40% of the total national rice production. Additionally, these regions are also known as Malaysian 'rice bowl' areas.

Meanwhile, Johor (0.792), Melaka (0.735), Perak (0.710), Terengganu (0.710), and Kelantan's (0.662) average efficiency scores are varied between 0.6 and 0.8 (Table 4), which shows that these regions can be categorized as medium efficient during the analyzed period and have the potential to obtain high efficiency through appropriate strategy approaches. For Kelantan and Terengganu, these regions are located at the east coast of Peninsular Malaysia, where generally the problem encountered in paddy cultivation are infertile soil compared to the other regions. Moreover, the Kelantan region is the second-largest rice production region in the country, contributing approximately 12% of the total national production, which in turn, obtaining the rice production efficiency for this region would directly help the overall performance of the Malaysian paddy and rice industry. Therefore, under the NAFP, the GoM can consider providing more specific soil treatment programs for this region's development.

Looking at Perak, a region located between Pulau Pinang, Kedah, and Selangor regions (the regions with high efficiency scores), where they relatively had almost similar cultivation profiles, can adopt the good agricultural practices from these regions to increase its average efficiency scores. However, for Johor and Melaka regions, these regions are part of non-granary areas, which generally have poor infrastructure, and only perform single cultivation in a year. Thus, focus can be given to building modern irrigation systems to increase cultivation frequency and enhance the production efficiency of these regions.

The remaining regions, Pahang, Sabah, and Sarawak, were deemed the least efficient regions in the country with Sarawak (0.305), had the lowest rank of average efficiency scores, followed by Sabah (0.487) and Pahang (0.529). However, there are some similarities between these regions, in that they all were part of the non-granary areas that have poor infrastructures, mainly equipped with traditional irrigation systems, and have low cultivation frequency. In 2014, under the NAFP 2011–2020 strategic development program to empower the domestic rice production, these regions predominantly were appointed as the new granary areas by the GoM. In the long run, the GoM aims to establish these regions by equipping them with modern irrigation systems, increasing cultivation frequency, and identifying potential new sites for paddy cultivation. Therefore, the lowest average estimation efficiency scores were expected because these regions lacked in many aspects of efficient rice production systems and required a specific period to attain

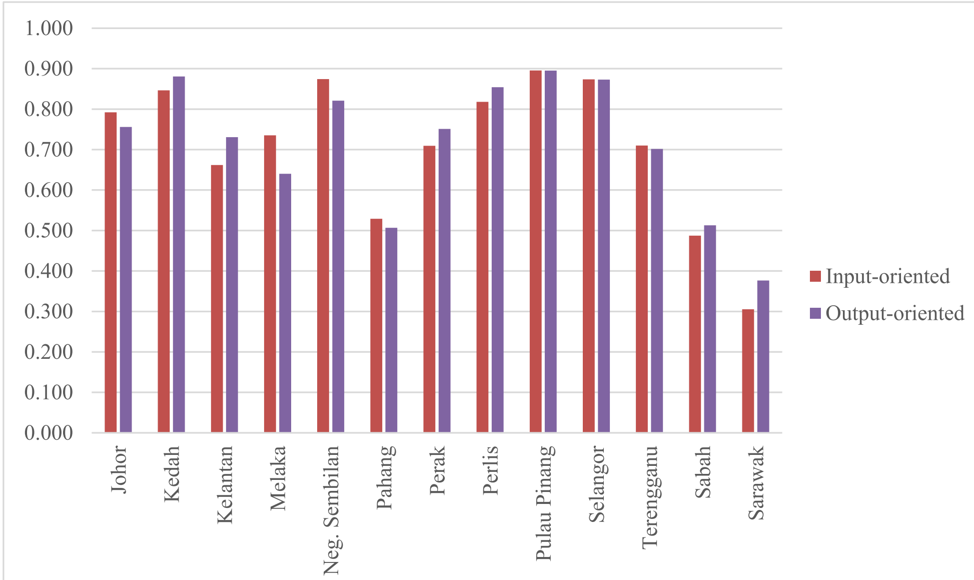

Fig. 2. Average input- and output-oriented efficiency scores of Malaysian Regions.

optimization in production.

The change in input-oriented efficiency scores during the 2009–2018 period is presented in the last column of Table 4 and is computed as the geometrical mean between the annual rate of change. The result indicates that, during this period, the change in input–oriented efficiency scores for the entire Malaysian paddy and rice industry deteriorated over time, with an average annual change in the growth rate of − 1.3%. Based on these findings, we can assert that the assessment of the RSS policy approach to Malaysia's food security planning in the input-oriented analysis requires relevant policy changes to improve the sector performance. Moreover, according to the regional level results, most of the regions had negative average efficiency scores varying between −0.2% and −4.9% except for Sarawak and Kelantan, which had positive efficiency values of 2.3% and 2.4%, respectively. Although Sarawak had the lowest input-oriented average efficiency scores in the country, it showed a significant improvement in its average efficiency score, registering an average value of 2.3%. This finding was unexpected and is a good indicator of East Malaysia's paddy and rice development. The average positive annual growth rate indicates the region's strong potential to achieve resources preservation and sustainable rice practices in the long run. Next, we discuss the input-oriented efficiency results of the analysis as shown in the boxplot (Fig. 3) and spatial distributions of efficiency level comparisons in 2009 and 2018 (Fig. 4). Both figures indicate the characteristics of regions from a resource saving perspective, wherein more developed regions, i.e., Kedah, Pulau Pinang, and Selangor, have more efficient rice production processes that utilize fewer inputs. As shown in Fig. 3, these regions have relatively small inter-quartile ranges for both the upper and lower whiskers, indicating that all the efficiency

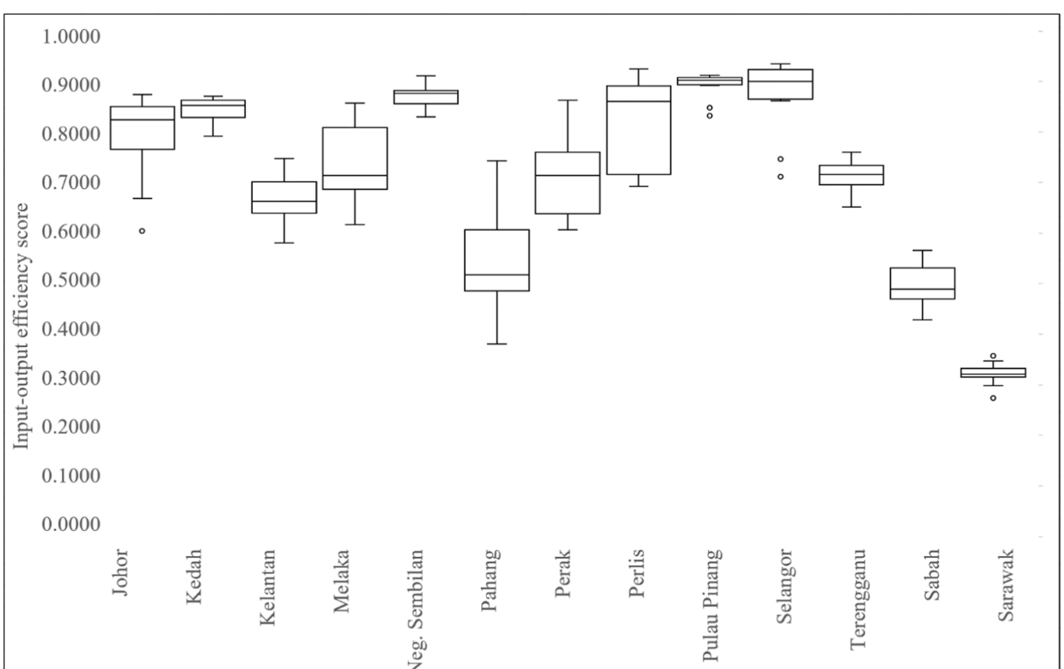

Fig. 3. Boxplot distribution of the input-oriented efficiency scores of Malaysian Regions.

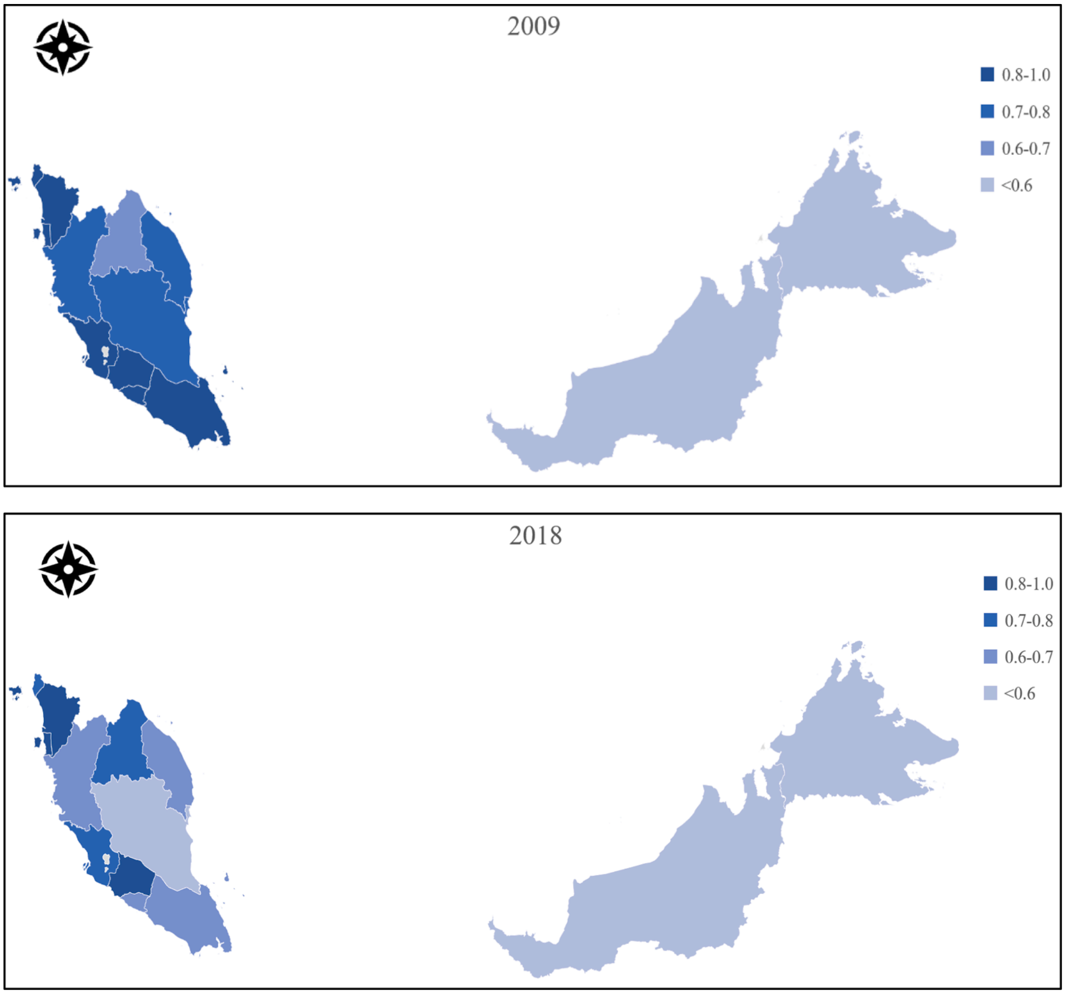

Fig. 4. Spatial distribution patterns of the input-oriented modeling efficiency levels in 2009 and 2018. Low efficiency < 0.6; 0.6 ⩽ Medium efficiency < 0.8; 0.8 ⩽ High efficiency ⩽ 1.0.

scores were concentrated in the small range. It should also be noted that, as shown in Fig. 4, Kelantan, a state located in the east coast of Peninsular Malaysia and the second largest paddy producer in the country, showed a significant improvement in its input-oriented efficiency score in 2018, obtaining higher production efficiency score than its score in 2009. The Kelantan performance is a positive indicator of the benefits of the RSS approach in terms of preserving resources while achieving production efficiency, and it may be beneficial for other regions with similar characteristics to adopt the approaches undertaken by this region in paddy and rice development.

Overall, for the input-oriented model, we found that, among the 13 regions, five regions were ranked as high efficiency level (0.8–1.0), another five regions had medium efficiency level (0.6–0.8), and the remaining three regions had low efficiency level (<0.6). Indeed, there is an enormous challenge to the key players (policymakers, planners, executors, economists, academicians, industrial players, etc.) of the Malaysian paddy and rice industry value-chain to cooperate in helping the nation to obtain production efficiency. Besides, at those rates, it is likely that the RSS policy did not significantly show a good achievement in terms of increasing production efficiency that related to minimizing environmental impacts and sustainable practices. In fact, the average annual change in efficiency was around − 1.3% (Table 3) during the analyzed period of the RSS policy implementation, indicating a general deterioration in industry growth. However, there is still room to improve this costly policy, particularly in terms of overcoming weaknesses in inputs management, such as the inefficient agrochemical inputs used during the cultivation process, which resulted in inefficient rice production.

Subsequently, we developed an output-oriented framework to estimate the average output-input efficiency scores. According to the output-oriented assumption, if a region can achieve its highest score or approaches frontier level 1, given its current quantity of inputs, the region is considered to be efficient. This approach is also known as the "maximizing production approach." In the Malaysian context, this approach could satisfy RSS policy goal of achieving the designated level of rice SSL by maximizing production while achieving production efficiency, using the current level of inputs.

The average output-oriented efficiency scores (VRS specification) of Malaysian regions are summarized in Table 5. The average output-oriented efficiency score for Malaysia was about 71.5%, implying that the current level of inputs generates about 71.5% of the output on average. Furthermore, as shown in Fig. 1, we observed that the annual average efficiency scores in the output-oriented analysis varied between a minimum of 65.4% to a maximum of 75.9%. Similar to the input-oriented analysis, this result shows that most of the regions could obtain better results while obtaining higher production efficiency through the efficient use of inputs.

In the same vein as the input-oriented model, the output-oriented results (Table 5 and Fig. 2) indicate that Pulau Pinang (0.895) is ranked as the most efficient region, followed by Kedah (0.881) and Selangor (0.873), and are operating almost at their optimum levels. These results suggest that these regions are maximizing their profits

Table 5
Descriptive statistics of average output-oriented efficiency scores[b] and geometrical mean change.

Regions	ConventionalTE	Bias-corrected TE	Lower bound	Upper bound	SD	Change (%) 2009–2018
Johor	0.792	0.756	0.718	0.785	0.113	−0.037
Kedah	0.954	0.881	0.788	0.947	0.030	−0.002
Kelantan	0.755	0.731	0.704	0.750	0.041	0.016
Melaka	0.683	0.640	0.593	0.678	0.073	−0.014
Negeri Sembilan	0.969	0.821	0.681	0.959	0.052	−0.008
Pahang	0.525	0.507	0.486	0.521	0.110	−0.049
Perak	0.782	0.751	0.722	0.777	0.070	−0.014
Perlis	0.903	0.854	0.805	0.897	0.068	−0.015
Pulau Pinang	0.955	0.895	0.834	0.949	0.032	−0.003
Selangor	0.931	0.873	0.821	0.924	0.087	−0.017
Terengganu	0.728	0.702	0.670	0.724	0.037	−0.001
Sabah	0.537	0.513	0.489	0.533	0.073	−0.029
Sarawak	0.392	0.376	0.357	0.389	0.024	0.019
MALAYSIA	0.762	0.715	0.667	0.756	0.062	−0.012

[b] Similar to the input-oriented, the average technical efficiency estimates of Malaysian regions have dropped after bias-corrected (3000 bootstrap replicates at 95% confidence interval). Bias-corrected regions' ranking is almost similar to conventional efficiency estimations except for Pulau Pinang (most efficient). The upper bound almost coincides with the conventional technical efficiency.

while obtaining production efficiency (Coluccia et al., 2020), given the constant level of a combination of inputs. Notice that Perlis (0.854) and Negeri Sembilan (0.821) regions can also be deemed to have high average efficiency scores and maximize their profits.

Next, Johor (0.756), Perak (0.751), Kelantan (0.731), Terengganu (0.702), and Melaka (0.640) regions can be considered as medium efficient in the Malaysia rice production context, similar to the input-oriented analysis. In fact, from the output-oriented perspective, the RSS policy goal to obtain the designated level of rice SSR as stated in the NAFP through increasing the domestic production, given the constant current inputs, could be realized if an appropriate strategic approach can be implemented based on these regions' necessity. Therefore, similar proposals to input-oriented analysis, for Kelantan and Terengganu, the infertile soil is the main issue, which requires soil treatments. At the same time, the poor infrastructures of non-granaries Johor and Melaka regions should be upgraded, and Perak regions should adopt the rice best practices from their efficient neighbors.

Meanwhile, similar to input-oriented analysis, for output specification, Sarawak (0.376) had the lowest rank of average efficiency scores in the country, followed by Pahang (0.507) and Sabah (0.513). This means that, on average, the output could be increased by 0.624, 0.493, and 0.487 for Sarawak, Pahang, and Sabah, respectively. Similar to the arguments in the input-oriented analysis, these regions predominantly were involved in the transformation from non-granaries to granaries area in 2014 under the NAFP 2011–2020. Therefore, it was expected that these regions had the lowest average estimation efficiency scores because they required an amount of time before the transformation process showed a positive result in terms of maximizing their production while obtaining rice production efficiency.

Next, the geometrical mean of the annual growth rate of change in output-oriented efficiency scores during the 2009–2018 period is shown in the last column of Table 5. We found that the change in output-oriented efficiency scores for the Malaysian paddy and rice industry deteriorated during this period, similar trend to the input-oriented analysis, showing an average annual change in the growth rate of −1.2%. Moreover, a majority of the Malaysian regions had negative values for the average annual change in output-oriented except for Kelantan and Sarawak, which registered positive values of 1.6% and

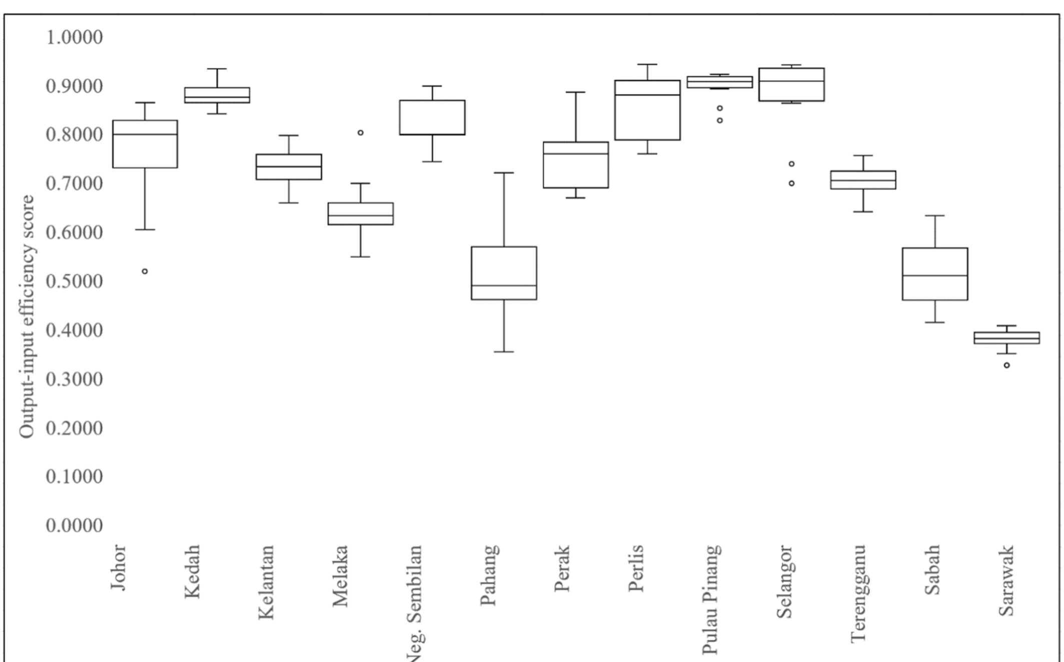

Fig. 5. Boxplot distribution of output-oriented efficiency scores for Malaysian Regions.

1.9%, respectively. In other words, the majority of the regions in the output-oriented analysis had decreased their efficiency scores performance in terms of maximizing production approach during the analyzed period of RSS policy implementation.

The boxplot and spatial distributions for the comparison of efficiency levels between 2009 and 2018 in the output-oriented analysis are shown in Figs. 5 and 6, respectively. Regarding the output-oriented analysis, the results confirmed that the more developed regions in the country, particularly Kedah, Pulau Pinang, and Selangor, were deemed efficient and maximized their rice production process using a combination of current-level inputs, highlighting their strong output maximization orientation. As shown in Fig. 5, these regions had a limited inter-quartile range of efficiency scores for both the upper and lower whiskers, implying that all the efficiency scores were concentrated in the small range. Additionally, from the output-oriented perspective, these regions, which constitute approximately 50% of the total national rice production, were able to optimize their existing current resources by exploiting economies of scale due to their larger cultivation areas (Coluccia et al., 2020).

On the other side, Kelantan showed a significant improvement in 2018 (Fig. 6), with this region was considered to achieve a high efficiency level under the RSS approach. Although, in general, the analysis showed that the RSS policy approach did not significantly increase the efficiency performance in maximizing production approach (output-oriented specification) of most Malaysian regions during the research period (Table 5), Kelantan, as well as Sarawak, was an exception. Further investigation could be conducted to understand better the self-sufficiency advantages approach for these regions.

The output-oriented analysis demonstrated results almost similar to those of the input-oriented analysis. Among the 13 regions, five regions were classified as having high efficiency levels (0.8–1.0), five regions were categorized as medium efficient (0.6–0.8), and three regions were the least efficient regions (<0.6). Moreover, from the average annual change viewpoint, the RSS approach did not significantly increase efficiency related to the maximization production approach. In other words, increasing production under the RSS approach by maximizing the output does not necessarily increase efficiency.

4.4. Geographical analysis of input- and output-oriented

We further our analysis based on the geographical classifications by dividing the Malaysian regions into five main production areas: the northern, central, southern, east coast, and East Malaysia. We carried

Table 6
Kruskal-Wallis test of efficiency estimates difference between the regions.

Hypothesis test of efficiency estimates differences between the regions	Kruskal-Wallis rank sum test	Conclusions
H_0: There is no difference in efficiency estimates between the regions H_A: There is a difference in efficiency estimates between the regions		
Input-oriented	2.823e-08***	Reject H_0
Output-oriented	1.060e-08***	Reject H_0

*** Significance at 10%, 5% and 1%

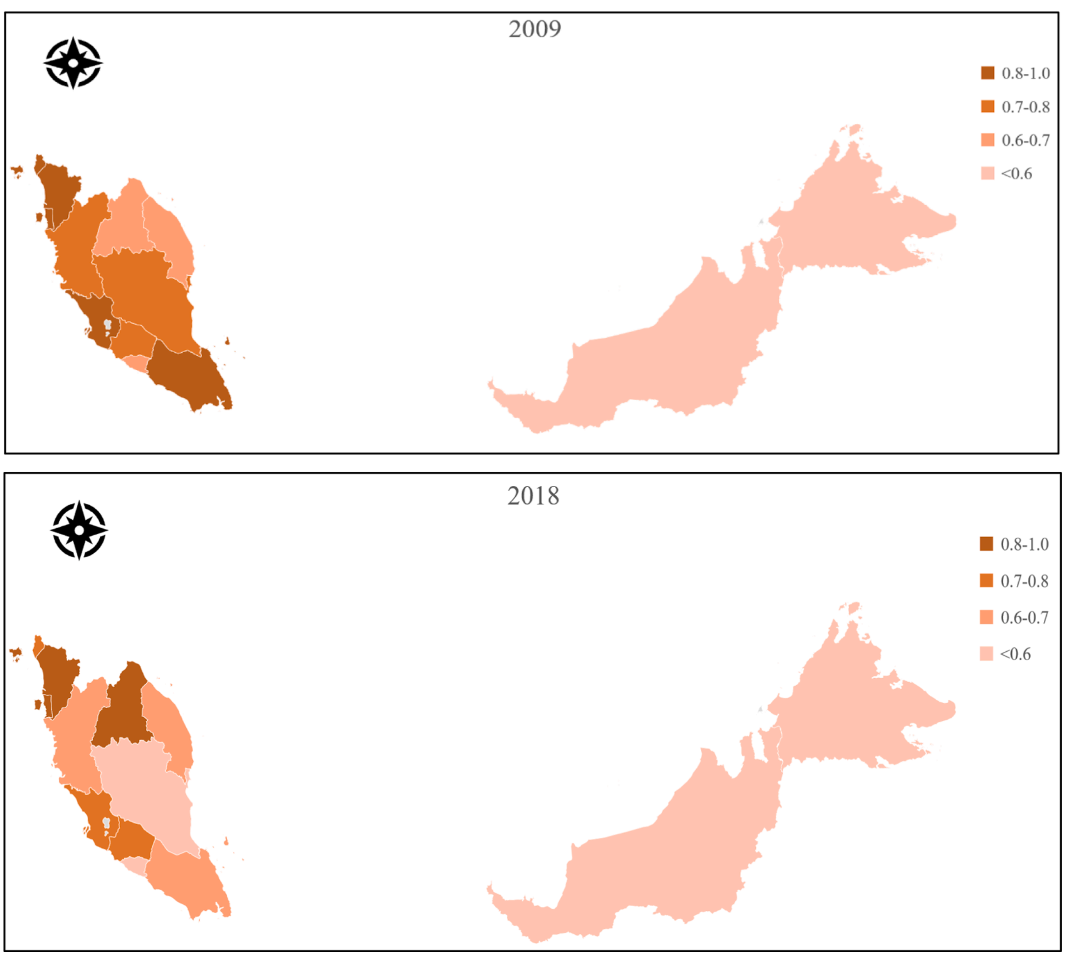

Fig. 6. Spatial distribution patterns of the output-oriented modeling efficiency levels in 2009 and 2018. Low efficiency < 0.6; 0.6 ⩽ Medium efficiency < 0.8; 0.8 ⩽ High efficiency ⩽ 1.0.

out the non-parametric Kruskal-Wallis test for input- and output-oriented specifications to assess whether there are efficiency estimates differences between these geographical regions classifications (Table 6). In this test, both specifications reject the null hypothesis, indicating there are differences in efficiency estimates between the regions.

Next, Table 7 shows the summary of input- and output-oriented analysis based on the geographical classifications. We found that three out of the five geographical areas, which were northern, east coast, and East Malaysia, had average output-oriented efficiency scores that outweighed their input-oriented scores. This confirms that, during the analyzed period, Malaysian rice production at the national level is oriented toward maximizing production rather than resources saving approach under the RSS policy implementation.

According to the average input-oriented efficiency scores, the northern and central showed a general orientation toward resource preservation. Hence, both geographical areas indicated a better orientation toward sustainable rice production through the efficient use of available resources. In contrast, the southern, east coast, and East Malaysia areas demonstrated the average efficiency scores lower than the northern and central areas. This indicates that, in general, inefficient agricultural resources occur during rice production, which negatively affects environmental protection and preservation efforts. Moreover, these findings are essential in RSS policy assessment because it helps policymakers identify the strengths and weaknesses of the areas to improve policy implementation within the context of optimization of agricultural resources for sustainability practices.

On the other hand, the average output-oriented efficiency scores according to Malaysia's geographical distribution showed that the northern and central regions exhibit a good capacity for production maximization, given a certain level of inputs. Both regions were also able to take advantage of economies of scale due to their larger cultivation areas and by exploiting existing resources. Comparatively, the southern, east coast and East Malaysia areas were considered inefficient in maximizing the production level and obtaining production efficiency. The east coast and East Malaysia, despite their large sizes, were not able to take advantage of economies of scale mainly because of the infertile soil issues and poor infrastructures. Therefore, at this rate, since the Malaysian rice production orientation can be deemed as a self-sufficiency approach, these findings could give valuable information to improve the existing policy by formulating an effective strategic approach under the NAFP to solve the prolonged issues of the particular regions.

Overall, northern and central Malaysia showed a strong orientation toward maximizing production approach and demonstrated a good attitude toward environmental preservation due to their resource saving characteristics. Meanwhile, the southern region has generally demonstrated a good ability toward sustainable resource management but requires efforts to achieve production efficiency. However, there is still room for improvement in terms of maximizing production, mainly by upgrading modern irrigation systems for efficient rice production, as this region is part of the non-granary area that lacks modern infrastructures for efficient cultivation purposes. Regarding the east coast and East Malaysia, both regions showed a relatively weak orientation toward the environment and demonstrated low capability with regard to production maximization. Therefore, an inclusive policy approach that encompasses environmental protection, maximizing their production potential while achieving production efficiency should be established to increase the competitiveness of these geographical regions.

Table 7
Summary of Malaysian geographical regions production efficiency.

Geographical Region	Input-oriented	Output-oriented
Northern Region	0.8174	0.8453
Central Region	0.8739	0.8470
Southern Region	0.7636	0.6982
East Coast	0.6337	0.6463
East Malaysia	0.3964	0.4447

Malaysia's geographical classification, the northern Region: Perlis, Kedah, Pulau Pinang and Perak; the central Region: Selangor and Negeri Sembilan; the southern Region: Johor and Melaka; the east coast Region: Kelantan, Terengganu and Pahang and; the east Malaysia: Sabah and Sarawak

5. Conclusion and policy implications

In response to the 2007–2008 international food crisis, the Malaysian NFSP was reformulated, particularly the rice policy toward bolstering the self-sufficiency approach. The main challenges arising from the implementation of the RSS approach were obtaining production efficiency while maximizing production and, at the same time, minimizing the utilization of its agricultural resources for sustainable rice development.

This study evaluated the RSS policy approach using the non-parametric bootstrap DEA method, which enabled an improved empirical analysis of the food self-sufficiency study. This evaluation can help policymakers and planners to identify the strengths and weaknesses of this policy approach and the relevance to maintaining this costly policy. On the other side, an improved self-sufficiency policy based on the appropriate analysis, i.e., regional analysis, as shown in this study, can be developed that could benefit many parties.

Furthermore, the bootstrap DEA approach allowed us to correct the traditional efficiency scores and obtain confidence intervals, resulting in more statistically accurate efficiency scores than those obtained using the conventional DEA procedure. Moreover, the bootstrap DEA model used in this study can serve as an effective tool in agriculture studies related to the policy development of monitoring environmental planning and maximizing production while obtaining production efficiency.

Next, the annual expenditures to sustain the Malaysian paddy and rice industry are considered costly mainly due to heavy agricultural inputs assistance provided by the GoM aiming toward production maximization approach than minimizing the available resources utilized. Thus, evaluating the efficiency performance of RSS using input- and output-oriented bootstrap DEA specifications related to these inputs allow policymakers and planners to establish an improved RSS approach based on regional orientation, whether the policy should focus on resource saving or maximizing the production, or both by considering the current level of available resources.

Subsequently, the study found that, based on the regional analysis, at 95% confidence interval of the bootstrap efficiency estimate (Table 4 and Table 5), the Malaysian RSS approach at the national level is better oriented toward maximizing the production level (71.5%) rather than resources saving (71.1%). This indicates that the designated RSS policy generally seeks to increase the production level. However, the findings based on the geographical classifications (Table 7) vary with the northern and central areas, which are deemed more developed, showed a good performance in minimizing their environmental impacts, and are able to maximize their production while obtaining production efficiency. In contrast, the lesser-developed regions, the southern, east coast, and East Malaysia regions, indicate a low efficiency performance. An improved RSS strategic approach could help the Malaysian region's balance rice production maximization, minimizing the environmental impacts, and obtaining production efficiency. These efforts could be made by focusing on modernizing the irrigation systems, efficient agrochemical inputs usage, adopting best agricultural practices, and implementing soil treatments programs.

According to further assessment of the RSS policy, the policy approach showed deterioration of efficiency performance during the analyzed period 2009–2018. The findings revealed that the average annual change at the national level for both specifications (input- and output-oriented) showed negative values in the efficiency growth rate of Malaysian rice production. These are the significant indicators regarding the recent efficiency performance of Malaysian rice production. At this rate, the GoM can consider a policy reform for the competitiveness of this industry.

At present, the Malaysian National Agrofood Policy 2.0 (NAFP 2.0) 2021–2030 is being drafted to outline a new policy approach for the agrofood industry, in line with the 2030 agenda and the UN's SDGs. Generally, the new NAFP planning places more emphasis on holistic and sustainable agricultural practices, without compromising the well-being and abilities of future generations, and preserving natural resources (Anon, 2020). From this assessment, it is critical that Malaysia improve its future food security policy by giving more consideration and focusing on the environmental elements besides production maximization approach. Although the concept of food self-sufficiency policy is subject to international debate, however, under particular circumstances such as for staple food production, at least, this concept is still relevant and accepted by several countries worldwide. Therefore, an improved self-sufficiency policy approach is crucial for countries' policy development, especially to obtain production efficiency that is closely linked to production maximization and environmental preservation. Additionally, since this policy approach is considered costly, it is momentous to establish an effective strategic approach in order to obtain policy efficiency in the long run.

There still exist limitations in this paper. The study applies the single bootstrap method in the efficiency ranking of the regions. However, to increase the consistency in efficiency estimation (Long et al., 2020), future research can consider applying the double bootstrap method by Simar and Wilson (2007). Another limitation is our assumption regarding the non-stochastic nature of DEA bootstrap modelling requires all DMUs in the sample should be similar in terms of technology and characteristics (homogeneous). Otherwise, the model would be subject to specification bias (Tziogkidis, 2012). In our approach, we assumed the regions to be homogenous so that we could estimate the relative technical efficiency of each region and conduct an empirical comparison. However, the consideration regarding stochastic elements (i.e., weather) would improve the efficiency estimation, such as by using alternative efficiency estimation approaches, i.e., Stochastic Frontier Analysis (SFA).

CRediT authorship contribution statement

Mohd Norazmi Nodin: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Zainol Mustafa:** Conceptualization, Supervision, Writing – review & editing. **Saiful Izzuan Hussain:** Formal analysis, Writing – review & 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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ARTICLES FOR FACULTY MEMBERS

SUSTAINING FOOD SECURITY IN MALAYSIA

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Original research article

Biofuels, environmental sustainability, and food security: A review of 51 countries

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ABSTRACT

Biofuels will not only be a solution for a good environmental quality, but may also bring an increase in food production. This scenario, which refers to sufficiently huge supply of biofuels, capable to bring better environmental quality vis-à-vis food security. Biofuels have the potential to offer a win-win opportunity to improve environmental quality, whereby better environmental quality may promote a sizeable increase in food production. Therefore, the objective of this paper is to investigate the impact of biofuels on food security, given the level of environmental quality in 51 developing countries. The results of dynamic generalized method of moments indicate that the interaction term between biofuels and environmental quality has a positive and significant impact on food security. This implies that biofuels will initially bring about a competition to food security but in a later stage it can lead to a favorable condition for agriculture. Therefore, significant expansion and consumption of biofuels could contribute to increment in food security and sustain the environmental quality.

1. Introduction

As a society, we need action to significantly reduce global greenhouse gas (GHG) emission in the coming decades, which primarily comes from the burning fossil fuels. This is because the GHG emission is projected to increase by fifty percent and becomes the fastest growing driver of climate change by 2050. Specifically, this would be far larger in developing countries, in which GHG emission is expected to grow from 63 percent in 2000 to 235 percent by 2050 than in developed countries [1]. Rapid increase in GHG emissions, which is predicted to be the main factor affecting the earth's climate, raises worldwide concern and imposes serious pressure to political leaders to design effective policy that can curb the emissions [2].

Accordingly, international energy agency has introduced renewable energy as part of the possible solutions to reduce GHG emission and ensure a stable climate all over the world [3]. Major types of renewable energy are wind, geothermal, solar, ocean power, hydropower and biomass. Specifically, the share of renewable energy has increased in heating, electricity and transport sectors. Out of various renewable energies, biofuels continue to represent the vast majority of the currently developed and consumed renewable energy. According to Fig. 1, biofuels production has surged from 142.6 mln L to 160.9 mln L in 2019, from which bioethanol made up 78 percent of total biofuels production with the remaining 22 percent accounted for biodiesel. Based on [4], developed countries' production of biofuels has grown progressively in 2019, which is 9.9 mln L greater than in 2015. For developed countries, the main biofuels producer is the United States, driven by the subsidies to bioethanol producer and environmental legislation [5]. While, in developing countries, the production of the renewable energy coming from biofuels has reached 66.3 mln L in 2019. In developing countries, the major biofuels producing countries are Brazil, Indonesia, China, Argentina and Thailand [6,5].

At present, biofuels are liquid fuels (either bioethanol or biodiesel) and mainly produced from agricultural products, leading to a stiff competition or head-aching trade-off between demand for food consumptions and biofuels production. Higher demand for agricultural outputs for biofuel production may adversely affect food availability or supply such as sugarcane, sugar beet, cassava, corn, rapeseed, soya bean, palm oil, wheat and others if they are switched from production of food to biofuels. As a result, it may aggravate the problem of currently insufficient supply of food, leading to acute hunger problem in many areas. Studies on the relationship between food security and biofuels, albeit limited, are sharing almost similar conclusion that the development of biofuels reduces food supplies and increases food

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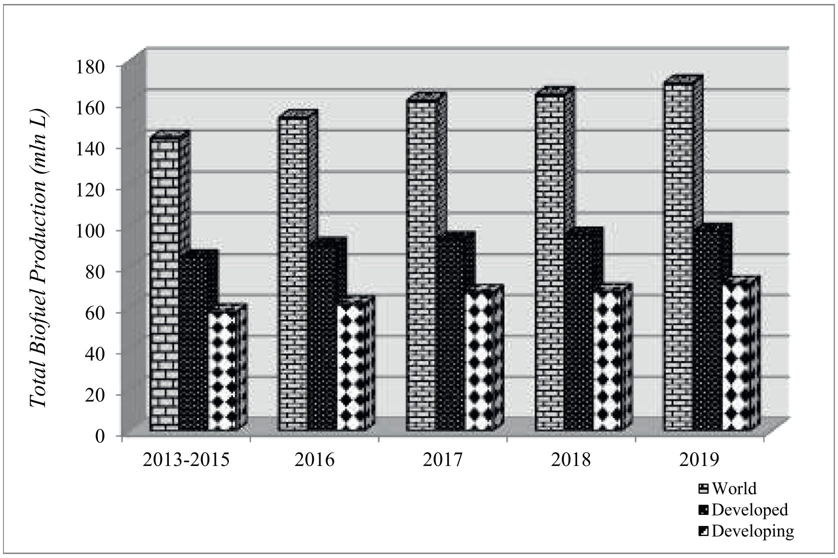

Fig. 1. World biofuels production. Source: [5,7].

prices, thereby worsens food insecurity for the poor [8–11]. The World Bank president, Robert Zoellick states that increasing biofuel production is a significant contributor to soaring food prices around the world in the future [12]. High price of food means that less people are now can afford to buy food. At the same time, [13] state that the use of agricultural commodities (such as cereals) as sources for biofuels will lead to an additional 150 million people at risk of hunger by 2020.

Among the reasons cited as the sources of the conflict are competition for resources, mainly agricultural outputs as well as price of agricultural products. Firstly, in terms of food availability, productive resources such as land, labor, and water are switched from the production of food to biofuels, leaving agricultural sector with less supply of those resources [10,14]. With other developments such as urbanization and industrialization are already seriously affecting the size of land and labor available for agricultural sector, progression of biofuels sector may offer another setback to this sector. Secondly, biofuels are likely to reduce food accessibility because biofuels production is one of the drivers of food commodity prices [15]. While rich people may still be unaffected by the soaring prices of food, the poor may have to satisfy with less food as their real income drops and most likely have to resort to less quality food. Apart from just getting the food, another important aspect which also embedded in the definition of food accessibility is on the quality of food that can support nutrients supply, especially to the poor [16]. High prices of nutrient-contained food may hinder the poor from getting them. Biofuels development is predicted strongly by past studies as having a negative impact on the world agricultural commodity that available to the poor at affordable prices. To further find support, Fig. 2 provides preliminary supporting evidence for the negative impact of biofuels on food consumption. It means that currently, production of biofuels does play a role in diverting the amount of agricultural supply for food productions to biofuels production, leading to shortage of food supply.

With all arguments so far tend to go against the development of biofuels, will that mean we have to abolish biofuels sector? There is actually a forgotten aspect that the development of biofuels is not always in the expense of production or supply of food. The report of Intergovernmental Panel on Climate Change (IPCC) has also supported that biofuels can lead to a substantial reduction in environmental degradation and is projected to contribute to the net reduction of carbon emissions by 94 percent relative to fossil fuels, which is merely at 60 percent [2]. From the fact in Fig. 3, it suggests that the annual greenhouse emissions of developing countries slightly decreased between 2011 and 2016, strongly argued as the positive consequence of biofuels development.

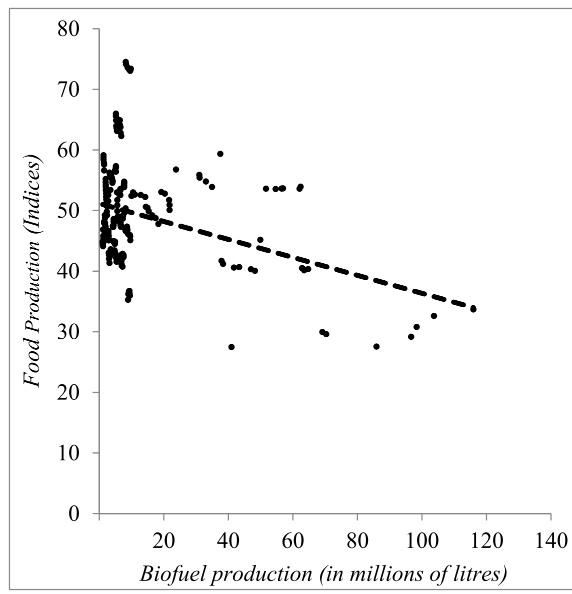

Fig. 2. Total biofuels and food production in 2011 and 2016.[1] Source: [5].

Beyond that, meeting the reduction in GHG emissions due to the biofuels production has the potential to also bring an *increase* in food production to populations. One of the main facts is that an accelerated reduction in greenhouse emissions is likely to recover the current threats to food security. In this case, it is suggested that a reduction in global temperature can potentially increase crop yield, cause better quality and more quantity of crops. According to [18], beyond a certain range of temperatures, warming tends to reduce yields. This is because higher temperatures are likely to impede the ability of plants to use the

[1] Angola, Argentina, Belarus, Bolivia, Brazil, Bulgaria, China, Colombia, Costa Rica, Ecuador, Egypt, El Salvador, Ethiopia, Guatemala, Honduras, India, Indonesia, Kazakhstan, Kenya, Malawi, Mexico, Mozambique, Nicaragua, Pakistan, Panama, Paraguay, Peru, Philippines, Romania, Russian Federation, Rwanda, Serbia, Sudan, South Africa, Thailand, Turkey, Ukraine, United Republic of Tanzania, Uruguay, Viet Nam, Barbados, Croatia, Cuba, Fiji, Iran, Jamaica, Mauritius, Swaziland, The former Yugoslav Republic of Macedonia, Trinidad and Tobago and Zimbabwe.

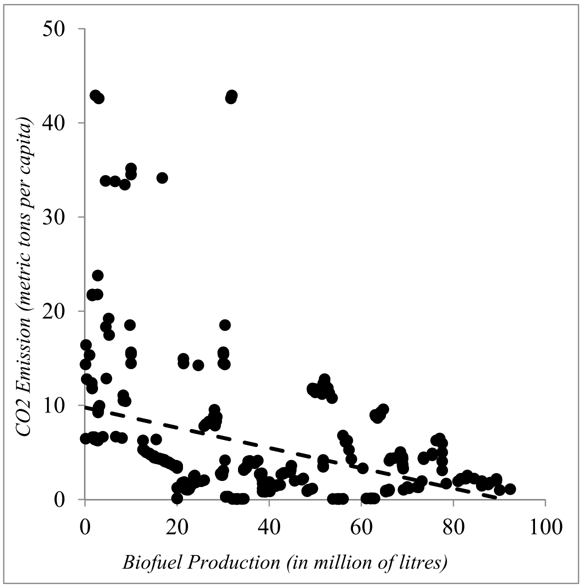

Fig. 3. Biofuels production and CO_2 emission in 2011 and 2016.[2] Source: [5, 17].

moisture. Therefore, increases in temperature with more dryness as a result of the changing climate are harmful to crop cultivation. Thereby, an increase in biofuels is expected to cause lower carbon emission and likely to affect global temperature to be more favorable to food production and supply. These highlight that production of biofuels may play a vital role in reducing greenhouse emission, whereby better environmental quality promotes a sizeable increase in food production. *Hence, this study specifically curious about what is the effect of biofuels production on food security, if biofuels sufficiently promote the level of environmental quality in developing countries.*

The rest of the article is organized as follows: Section 2 reviews past studies, Section 3 provides the research methodology, including model specification and the estimation strategy. The empirical results are reported in Section 4 and finally, Section 5 concludes the article.

2. Literature review

In respect to empirical analysis, several factors such as population growth, environmental degradation, arable land and biofuels production have been confirmed theoretically and also by past studies as crucial determinants of food security. Basically, there are four research strands pertaining to determinants of food security.

The role of population in food supplies has been considered one of the basic principles in economics. The pioneering work in this field, which links food security and population growth, can be traced back to [19]. Malthusian theory identifies that food shortages exist due to the presence of too many people compared to the amount of food supply and thus exacerbated long-run food insecurity [19]. Many studies conclude that the rate of population growth determines the rate of food supplies [20–23]. Recently, [24] and [25] find that population affects demand for food, leading to an excessive use of resources. A pressure on limited resources increases the challenge of efforts to adequately meeting sufficient and nutritious food. [26] also discuss the challenges and opportunities in food security as well as maintaining the food supply chain globally. The challenge in food security is the increase in population, putting major adverse impact on food availability and threatening food security. Noticeably, world population plays a vital role in determining food production for a country, specifically in the year 2050 [26–28], especially when world population is projected to reach 9 billion in 2050, which is more than double from 1950. Therefore, rapid increasing number of populations makes securing food for everyone a mounting task [29].

H_1: There is a negative impact of population on food security.

In keeping with original Malthus, neoMalthusians adds land in addition to population size. Land has been set as another important basis for food security. It plays an essential role in production of agricultural crops as well as making more food available for growing population [15, 22, 26, 30]. In this context, availability of more land for the agricultural activities can raise household food security by contributing directly to more food production. Additionally,

[22] and [31] find that increases in land access to the poor can contribute to poverty alleviation and an increase in food security via increasing household accessibility. In this respect, it shifts up the willingness and ability of households to buy food and thereby contributes directly to increased household food security. Therefore, the increment in arable land as a mean of higher resources to promote agricultural outputs and livelihood may help to sustain food productivity and assure household food supplies.[3]

H_2: There is a positive impact of land on food security.

Theoretically, Food Availability Decline (FAD) approach proposes that food insecurity is primarily caused by a decline in food availability that leads to insufficient food to feed the growing population. The theory strongly emphasizes the supply side failure as the source of the problem. As one crucial factor leading to the failure, the FAD suggests that food production is vulnerable to environmental degradation. Empirically, [32, 33, 23, 34, 35, 25, 26, 36, 37, 38], and [39] explore the impacts of environmental degradation on food production. These studies show that environmental degradation has a negative significant impact on food production. Changing in climate is expected to increase temperature unfavorably, thereby reduces crop yield and production in short- and long-term [40, 41]. [34] recognize that flooding is destroying growing seasons, leading to crop loss, low yields, and reduction in the availability of food. There are few literatures investigating the link between food security and environmental degradation in African countries, for instances, [36] for North Africa and Southern Africa, as well as [42] for Southern Africa. Overall, past studies suggest that food security might be negatively affected by environmental degradation.

H_3: There is a positive impact of environmental quality on food security.

In addition, biofuels are another specific factor that has been identified by past studies as important in mitigating climate change and alleviating global energy concern. However, a number of studies namely [8, 43, 44, 45, 9, 10, 11, 46, 47, 48, 49, 50, 51, 52] and [53] claim that rapid growth in biofuel production worsens food security. Increases in production of biofuels lead food supplies to be unlikely sufficient as the production of biofuels require agriculture-feedstock. Biofuels are primarily produced from agricultural products such as corn, oleaginous sugarcane, forest biomass, oil seeds and other crops.

[2] Angola, Argentina, Belarus, Bolivia, Brazil, Bulgaria, China, Colombia, Costa Rica, Ecuador, Egypt, El Salvador, Ethiopia, Guatemala, Honduras, India, Indonesia, Kazakhstan, Kenya, Malawi, Mexico, Mozambique, Nicaragua, Pakistan, Panama, Paraguay, Peru, Philippines, Romania, Russian Federation, Rwanda, Serbia, Sudan, South Africa, Thailand, Turkey, Ukraine, United Republic of Tanzania, Uruguay, Viet Nam, Barbados, Croatia, Cuba, Fiji, Iran, Jamaica, Mauritius, Swaziland, The former Yugoslav Republic of Macedonia, Trinidad and Tobago and Zimbabwe.

[3] It is important to note that the immediate effect of land is expected to be positive but land expansion for agricultural activities will always impose bad repercussions to environmental quality. Similar to the case of biofuels, the final effect of land size on food security could also be ambiguous, depending on how much destruction to the environment the land expansion will offer. Nevertheless, this issue could be beyond the scope of this study and we leave it for future study. In this study, we simply assume, in drawing the hypothesis, that the land expansion is accompanied with environmentally friendly agricultural techniques.

Therefore, [8, 54] and several others suggest the occurrence of negative impact of biofuels development on food production.[4]

H_4: There is a negative impact of biofuels on food security.

Past studies on biofuels-food security nexus tend to oagainst the biofuels development via their negative finding. In other words, these studies argue that biofuels production may aggravate the problem of insufficient supply of food, leading to acute hunger problem in many areas [55, 56]. There is actually a forgotten aspect that the development of biofuels it is not always in the expense of production or supply of food. While there is no specific theory available and capable to link biofuels, environment and food security, the recent statement by [57] argues that producing bioenergy does not have to conflict with food security. [57] views bioenergy as a way to improve energy security and food productivity as well as to ensure household food supplies. Likewise, [8] also raise the question of whether the sustainable development goals of alleviating global hunger can be achieved with the expansion of biofuels production.

One of the main facts is that a reduction in global temperature can potentially increase crop yield, cause better crop quality and more crop quantity [18]. This is because each crop has its own temperature requirement that plays a role in crop development and yields. Plant development decreases as temperature rises beyond the optimum level [58]. Beyond the optimum, higher temperatures adversely affect crop yield, pollination, plant growth and reproductive process [59]. For example, an analysis by [60] indicates that yield growth for chili, eggplant, okra, sweet potato, watermelon would gradually increase with temperature up to 21 °C to 29 °C, but decreases with temperature increase beyond this range. Climate change has been one of the factors affecting sugarcane production through higher temperatures in Brazil and Thailand. The maximum temperature in Brazil was 30.8 °C, which leads to higher evapotranspiration, reduction in the amount of water available in soils and thus higher difficulty of planting sugar cane [27]. Likewise, tomato is grown worldwide with China and India are ranked as the world's top two tomato-producing countries. The optimum temperature for tomato growth is between 21 °C and 24 °C. Temperature, which is above 27 °C leads to the deterioration of tomato quality and quantity. Tomato planting is highly affected by adverse climatic conditions, particularly in India, Egypt and Brazil as currently their temperatures stand at 29.9 °C, 27.8 °C and 30.8 °C, respectively. Tomato is a warm seasonal crop that requires a warm and cool climate, but cannot withstand frost and high humidity. High temperature beyond the favorable degree will therefore significantly influence the growth processes of tomato from seed germination, seed growth, flower and flower set and fruit quality. This is because if temperature rises unfavorably exceeding the optimum range for many crops, plant growth, pollination, reproductive processes and development along with crop yield are adversely affected [59]. As a result, an increase in biofuels is expected to cause decreased carbon emissions and is likely to affect global temperature in food supplies.

Accordingly, this study allows us to emphasize a clear distinction regarding the effect of biofuels production on food security, if biofuels sufficiently promote the level of environmental quality in developing countries, the point that is missing in the previous studies. Most of past studies indicate that biofuels production has received an increasing attention by environmentalists as a mean to mitigate greenhouse gases emissions, particularly to tackle the unprecedented climate change. Thereby, a reduction in emission is likely to affect global temperature to be more conducive for plantation. This highlights that the production of biofuels may play a vital role in reducing greenhouse emission whereby better environmental quality promote a sizeable increase in food production in the long run. This is the missing link in the literature. To our limited knowledge, the outcome of this study may be useful for providing a framework for future development, not only in food production but also in biofuels development.

H_5: There is a threshold effect of biofuels on food security, given the level of environmental quality.

3. Model specification

The Malthusian and neoMalthusian model assume that human population tends to grow in geometric progression, while human substance such food and agriculture-based products only grow in arithmetic progression. In other worlds, population tends to grow at much faster rate than human substances, thereby increases in number of populations leads to shortages of food supplies. The studies by [20] and [61] indicate that food shortages exist due to the presence of too many people compared to the amount of food supply and thus exacerbated food insecurity in the long-run. Since it is widely assumed that rapid population growth leads to the considerably lesser amount of food, the basic food security function can be written as:

$$FS_{i,t} = \alpha + \beta_1 POP_{i,t} + \varepsilon_{i,t} \quad (1)$$

where *FS, POP* and ε represent food security, population growth and error term, respectively. Subscripts *i* refers to country and *t* refers to period. In addition, combining the literature, we extend Eq. (1) to also incorporate arable land (*AL*), biofuels production (*BP)* and environmental quality (*EQ*) as controlled variables [24, 25, 35, 25], written as:

$$FS_{i,t} = \alpha + \beta_1 POP_{i,t} + \beta_2 AL_{i,t} + \beta_3 EQ_{i,t} + \beta_4 BP_{i,t} + \varepsilon_{i,t} \quad (2)$$

To examine our central thesis that environmental quality can be the turning factor governing the positive effect of biofuels on food security, we extend Eq. (2) by adding the interaction terms of biofuels and environmental quality. Our final estimating model will then be:

$$FS_{i,t} = \alpha + \beta_1 POP_{i,t} + \beta_2 AL_{i,t} + \beta_3 EQ_{i,t} + \beta_4 BP_{i,t} + \beta_5 (BP_{i,t} * EQ_{i,t}) + \varepsilon_{i,t} \quad (3)$$

Accordingly, Eq. (3) can be simplified as:

$$FS_{i,t} = \alpha + \beta_1 X_{i,t} + \varepsilon_{i,t} \quad (4)$$

where *X* represents all explanatory variables in Eq. (3). In addition to aggregate measure of food security (FS), we also examine the similar issue for individual of all four dimensions of food security, namely food availability *(FSAVA),* food accessibility *(FSACC),* food utilization *(FSUTI)* and food stability *(FSSTA)*. In doing so, apart from the standard explanatory variables set as *X* in Eq. (4), for each dimension, we also include several other unique factors to each of them. Firstly, *FSAVA* equation is finalized as follows:

$$FSAVA_{i,t} = \alpha + \beta_1 X_{i,t} + \beta_2 CA_{i,t} + \varepsilon_{i,t} \quad (5)$$

where in Eq. (5), *CA* is credit to agriculture. A number of studies have suggested that credit to agriculture [62] appears to be necessary to maintain and improve the food security. On the set up of *FSACC* function, income inequality (*GINI*) and food prices (*PRI*) are two additional variables as the following Eq. (6):

$$FSACC_{i,t} = \alpha + \beta_1 X_{i,t} + \beta_2 GINI_{i,t} + \beta_3 PRI_{i,t} + \varepsilon_{i,t} \quad (6)$$

[63, 64] and [65] find that income inequality intensifies food insecurity by perpetuating poverty and widening the inequalities in accessibility. Thereby, unlike the poor, riche people would always have enough money to spend on healthy foods and to fulfill their basic needs of life. Besides that, [48] has examined the food security in terms of the relationship between food production and food price. Food price can constrain household purchasing power and force them to resort to less food. For *FSUTI* function, we add two more variables, namely food price

[4] Biofuels are not necessarily agriculture-based. There are second and third generations of biofuels, which if properly and successfully developed, may minimize this issue. Nevertheless, the second (i.e. lignocellulosic feedstocks and municipal solid wastes based.) and third generations (i.e. algal biomass-based) biofuels are still at their infancy stage and therefore, the composition of agriculture-based biofuels dominate the total production of the industry.

Table 1
The list of developing countries based on region and income groups.

Region	Income groups	Countries
Asia & Pacific	Lower-Middle Income	Indonesia, The Philippines, Vietnam
	Upper-Middle Income	China, Fiji, Thailand
Europe & Central Asia	Lower-Middle Income	Ukraine
	Upper-Middle Income	Belarus, Bulgaria, Kazakhstan, Romania, Russian Federation, Serbia, Turkey
	High Income	Croatia
Latin America& Caribbean	Lower-Middle Income	Bolivia, El Salvador, Guatemala, Honduras, Nicaragua
	Upper-Middle Income	Brazil, Colombia, Costa Rica, Cuba, Ecuador, Jamaica, Mexico, Paraguay, Peru
	High Income	Argentina, Barbados, Panama, Trinidad and Tobago, Uruguay
Middle East & North Africa	Lower-Middle Income	Egypt
	Upper-Middle Income	Iran
South Asia	Lower-Middle Income	India, Pakistan
	Low Income	Ethiopia, Malawi, Mozambique, Rwanda, Tanzania, Zimbabwe
Sub-Saharan Africa	Lower-Middle Income	Angola, Côte d'Ivoire, Kenya, Sudan, Swaziland
	Upper-Middle Income	Mauritius, South Africa

Table 2
List of variables, definition and sources.

Variables	Definition/ measurement	Sources
POP	Annual population growth rates	[17]
EQ	Carbon dioxide emissions in metric tons per capita	
AL	Land area in percentage of total land	
GDP	GDP per capita in constant 2010 US dollar	
UNE	Unemployment of percentage of total labor force	
GFSI	Global Food Security Index	[74]
BP	Total biofuels production in thousand barrels per day	[5] and [7]
CA	Credit to agriculture as percentage of total credit	[75]
PRI	Food price index	[76]
IE	Income inequality in Gini index	[76] and [7]
TEMP	Temperature	[5]
NUM.DISAS	natural disasters occurrences	[77]
EPI	Environmental Performance Index	[78]

(*PRI*) and income (*GDP*) as follows:

$$FSUTI_{i,t} = \alpha + \beta_1 X_{i,t} + \beta_2 PRI_{i,t} + \beta_3 GDP_{i,t} + \varepsilon_{i,t} \quad (7)$$

A number of studies [66, 32, others] indicates that the more the income, the more food secure the household will be, justifying its inclusion in Eq. (7). Income widens the range of food consumption to include healthy and nutritious food. Finally, *FSSTA* equation is set as Eq. (8) by adding unemployment (*UNE*) as follows:

$$FSSTA_{i,t} = \alpha + \beta_1 X_{i,t} + \beta_2 UNE_{i,t} + \varepsilon_{i,t} \quad (8)$$

Unemployment *(UNE)* is generally accepted to be important to explain food security [67]. This is because unemployment disables the household ability to buy food items in order to meet the food needs of household members. To sum up, *AL, EQ, CA, GDP and BP*EQ* are expected to be positive while *POP, BP, PRI, GINI, UNE* are expected to be negative.

3.1. Marginal effect computation

According to [68], if the model is interactive model, then the attention should pay to the interaction term (*BP*EQ*), rather than individual term (*BPor EQ*). This is because the coefficients β_3 and β_4 only capture the effect of environmental quality (or biofuels production) on food security when biofuels production (or environmental quality) does not exist. On the other hand, as shown in Eq. (9) below, environmental quality function as the mediator and is expected to buffer the effect of biofuels on food security. Thereby, β_5 is expected to be marginally positive or negative depending on the condition of environmental quality. [68] suggest that at margin, the net effect of decreasing (or increasing) food security due to production of biofuels can be calculated by examining the partial derivative of food supply as in Eq. (9):

Table 3
Descriptive statistics of the variables.

	Mean	Std. dev.	Min	Max
FSAVG	43.726	3.701	35.790	59.180
FSAVA	51.939	7.831	35.272	74.506
FSACC	31.500	22.166	6.179	99.486
FSUTI	68.669	12.345	34.919	85.830
FSSTA	22.798	7.124	6.461	42.792
GFSI	53.652	11.658	30.800	80.200
AL	18.740	16.367	0.074	112.184
EQ	90.63	13.70	2.28	99.86
POP	1.204	1.051	−1.191	3.721
BP	2.811	4.008	0.086	7.398
CA	0.056	0.051	0.020	0.227
GINI	39.826	9.211	24.000	75.700
CPI	173.352	111.833	38.492	788.684
GDP	6.851	7.076	3.690	3.677
UNE	7.975	6.928	0.160	31.380

Note: GDP (per capita) and BP are in thousand.

$$\frac{\partial FS_{it}}{\partial BP_{it}} = \beta_4 + \beta_5 EQ \quad (9)$$

To evaluate the significance of the marginal effect, we need to compute the new standard error. Accordingly, the mean, minimum and maximum values of these levels are used to compute the t-statistics to evaluate the significant of the marginal effect.

3.2. Econometric methodology: generalized method of moments

Our empirical models, as pointed out, have been estimated with panel data methodology. Panel data has advantages that it can control for some unobserved heterogeneity and to model individual dynamics. Like heterogeneity, endogeneity also may affect the estimates and at the same time, it is hard to assume strict exogeneity of all the independent variables [69]. To control for the potential endogeneity, generalized method of moments (GMM) estimation is employed. Specifically, we utilize dynamic panel specification which characterized by the presence of lagged dependent variables among the regressors [69]. Hence, Eq. (4), following benchmark specification for GMM estimation will be as follows:

$$FS_{i,t} = \alpha + \beta X_{i,t} + \gamma FS_{i,t-1} + \mu_i + \nu_{i,t} \quad (10)$$

where μ_i is the individual effect and $\nu_{i,t}$ is the error term in Eq. (10). The GMM approach is usually considered the work of [70], but they in fact popularized the work of [71]. It is based on the notion that the instrumental variables approach noted above does not exploit all information available in the sample. Therefore, we may construct more efficient estimates of the dynamic panel data model via GMM. Initially, [70] propose using extra moment conditions in matrix form:

Table 4
Correlation analysis.

Variable	FSAVG	FSAVA	FSACC	FSUTI	FSSTA	GFSI	AL	ENV_QUA	POP	BP	CA	GINI	CPI	GDP	UN
FSAVG	1.000														
FSAVA	0.124	1.000													
FSACC	0.281	−0.811	1.000												
FSUTI	0.661	0.430	−0.317	1.000											
FSSTA	0.272	0.754	−0.792	0.558	1.000										
GFSI	0.236	0.601	−0.475	0.363	0.575	1.000									
AL	0.122	0.093	0.083	0.022	0.076	0.112	1.000								
EQ	0.055	−0.268	0.298	−0.203	−0.133	0.265	−0.093	1.000							
POP	−0.093	−0.353	0.345	−0.187	−0.421	−0.729	−0.186	−0.276	1.000						
BP	−0.078	−0.211	0.170	−0.058	−0.113	−0.209	−0.098	0.007	−0.120	1.000					
CA	0.136	0.135	0.133	0.136	0.251	−0.385	0.224	−0.245	0.176	−0.156	1.000				
GINI	−0.031	−0.330	0.287	−0.189	−0.245	−0.138	−0.297	−0.036	0.339	0.149	−0.178	1.000			
CPI	−0.052	−0.137	−0.178	−0.141	−0.225	−0.387	0.074	−0.113	0.326	−0.074	0.408	−0.140	1.000		
GDP	0.214	0.553	0.326	0.270	0.354	0.797	−0.174	0.409	−0.330	0.146	−0.329	−0.113	−0.304	1.000	
UNE	−0.257	−0.039	−0.053	−0.113	−0.134	0.008	−0.160	0.145	0.016	0.018	−0.157	0.261	−0.117	0.017	1.000

Table 5
Regression analysis [DV = *LFS*].

	FS DIFF-GMM	SYS-GMM	FSAVA DIFF-GMM	SYS-GMM	FSACC DIFF-GMM	SYS-GMM	FSUTI DIFF-GMM	SYS-GMM	FSSTA DIFF-GMM	SYS-GMM
Constant	–	4.7132***	–	4.9346***	–	3.2420***		4.3222***	–	2.7461***
		[17.24]		[17.27]		[13.07]	-	[16.63]		[14.05]
LFS_{t-1}	−0.0019*	−0.0174***	0.0014	−0.0023***	−0.5956***	−0.4678**	−0.9774***	−0.8216***	3.465*** [13.21]	−1.2068***
	[−1.77]	[−2.66]	[1.34]	[−3.65]	[−7.86]	[−2.78]	[−9.23]	[−3.95]		[−15.35]
LAL	−0.0043	0.0143***	0.0022***	0.0038***	0.0455***	0.0475***	–	–	0.0396	0.0282**
	[−1.63]	[5.86]	[6.22]	[2.88]	[5.41]	[3.13]			[1.44]	[2.09]
LEQ	0.0031***	0.0361**	0.0015***	0.0090***	0.0297***	0.0261***	0.1506***	0.2129***	0.740***	0.0201**
	[2.73]	[2.12]	[10.42]	[10.74]	[12.93]	[7.28]	[10.66]	[5.65]	[2.61]	[9.56]
LPOP	0.7301***	−1.1399***	−0.0204***	−0.1463***	−0.7455***	−1.4080***	−1.3273***	−1.2716***	−0.1695	−0.1228*
	[6.74]	[−4.02]	[−2.56]	[−4.74]	[−16.20]	[−10.09]	[−19.25]	[−7.83]	[−1.20]	[−1.84]
LBP	−0.1761***	−1.3493***	−0.0703***	−0.1701***	0.7512***	0.6773***	−0.8123***	−0.6832***	−0.4742***	−0.5766***
	[−2.95]	[−2.91]	[−4.84]	[−15.60]	[7.22]	[6.98]	[−14.83]	[−8.55]	[−3.87]	[−8.40]
*LBP*LEQ*	0.1735***	1.3973***	0.0748***	0.0948***	0.7548***	0.7046***	0.8650***	0.7237**	0.5188***	0.6334***
	[2.94]	[3.01]	[5.15]	[5.15]	[17.22]	[7.29]	[15.93]	[8.60]	[4.24]	[8.88]
LCA	0.0368***	0.0216*	0.0039*	0.0167***	–	–	–	–	–	–
	[3.89]	[1.77]	[1.78]	[3.93]						
LGINI	−0.0257*	−0.9421***	–	–	−1.2531***	−0.6591***	–	–	–	–
	[−1.71]	[−2.53]			[−3.66]	[−10.79]				
LPRI	−0.0293*	−0.5729***	–	–	−0.0194	−0.0778*	−0.3187***	−0.294***	–	–
	[−1.99]	[−2.80]			[−1.10]	[−1.87]	[−13.18]	[−5.72]		
LGDP	0.0374*** [2.66]	0.1325*	–	–	–	–	0.0268***	0.0226***	–	–
		[1.99]					[14.13]	[8.64]		
LUNE	−0.0237**	−0.0944***	–	–	–	–	–	–	−0.1378***	−0.1383***
	[−2.03]	[−2.55]							[−5.73]	[−6.96]
	Model criteria									
Hansen	0.589	0.469	0.557	0.722	0.178	0.643	0.823	0.665	0.399	0.505
AR(1)	0.087*	0.008***	0.001***	0.050**	0.068*	0.006***	0.008***	0.022**	0.001***	0.022**
AR(2)	0.208	0.121	0.376	0.977	0.198	0.176	0.372	0.111	0.252	0.271
Difference-Hansen	–	0.917	–	0.191	–	0.997	–	0.983	–	0.917
#instruments	33	33	33	33	33	33	33	33	33	33
#Groups	56	56	56	56	56	56	56	56	56	56
#Obs	336	336	336	336	336	336	336	336	336	336
	Marginal effect									
Mean	0.6005	4.9052	0.2645	0.0647	4.1298	3.8312	3.0595	2.5562	1.8481	2.2586
Min	−1.5835	−12.6838	−0.6771	−0.9391	−5.3715	−5.0382	−7.8290	−6.5536	−4.6825	−5.7146
Max	0.9176	7.4590	0.4012	0.4275	5.5093	5.1190	4.6405	3.8789	2.7962	3.4162
Threshold	2.7593	2.6265	2.5596	6.0153	0.3696	0.3824	2.5576	2.5703	2.4944	2.4851

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t-statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

$$\begin{bmatrix} FS_{i1} & 0 & 0 & \ldots & 0 & \ldots & 0 \\ 0 & FS_{i1} & FS_{i2} & \ldots & 0 & \ldots & 0 \\ \cdot & \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ 0 & 0 & 0 & \ldots & FS_{i1} & \ldots & FS_{iT-2}, \end{bmatrix}, \tag{11}$$

where rows in Eq. (11) correspond to the first-differenced equations for the period $t = 3, 4, \ldots, T$ for individual, and exploit the moment condition as shown in Eq. (12) below:

$$E[Z_i' \Delta v_i] = 0 \; for \; i = 1, 2, \ldots, N \tag{12}$$

While the deail can be obtained from [70], based on the moment conditions, GMM minimizes the discrepancy between the sample moments and the values in probability, giving the GMM estimator for β as follows:

$$\hat{\beta}_d = (\Delta FS_{-1}' Z W_N Z' \Delta FS_{-1})^{-1} \Delta FS_{-1}' Z W_N Z' \Delta FS$$

Using the optimal weight matrix expressed as in Eq. (13) :

Table 6
Regression analysis [DV = *LGFSI*].

	DIFF-GMM	SYS-GMM
Constant	–	2.6364***
		[15.16]
$LGFSI_{t-1}$	−0.51976***	−0.64137***
	[−11.37]	[−10.45]
LAL	0.1471*	0.1834*
	[1.86]	[1.4]
LEQ	2.2723***	0.93995*
	[3.03]	[1.82]
LPOP	−11.7475*	−5.4903***
	[−1.80]	[−3.43]
LBP	−2.8202**	−3.6374*
	[−2.31]	[−1.85]
*LBP*LEQ*	1.0474**	1.7137***
	[2.23]	[2.66]
LCA	2.7863***	0.5438*
	[6.13]	[1.69]
LGINI	−0.0452*	- 2.1715***
	[−2.02]	[−2.88]
LPRI	−3.4069***	−1.0570*
	[−3.30]	[−1.98]
LGDP	5.8985***	2.9953***
	[3.13]	[6.27]
LUNE	−3.9855**	−0.2159*
	[−2.19]	[−1.92]
	Model criteria	
Hansen	0.899	0.263
AR(1)	0.010***	0.001***
AR(2)	0.129	0.610
Difference-Hansen	–	0.869
#instruments	33	33
#Groups	44	44
#Obs	264	264
	Marginal effect	
Mean	0.4493	1.7119
Min	−10.055	−15.4753
Max	3.7824	7.1654
Threshold	14.7696	8.3523

Note: Asterisks *, **, and *** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t-statistics. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

$$W_N = \left[\frac{1}{N}\sum_{i=1}^{N}(Z_i'\Delta\hat{\nu}_i\Delta\hat{\nu}_i' Z_i)\right]^{-1} \tag{13}$$

This is known as two-step GMM estimator. Besides that, under the homoscedasticity of the error disturbances, the particular structure of the first-differenced model implies that an asymptotically equivalent GMM estimator can be obtained in one-step using the weight matrix as Eq. (14):

$$W_{1\,N} = \left[\frac{1}{N}\sum_{i=1}^{N}(Z_i'HZ_i)\right]^{-1}, \tag{14}$$

where H is a *(T-2)* square matrix with 2′s on the main diagonal, −1′s on the first off-diagonal and zero elsewhere. Notice that W_{1N} does not depend on any estimated parameters.

It is also important to take note that the generated instruments could be extremely weak, which leads to the well-known weak instrumental problems of inconsistency and inaccurate inference. For an example, if *FS* is extremely persistent, the lagged level of *FS* will be weak instruments for ΔFS in first- difference GMM. This problem can be solved using system GMM approach by [73]. Their modification of the estimator includes lagged level as well as lagged differences instead of transforming the regressors as instruments to make it exogenous on the fixed effect. The additional moment's conditions for the system GMM are as Eq. (15) and Eq. (16):

$$E\left[(FS_{i,t-s} - FS_{i,t-s-1})(\mu_i + \nu_{i,t}) = 0 \ \text{for}\ s = 1\right. \tag{15}$$

$$E\left[(X_{i,t-s} - X_{i,t-s-1})(\mu_i + \nu_{i,t}) = 0 \ \text{for}\ s = 1\right. \tag{16}$$

The additional moment conditions are employed to generate consistent and efficient parameter estimates based on GMM procedure. Moreover, for either first-difference GMM or system GMM, the degree of serial correlation of ν will determine the validity of instruments based upon the dependent variable. [70] devise a test of serial correlation based on first-difference moment conditions. Under serial correlation test, rejection of the null of the absence of the first-order serial correlation AR (1) and failure to reject the absence of the second-order serial correlation AR (2) are valid and the models are correctly specified. Secondly, given the surfeit of instruments, it is natural to consider overidentification test. The overidentification restriction is verified with Hansen test [72].

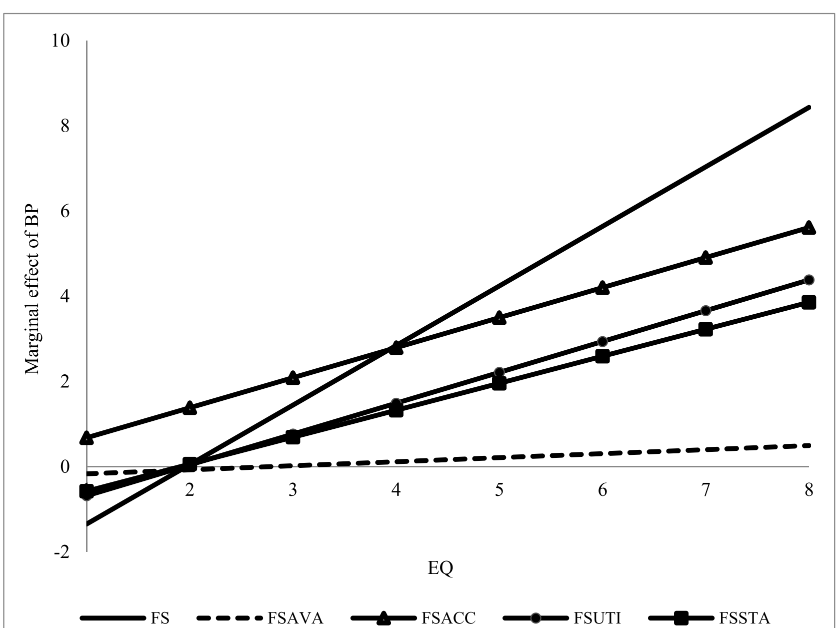

Fig. 4. The marginal effect of *BP* on *FS*, conditional upon *EQ*.

3.3. Data sources

In this study, we employ a panel sample of 51 developing countries over the period 2011 to 2016 dictated by the availability of data on food security and biofuels production. The list of developing countries is taken from [17] are shown in Table 1.

Additionally, the present study uses various data sources to obtain the datasets of developing countries from 2011–2016 as summarized in Table 2.

On the measurement of each variable, the percentage of population growth is used as a proxy for population. We utilize the percentage of land area and biofuels production as measures of arable land and biofuels, respectively. As for the other control variables, we use the percentage share of total credit to proxy credit to agriculture, the index of GINI for income inequality, the price of food for price, *real GDP* for economic growth, and the percentage of total labor force for unemployment. For environmental quality, instead of directly apply CO_2 emission metric tons per capita, we reverse the measurement so that it can reflect environmental quality, by which the higher EQ will imply better quality. In doing so, we design the following Eq. (17):

$$EQ_{CO2} = \left(1 - \frac{CO_2}{World\ Worst\ CO_2}\right) \times 100 \tag{17}$$

where *World Worst* CO_2 is represented by the world highest emission level of 10,357 million metric tons in China in year 2017.

The measurement of food security index is a bit complicated as FAO does not provide a single index to represent its definition of food security. In this study, we construct the index based on the average of four components or dimensions of food security defined by FAO, namely the index of food availability (*FSAVA*), food accessibility (*FSACC*), food utilization (*FSUTI*), and food stability (*FSSTA*). Each dimension has its own but different set of elements. For instance, food availability (*FSAVA*) has 5 elements. Before we can construct the food security index based on the 4 dimensions, we have to ensure that all elements in each dimension are in the same format. To do so, we establish each dimension in the form of index. To summarize, food security index is the average index of 4 food security dimensions and each dimension is an average index of all elements under each of the dimensions. The detail explanation is available in Appendix A.

Although there are other food security index such as the Global Food Security Index (GFSI) by DuPont, this study opts for FAO framework but with slight modification. The GFSI index score is based on the four broad dimensions that measure consumers' ability to purchase food, availability that measures the sufficiency of the national food supply, quality and safety that measures variety and nutritional quality of average diets and safety of the food supply and natural resources that ensures country's exposure to the impacts of changing climate. However, [79] indicate that GFSI does not describe the real food security situation. This is because GFSI tends to measure the conditions for food security or an enabling environment for food security instead of actual food security level [79]. Besides that, according to FAO definition, food security is people-centered, while GFSI is country-centered and fails to provide information about food security status of vulnerable households [79]. Among the modification that we introduce in constructing FS index based on FAO framework is to remove imports component and political stability.

According to the descriptive statistics indicated in Table 3, the largest food security index (*FSAVG*) is 59.180 and could be represented by the case of Thailand in 2013, whereas the lowest food security is observed at 35.79 and potentially refers to Sudan in 2011. What is interesting to note is the relatively huge gap between the measure constructed by this study, which is *FSAVG* and global food security index (*GSFI*) by World Bank. *GSFI* tends to underestimate the severity of the issue as the mean demonstrates that the level of food security is likely to be at satisfactory level if above average or more than 50 percent rule is applied.[5] Another important point is about the huge discrepancy among the dimensions of food security, with food utilization has the highest mean (68.7) and food stability has been at critical condition with mean of 22.8 only. In addition, Brazil is the largest producer of biofuels as described by the maximum score of biofuels (7.398) relative to the lowest size of biofuels production (0.086) in Bosnia and Herzegovina in 2012. What intriguing point is that the mean of biofuels production is merely 2.811, skewed towards lower end of the production level. This may imply that there is still huge potential for the industry to grow as well as the incapability of biofuels to effectively improve the environmental quality.

Besides that, the correlation matrix for the key variables is offered in Table 4. As estimated, food security has a positive correlation with arable land, which supports the existing literature that arable land, is among the main resources to farmers in order to produce more food. On the other hand, the correlation between food security and population growth, environmental degradation, biofuels production is highly negatively. In summary, we do not see any serious issue of multicollinearity in this study.

4. Results and discussions

The results of GMM estimates of the dynamic equation are shown in Table 5. The validity of instruments that give a set of over-identifying restriction has been verified with the standard Hansen test, which confirm that in all cases our set of instruments are valid. The correct statistical specification of the models has been additionally checked with tests for the presence of first and second order residual autocorrelation. The results of AR9(1) and AR(2) indicate that there is evidence of first order but not second order autocorrelation, implying that the models are correctly specified. Besides that, the results of the *Difference-Hansen* statistic also reported as a test of the additional moment conditions used in the system GMM estimators relative to the corresponding first-difference GMM estimator. The *Difference-Hansen* shows that system GMM estimates appear to be reasonable than first-GMM.

In respect to environmental quality, the results in Table 5 demonstrate that environmental quality has a significant positive impact on food security in all models, which are supported by the past studies [23, 35, 25]. Reduction in carbon dioxide emissions have been associated with a decrease in global temperature, and will have favorable impacts on agricultural production. Under optimum temperature regime, the growing seasons, soil moisture conditions and quality of the yield will be positively affected. Beyond that, to the extent that food production is increased by better environmental quality, price of food will decrease [23, 35, 25]. In the presence of lower food price, the buying power of people will be higher and allow people to obtain food regularly. An increase in accessibility of food would also mean higher intake of nutritious food. Improved environmental quality may also decrease the pressure on food stability due to little uncertainty in phenomena such as flooding, hurricanes, and drought, associated with greater risks of landslide and erosion [34].

Meanwhile, the effect of biofuels on food security is observed to be significantly negative in all models, as expected and consistent with [11, 47, 48], to mention only few. Although biofuel development has received growing attention as a mean to reduce carbon dioxide emission and support energy security all over the world, one of the most critical problems with biofuel production is that it poses threat to food security. This is because biofuels are primarily produced from food crops such as sugar cane, maize, rapeseed and others, where it may reduce the of proportion of agricultural resources for food productions and food-related uses [47, 48]. Consequently, the overall availability of

[5] This reminds us the need to relook at the measurement of food security index. GSFI is still used for robustness test in this study, albeit the issue.

food is affected by an increment in demand for agricultural crops by biofuel production. Competition between biofuels and food production will also trigger food price to go up. The conversion of high quality and suitable food crop to biofuels production may adversely affect the ability to consume nutrient food, and in turn would result in increasing undernourishment and lower food utilization. Therefore, the development of biofuels may substantially reduce global food security.

When biofuels industry is currently threatening food security level, should we propose that biofuels production should be abandoned? As shown in Table 3, most developing countries have small and negligible size of biofuels industry. The current size of biofuels industry or production may not be able to produce the desirable outcome, in terms of reduction in CO_2. But it is expected to be more successful in lowering the CO_2, and eventually preserving climate from further deteriorating or unfavorable to crop productions, should the volume can be extended [8, 57]. As been discussed about the effect of environmental quality on food security, once the size of biofuels can minimize CO_2 emission and environmental quality is at higher possible level, climate condition can be promoted or maintained, then crop productions are expected to be supporting food security problem. The results of interaction term between biofuels and environmental quality (*LBP*LEQ*) are found to be positively significant in all models, justifying the validity of out intuition. The positive and statistically significant coefficient of the interaction term between measure of biofuels production and environmental quality indicates that the relationship between biofuels and food supply varies across countries depending on the degree to which the biofuels sector is developed and the resulted environmental quality. These results point out to the significant moderating effect of environmental quality on the relationship between biofuels and food supply. In other words, the negative effect of biofuels production may disappear as country's environmental quality increases.

When examining the relationship between biofuels and food security conditional upon the level of environmental quality, it is essential to compute the turning point. This is important in order to explain why there is a substantial difference in minimum threshold values that need to be achieved by developing countries in order to transform the negative effect of biofuels on food supplies into positive influence. The estimated threshold values are summarized at the bottom of Table 5 and these threshold values are quite different among the dimensions of food security. The threshold values of biofuels in developing countries, for example, implies that the negative impact of biofuels can be transformed into positive impact if the environmental quality has achieved a minimum improvement level of 2.75 percent. Thus, the positive impact of biofuels production is not unconditional, but is likely to depend upon the improvement of the environmental quality.

Having established the existence of a moderating effect, the following step is to compute the marginal effect [80]. We compute the new standards error to evaluate the significance of the marginal effect of changes in food supply due to changes in biofuels production. Fig. 4 illustrates the increasing marginal effects for the four dimensions of food security, namely the index of food availability (*FSAVA*), food accessibility (*FSACC*), food utilization (*FSUTI*), and food stability (*FSSTA*) as well as the aggregate measure of food security *(FS)*. All dimensions in Fig. 4 demonstrates that when the level of environmental quality improves, partly could be due to biofuels production, the marginal effect of biofuels is getting positively higher. The marginal effect reported in Table 4 shows that biofuels production and environmental quality are positive at mean and maximum levels, and statistically significant but weak at the minimum level where marginal effect is negative. For example, each additional percentage point of biofuels benefits 0.60 percentage points of annual growth in food supply at mean level. More essentially, the marginal effect at the maximum level has a greater beneficial effect of biofuels on food security, which is 0.91 and greater than when environmental quality is at the mean level. This implies that the higher level of biofuels production tends to increase food supply as high biofuels will also contribute to preservation of environmental quality.

The other variables are also found to have their results as expected. We do not discuss them here to conserve space. The full-length original working paper, which includes detail explanation on each result is available upon request. While we disagree with GSFI, we still employ it as an alternative measure of food security to check the consistency and robustness of the above results. Using the alternative measure of food security, our results in Table 6 confirm that the negative impact of biofuels can be transformed into a positive one as country's environmental quality improves. Turning to the threshold results themselves, we find evidence of a significant threshold for biofuels production. The outcomes again highlight a better level of environmental quality is required before the benefits of biofuels can be realized. Overall, the result of alternative measure of food security is consistent with findings reported in Table 5 and in line with the notion that environmental quality plays a greater role in moderating the negative effect of biofuels on food supply.

We further check the robustness of the results by: (i) using full elements introduced by FAO in Table B.1, (ii) using various indicators of environmental quality, namely methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (*FGAS*) in Table B.2 for the aggregate FS and in Table B.3 for each domain of FS, (iii) using consistently all explanatory variables in the dimensional models in Table B.4 , (iv) adding two additional explanatory variables, namely temperature and natural disaster in Table B.5, and (v) using Distance Approach in Table B.6. The findings are similar to the earlier results and shown in Appendix B.

5. Conclusion

This paper examines the effect of biofuels production on food security, given the level of environmental quality in developing countries for the period between 2011 and 2016. We carry out an empirical investigation using GMM estimator, where food security is measured by a total of 18 indicators grouped in 4 dimensions. More specifically, this study empirically examines whether food security increases as the level of biofuels production is at a stage of capable to improve environmental quality. Our analysis provides supporting evidence that the coefficient of *BP*EQ* is positive and statistically significant. This result implies that the negative effect of biofuels production on food security declines as a country's environmental quality improves. As a result, it is important to promote biofuel development as it can bring better environment quality and greater production of food.

In this regard, government in developing countries may need to ensure that any policies promoting biofuels are consistent with reducing emission as well as making a contribution to food production. For example, government can initiate the development of the biofuel sector by setting up, for instance, a government-linked company or to offer significant incentives to private sectors to get involved in the development process. In addition, developed countries should continue to provide financial support to developing countries for the adaptation and use of biofuels and other new environmental friendly technologies to move developing countries away from food insecurity problem [3]. The easiest way to do this is by encouraging multinational corporations (MNCs) to join the projects, particularly to those developing countries which own huge reserves of resources related to biofuels production. Government should also promote development of second and third generations of biofuels, which certainly free from food competition as well as capable in preserving environmental quality, and support agriculture production. Although the second and third generations of biofuels are showing no significant progress so far in the case of developing countries, this study partly hints that the two generations need be taken up seriously especially when the assumption of environmental friendly agricultural practices are violated.

Nevertheless, our finding should also be treated cautiously as our study is meant to justify the need to continue the effort to promote biofuel industry as one of the renewable energies without sacrificing food security issue. In doing so, we put a strict assumption that agricultural activities, which are the main source of food security, are conducted in the most environmental friendly. The real fact is that deforestation or expansion of agricultural land will always be accompanied by various environmental issues [81]. Hence, government should also pay attention on improving agricultural techniques so that it would be more environment-promoting.

Dedclaration of Competing Interest

The authors declare that they have no conflict of interest.

Appendix A

To provide a more accurate measurement of food security, this study excludes two elements in the calculation of food security.[6] In constructing the index of food security, there are three steps. Firstly, we need to transform each element within each of the four major dimensions (i.e. availability, accessibility, utilization and stability) of food security by FAO to be similar in range, which is set to be between 0 and 100. To normalize the scores, we refer to the methodology employed by United Nation in the construction of human development index as follows:

$$FS_{element} = \frac{Country\ Index - World\ Minimum}{World\ Maximum - World\ Minimum} \times 100$$

The world maximum value will be proxied by the United States (US) by an assumption that the US is the world most secured country in terms of food. The world minimum will be represented by Sudan as Sudan is the world hungriest country (World Bank, 2018).

Secondly, we create four separate indices for each of the four dimensions. This is done by taking the average of all indices of elements, which belong to each dimension. For instance, as shown in Table A.1, food availability index (*FSAVA*) comprises 5 elements and therefore, the index is represented by the average of 5 indices as the equation below:

$$FSAVA = (FS_{element1} + FS_{element2} + \ldots)/5$$

The last step is to calculate the composite food security index by taking the average of four dimensions as follows:

$$FS = (FSAVA + FSACC + FSUTI + FSSTA)/4$$

where *FSACC* is food accessibility index, *FSUTI* stands for food utilization index and *FSSTA* denotes food stability index. In this case, we add all these four dimensions together and then divid by 4 (total dimensions). Therefore, the food security index is expressed as a value between 1 and 100, where the higher the value of food security, the better the level is.

Table A.1
The FAO framework of food security.

Dimension	Source
Availability	
Average dietary energy supply adequacy	FAOSTAT
Average value of food production	FAOSTAT
Share of dietary energy supply derived from cereals, roots and tubers	FAOSTAT
Average protein supply	FAOSTAT
Average supply of protein of animal origin	FAOSTAT
Access	
Gross domestic product per capita (in purchasing power equivalent)	World Bank
Prevalence of undernourishment	FAOSTAT
Depth of the food deficit	FAOSTAT
Stability	
Food per capita	FAOSTAT
Percent of arable land equipped for irrigation	FAOSTAT
Political stability and absence of violence/terrorism	World Bank
Per capita food production variability	FAOSTAT
Per capita food supply variability	FAOSTAT
Utilization	
Percentage of population with access to improved drinking water sources	World Bank
Percentage of population with access to sanitation facilities	World Bank
Prevalence of obesity in the adult population (18 years and older)	GHO
Prevalence of anemia among women of reproductive age (15–49 years)	World Bank

Note: FAOSTAT indicates the food and agriculture organization corporate statistical database; GHO indicates Global Health Observatory.

[6] Nevertheless, we still provide the results based on complete FAO framework for stability test in Appendix B.

Appendix B

Tables B.1–B.6

Table B.1
Regression results based on complete FAO framework [DV = LFS].

	FSAVG		FSAVA		FSACC		FSUTI		FSSTA	
	DIFF-GMM	SYS-GMM	DIFF-GMM	SYS-GMM	DIFF-GMM	SYS-GMM	DIFF-GMM	SYS-GMM	DIFF-GMM	SYS-GMM
Constant	–	0.045***	–	0.092***	–	0.014***	–	0.0319***	–	0.0993***
		[2.02]		[3.95]		[2.71]		[7.28]		[10.23]
LFS_{t-1}	−0.067**	0.067***	1.508***	0.2465***	6.947**	1.922**	2.129**	0.593*	0.182*** [7.87]	0.1900***
	[2.84]	[2.89]	[2.75]	[9.81]	[2.15]	[2.27]	[2.17]	[1.93]		[8.79]
LAL	0.709***	0.710***	1.555	0.145*	0.975*	0.741*	–	–	0.515*	0.897*
	[5.29]	[5.46]	[1.78]	[1.99]	[1.98]	[1.97]			[1.94]	[1.89]
LEQ	0.348	0.349**	0.193*	3.763***	0.363**	0.103**	4.152***	3.719***	0.740***	0.079**
	[1.71]	[2.39]	[1.84]	[2.51]	[2.12]	[2.31]	[3.17]	[3.59]	[2.61]	[2.25]
LPOP	0.118***	−0.113*	−1.151***	−0.904**	−0.366**	−0.229***	−0.174	−0.589***	−0.825***	−0.767***
	[6.48]	[−1.87]	[−2.47]	[−2.30]	[−2.11]	[−2.53]	[−1.65]	[−6.47]	[−2.78]	[−2.74]
LBP	−0.281**	−0.254**	−0.096**	−0.135***	0.217***	0.153**	−0.465	−0.293***	−0.352*	−0.323***
	[−2.23]	[−2.15]	[−2.10]	[−3.55]	[2.52]	[2.32]	[−1.78]	[−2.42]	[−2.09]	[−2.55]
*LBP*LEQ*	0.196*	0.919***	0.064**	0.087***	0.199*	0.619***	0.294**	0.271**	0.182*	0.182***
	[1.89]	[8.53]	[2.10]	[4.33]	[2.02]	[5.33]	[2.03]	[2.15]	[1.86]	[3.29]
LTR	0.295***	0.299**	1.421	3.421*	–	–	–	–	–	–
	[4.98]	[2.37]	[1.51]	[1.91]						
LCA	0.160**	0.158***	0.145***	0.162**	–	–	–	–	–	–
	[2.19]	[3.10]	[2.99]	[2.10]						
LGINI	−0.031***	−0.032***	–	–	−2.730	−4.194***	–	–	–	–
	[−11.91]	[−3.95]			[−1.56]	[−9.42]				
LPRI	−0.108***	−0.116***	–	–	−0.2567**	−0.450***	−0.101***	−0.420***	–	–
	[−5.07]	[−2.68]			[−2.10]	[−4.14]	[−2.97]	[−2.42]		
LGDP	0.105	0.103***	–	–	–	–	0.788*	0.237***	–	–
	[1.70]	[3.88]					[1.93]	[2.76]		
LUNE	−0.153***	−0.160***	–	–	–	–	–	–	−0.123***	−0.123***
	[−3.77]	[−2.55]							[−3.78]	[−3.71]
LEX	−0.133***	−0.130***	–	–	–	–	–	–	0.865	−0.688*
	[−3.02]	[−4.09]							[1.68]	[−2.24]
Model criteria										
Hansen	0.492	0.501	0.223	1.000	0.178	0.212	0.227	0.225	0.191	0.139
AR(1)	0.015***	0.009**	0.084*	0.037**	0.097*	0.097*	0.039**	0.014**	0.035**	0.017***
AR(2)	0.143	0.284	0.681	0.996	0.748	0.830	0.859	0.120	0.187	0.890
Difference-Hansen	–	0.479	–	0.980	–	0.938	–	0.961	–	0.995
#instruments	33	33	33	33	33	33	33	33	33	33
#Groups	56	56	56	56	56	56	56	56	56	56
#Obs	336	336	336	336	336	336	336	336	336	336
Marginal effect										
Mean	0.5963	3.8594	0.1905	0.2544	0.6737	2.9236	0.8509	0.9177	0.4626	0.4916
Min	−1.8709	−7.7087	−0.6152	−0.8407	−1.3972	−4.8682	−2.8500	−2.4936	−1.8283	−1.7993
Max	0.545	5.5391	0.3074	0.4134	1.4714	4.0550	13,883	1.4130	0.7953	0.8243
Threshold	4.1938	1.3183	4.4817	4.7195	0.3360	0.7810	4.8627	2.9482	6.9178	5.8985

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t-statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

Table B.2
Regression analysis for various indicators of environmental quality [DV = *LFS*].

	FSAVG *EQ = CH4*	*EQ = N2O*	*EQ = FGAS*
Constant	3.0441***	2.9226***	1.1948***
	[11.40]	[14.57]	[4.98]
LFS_{t-1}	−0.8051***	−0.7956***	−0.7989***
	[−21.36]	[−20.75]	[−22.38]
LAL	0.0020*	0.0037*	0.0017*
	[1.74]	[1.85]	[1.62]
LEQ	0.0122***	0.0133***	0.0063***
	[4.61]	[4.94]	[2.82]
LPOP	−0.1009***	−0.1171***	−0.0656***
	[−3.80]	[−4.81]	[−2.64]
LBP	−0.0226***	−0.0233***	−0.0093***
	[−5.28]	[−5.29]	[−2.70]
*LBP*LEQ*	0.0113**	0.0098***	0.0091***
	[2.76]	[2.89]	[2.84]
LCA	0.0064*	0.0073*	0.0043*
	[1.75]	[1.96]	[1.81]
LGINI	−0.0645***	−0.0727***	−0.0343
	[−2.49]	[−3.21]	[−1.51]
LPRI	−0.0208*	−0.0180*	−0.0158*
	[−2.06]	[−1.73]	[−1.75]
LGDP	0.0104*	0.0154***	0.0196*
	[1.68]	[2.23]	[1.85]
LUNE	−0.0106*	−0.0103*	−0.0172***
	[−1.87]	[−1.87]	[−3.27]
	Model Criteria		
Hansen	0.161	0.124	0.192
AR(1)	0.000***	0.000***	0.000***
AR(2)	0.145	0.150	0.173
Difference-Hansen	0.827	0.915	0.958
#instruments	33	33	33
#Groups	56	56	56
#Obs	336	336	336
	Marginal effect		
Mean	0.0138	0.0181	0.0200
Min	−0.1143	−0.1028	−0.0831
Max	0.0486	0.0385	0.0481
Threshold	7.3891	10.7785	2.7787

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t-statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

Table B.3
Regression analysis of dimensional model for various indicators of environmental quality [DV = *LFS*].

	FSAVA			FSACC			FSUTI			FSSTA		
	CH4	*N2O*	*FGAS*	*CH4*	*N2O*	*FGAS*	*CH4*	*N2O*	*FGAS*	*CH4*	*N2O*	*FGAS*
Constant	2.0763***	1.5302***	2.2651***	1.6394***	1.5188***	2.8793***	1.0798***	1.8693***	1.1746***	2.7499***	2.8596***	1.7165***
	[4.89]	[4.29]	[4.48]	[2.62]	[2.53]	[2.59]	[2.98]	[4.24]	[4.61]	[4.68]	[3.48]	[2.67]
LFS_{t-1}	- 1.0103***	−1.0218***	−0.9886***	−0.9693***	−0.9274***	−0.9270***	−0.9123***	−0.4969***	−0.4636***	−0.5106***	−0.5330***	−0.4022***
	[−16.49]	[−18.69]	[−4.06]	[−6.77]	[−5.17]	[−9.57]	[−2.35]	[−16.79]	[−16.59]	[−17.41]	[−19.14]	[−14.54]
LAL	0.0030***	0.0032***	0.0006	0.0156***	0.0248***	0.0209***	–	–	–	0.1884***	0.2199***	0.1023***
	[5.54]	[5.34]	[1.54]	[12.42]	[6.34]	[4.79]				[5.86]	[6.09]	[2.74]
LEQ	0.0063**	0.0049***	0.0067***	0.0036***	0.0019*	0.0043*	0.0973***	0.0783***	0.1472***	0.1487***	0.0381***	0.2876***
	[8.69]	[5.77]	[8.44]	[4.29]	[2.05]	[1.84]	[4.95]	[6.20]	[4.08]	[5.09]	[2.48]	[5.34]
LPOP	−0.0451***	−0.0396***	−0.0164***	−0.0916***	−0.0775***	−0.1047***	−0.5015*	−0.6150***	−0.5747*	−0.8949***	−0.4645***	−0.2336*
	[−11.09]	[−8.36]	[−3.08]	[−2.81]	[−2.38]	[−2.69]	[−2.18]	[−3.06]	[−2.15]	[−5.09]	[−2.28]	[−1.87]
LBP	−0.0075***	−0.0073***	−0.010**	0.0292***	0.0284***	0.0269***	−0.1639***	−0.1527***	−0.1835**	−0.0281***	−0.0180*	−0.0434***
	[−8.6]	[−6.80]	[−10.03]	[3.36]	[3.82]	[4.35]	[−4.38]	[−5.24]	[−3.66]	[−3.88]	[−1.80]	[−4.34]
*LBP*LEQ*	0.0099***	0.0063**	0.0082*	0.0120*	0.0132***	0.0124***	0.1076*	0.0980**	0.1089*	0.0185***	0.0096***	0.0199*
	[2.57]	[2.99]	[2.48]	[1.96]	[4.08]	[3.56]	[2.14]	[2.32]	[1.87]	[2.00]	[2.72]	[1.93]
LCA	0.0095***	0.011***	0.0026***	–	–	–	–	–	–	–	–	–
	[6.85]	[7.21]	[4.29]									
LGINI	–	–	–	−0.1432***	−0.1647*	−0.1488***	–	–	–	–	–	–
				[−5.56]	[−6.27]	[−5.43]						
LPRI	–	–	–	−0.0183*	−0.0125*	−0.0230*	−0.3548***	−0.3638***	−0.3054***	–	–	–
				[−1.84]	[−1.78]	[−1.74]	[−3.38]	[−3.97]	[−2.79]			
LGDP	–	–	–	–	–	–	0.0560*	0.0803*	0.0113 [1.57]	–	–	–
							[1.85]	[1.84]				
LUNE	–	–	–	–	–	–	–	–	–	−0.0778*	−0.0963*	−0.0837*
										[−1.90]	[−1.73]	[−1.75]
	Model criteria											
Hansen	0.482	0.377	0.226	0.671	0.701	0.742	0.231	0.174	0.253	0.187	0.421	0.191
AR(1)	0.003***	0.002***	0.001***	0.047**	0.087*	0.074*	0.005***	0.005***	0.003***	0.004***	0.010**	0.012**
AR(2)	0.333	0.112	0.406	0.200	0.206	0.311	0.410	0.364	0.668	0.677	0.153	0.767
Difference-Hansen	0.640	0.999	0.759	0.826	0.519	0.884	0.725	0.914	0.824	0.900	0.898	0.996
#instruments	33	33	33	33	33	33	33	33	33	33	33	33
#Groups	56	56	56	56	56	56	56	56	56	56	56	56
#Obs	336	336	336	336	336	336	336	336	336	336	336	336
	Marginal effect											
Mean	0.0145	0.0130	0.0164	0.0679	0.0709	0.0668	0.1827	0.1630	0.1673	0.0315	0.0129	0.0207
Min	−0.0878	−0.0584	−0.0765	−0.0682	−0.0787	−0.0737	−1.0367	−0.9476	−1.0669	−0.1782	−0.0959	−0.2048
Max	0.0549	0.0324	0.0417	0.1048	0.1116	0.1051	0.5144	0.4651	0.5030	0.0885	0.0425	0.0820
Threshold	2.1331	3.1859	3.3855	0.0877	0.1163	0.1143	4.5870	4.7501	5.3926	4.5673	6.5208	8.8543

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t- statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

Table B.4
Regression analysis of dimensional model for all control variables [DV = *LFS*].

	FSAVA DIFF-GMM	SYS-GMM	FSACC DIFF-GMM	SYS-GMM	FSUTI DIFF-GMM	SYS-GMM	FSSTA DIFF-GMM	SYS-GMM
Constant	–	.298 ***	–	3.2420***	–	4.3222***	–	2.7461***
		[17.27]		[13.07]		[16.63]		[14.05]
LFS_{t-1}	0.646***	0.923 ***	0.956 ***	0.997***	0.061***	0.985***	0.372*** [5.50]	0.918***
	[3.51]	[9.23]	[16.77]	[15.48]	[2.78]	[14.79]		[18.17]
LAL	0.001 ***	0.002*	0.010 *	0.003**	0.005**	0.049**	0.007*** [2.95]	0.009*
	[2.56]	[1.71]	[1.72]	[2.30]	[2.15]	[2.29]		[1.82]
LEQ	0.004 *	0.013 *	0.005*	0.045***	0.030*	0.008**	0.006***	0.052*
	[1.89]	[1.97]	[1.51]	[2.42]	[1.86]	[2.20]	[2.40]	[1.96]
LPOP	−0.040 ***	−0.020 *	−0.011***	−0.022***	−0.008*	−0.034**	−0.121	−0.035*
	[−5.34]	[−2.03]	[−2.51]	[−3.15]	[−1.97]	[−2.16]	[−1.83]	[−2.09]
LBP	−0.009 ***	−0.042 ***	0.038**	0.040***	−0.008**	−0.002***	−0.189*	−0.305***
	[−2.89]	[−2.37]	[2.22]	[4.08]	[−2.31]	[−2.72]	[−1.77]	[−2.54]
*LBP*LEQ*	0.013 ***	0.039 **	0.033*	0.038***	0.022***	0.012**	0.173*	0.312***
	[1.69]	[2.29]	[1.92]	[3.79]	[5.24]	[2.17]	[1.87]	[2.61]
LEXP	−0.007***	−0.002 ***	−0.013***	−0.004***	−0.042***	−0.051***	−0.007**	−0.002**
	[−2.95]	[−2.65]	[−3.11]	[−2.70]	[−3.24]	[−5.63]	[−2.24]	[−2.09]
LCA	0.002 ***	0.010 ***	0.085***	0.001*	0.002**	0.050**	0.009**	0.079***
	[3.24]	[4.18]	[2.51]	[1.81]	[2.17]	[2.30]	[2.38]	[3.69]
LGINI	−0.021**	−0.054***	−0.037**	−0.010**	−0.091***	−0.075***	−0.353**	−0.003**
	[−2.33]	[−3.00]	[−2.19	[−2.23]	[−5.91]	[−3.37]	[−2.15]	[−2.10]
LPRI	−0.017***	−0.007***	−0.021*	−0.004*	−0.056**	−0.076***	−0.018**	−0.018**
	[−3.79]	[−2.94]	[−2.02]	[−2.04]	[−2.18]	[−3.55]	[−2.23]	[−2.31]
LGDP	0.005*	0.032	0.036**	0.006*	0.120***	0.051**	0.069***	0.008*
	[1.96]	[3.11]	[2.29]	[1.69]	[8.98]	[2.37]	[2.75]	[2.13]
LUNE	−0.003***	−0.001***	−0.008***	−0.003***	−0.004***	−0.001***	−0.179*	−0.010*
	[−4.59]	[−2.27]	[−3.30]	[−2.93]	[−2.97]	[−3.39]	[−1.82]	[−2.08]
	Model criteria							
Hansen	0.438	0.239	0.282	0.472	0.153	0.379	0.461	0.418
AR(1)	0.006 ***	0.002 ***	0.039**	0.003***	0.001***	0.021**	0.081*	0.044**
AR(2)	0.154	0.162	0.478	0.652	0.831	0.308	0.788	0.235
Difference-Hansen	–	0.977	–	0.999	–	0.999	–	0.920
#instruments	33	33	33	33	33	33	33	33
#Groups	56	56	56	56	56	56	56	56
#Obs	336	336	336	336	336	336	336	336
	Marginal effect							
Mean	0.0491	0.1326	0.1857	0.2101	0.0905	0.0517	0.5853	1.0915
Min	−0.1145	−0.3584	−0.2297	−0.2682	−0.1865	−0.0993	−1.5923	−2.8359
Max	0.0729	0.2038	0.2460	0.2795	0.1307	0.0736	0.9015	1.6618
Threshold	1.9983	2.9355	0.3162	0.3490	1.4385	12,214	2.9814	2.6580

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t-statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

Table B.5
Regression analysis for additional controlled variables [DV = *LFS*].

	FSAVG			FSAVA			FSACC			FSUTI			FSSTA		
	(1)	*(2)*	*(3)*	*(1)*	*(2)*	*(3)*	*(1)*	*(2)*	*(3)*	*(1)*	*(2)*	*(3)*	*(1)*	*(2)*	*(3)*
Constant	0.840***	1.661 ***	0.880**	0.024*	0.716**	0.263***	0.108***	0.202***	0.443***	0.082***	0.305***	0.312***	0.177***	2.148***	1.916***
	[2.69]	[7.52]	[2.30]	[2.00]	[2.21]	[5.43]	[2.86]	[5.75]	[5.18]	[11.00]	[6.82]	[3.22]	[2.62]	[3.69]	[2.60]
LFS_{t-1}	0.952***	0.536 ***	0.832***	1.016***	0.996***	0.966***	1.004***	0.962***	0.915***	0.979***	0.937***	0.965***	0.865***	0.697***	0.894***
	[18.02]	[11.30]	[14.60]	[16.76]	[17.63]	[18.15]	[9.72]	[12.06]	[8.48]	[16.65]	[14.75]	[16.87]	[12.89]	[6.49]	[12.57]
LAL	0.027***	0.087 ***	0.021*** [4.84]	0.001*	0.001***	0.001*	0.001	0.004	0.002*	–	–	–	0.003	0.047	0.137***
	[5.25]	[9.30]		[1.80]	[6.65]	[1.97]	[1.42]	[1.63]	[1.95]				[1.24]	[1.40]	[3.13]
LEQ	0.006*	0.029***	0.010*	0.041***	0.005**	0.006***	0.002***	0.014***	0.009***	0.026**	0.014***	0.001***	0.006***	0.538***	0.018*
	[1.91]	[4.29]	[1.79]	[2.72]	[2.23]	[2.55]	[4.52]	[2.60]	[2.52]	[2.13]	[4.51]	[1.96]	[2.65]	[3.61]	[1.85]
LPOP	−0.001*	−0.020 ***	−0.004***	−0.001***	−0.009***	−0.003	−0.001**	−0.017	−0.002	−0.002***	−0.211	−0.129***	−0.007***	−0.004	−0.014
	[−2.86]	[−2.78]	[−4.19]	[−3.79]	[−4.80]	[−1.60]	[−2.38]	[−1.69]	[−1.66]	[−4.85]	[−1.57]	[−2.73]	[−1.86]	[1.25]	[−1.23]
LBP	−0.001*	−0.088***	−0.109***	−0.003***	−0.001*	−0.070**	0.003***	0.058***	0.006**	−0.014***	−0.008***	−0.009**	−0.011***	−0.260***	−0.140***
	[−2.84]	[−8.72]	[−7.90]	[−5.34]	[−1.82]	[−2.26]	[4.35]	[6.78]	[2.10]	[−4.17]	[−3.81]	[−2.28]	[−3.05]	[−2.79]	[−1.75]
*LBP*LEQ*	0.080***	0.087***	0.089***	0.021***	0.005***	0.073**	0.002***	0.053***	0.003*	0.013*	0.009***	0.008***	0.046***	0.256***	0.166***
	[4.15]	[8.90]	[4.78]	[2.35]	[3.21]	[2.31]	[4.32]	[6.62]	[2.05]	[1.87]	[4.86]	[5.01]	[3.16]	[3.05]	[5.36]
LCA	0.001	0.028***	0.002***	0.039***	0.016***	0.005***	–	–	–	–	–	–	–	–	–
	[1.43]	[3.29]	[2.75]	[2.67]	[7.89]	[4.17]									
LGINI	−0.006***	−0.011	−0.041***	–	–	–	−0.011***	−0.029**		−0.044***	–	–	–	–	–
	[−2.99]	[−1.59]	[−3.58]				[−2.66]	[−6.22]		[−5.36]					
LPRI	−0.028***	−0.004***	−0.018***	–	–	–	−0.003***	−0.006**	−0.006***	−0.001***	−0.002***	−0.005***	–	–	–
	[−4.24]	[−3.58]	[−3.61]				[−3.03]	[−2.23]	[−3.06]	[−2.48]	[−2.60]	[−2.60]			
LGDP	0.017***	0.048***	0.030***	–	–	–	–	–	–	0.001*	0.007***	0.003	–	–	–
	[8.31]	[6.34]	[6.44]							[1.79]	[4.18]	[1.56]			
LUNE	−0.004**	−0.010*	−0.011***	–	–	–	–	–	–	–	–	–	−0.021 ***	−0.007***	−0.006***
	[−2.33]	[−1.74]	[−4.16]										[−9.79]	[−3.84]	[−3.59]
TEMPE	–	−0.017**	–	–	−0.013***	–	–	−0.010**	–	–	−0.013***	–	–	−0.042*	–
		[−2.07]			[−6.57]			[−2.10]			[−5.93]			[−1.78]	
NUM.DISAS	–	–	−0.015***	–	–	−0.002***	–	–	−0.009***	–	–	–	–	–	−0.134***
			[−4.10]			[−2.82]			[−5.75]						[−4.55]
Model criteria															
Hansen	0.499	0.498	0.518	0.391	0.673	0.662	0.210	0.645	0.330	0.243	0.675	0.334	0.485	0.270	0.474
AR(1)	0.016**	0.072*	0.035**	0.016**	0.046**	0.005***	0.014**	0.036**	0.009***	0.097*	0.009***	0.007***	0.036**	0.097*	0.032**
AR(2)	0.550	0.340	0.334	0.407	0.134	0.324	0.256	0.383	0.305	0.432	0.346	0.36	0.588	0.168	0.474
Difference-Hansen	0.499	0.639	0.928	0.992	0.999	0.953	0.993	0.973	0.953	0.964	0.992	0.951	0.999	0.960	0.996
#instruments	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33
#Groups	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56
#Obs	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336
Marginal effect															
Mean	0.3571	0.3014	0.2894	0.0910	0.0214	0.2567	0.0120	0.2952	0.0194	0.0442	0.0322	0.0268	0.1949	0.8859	0.6030
Min	−0.6499	−0.7937	−0.8310	−0.1733	−0.0416	−0.6622	−0.0132	−0.3719	−0.0183	−0.1195	−0.0810	−0.0739	−0.3841	−2.3366	−1.4866
Max	0.5033	0.4604	0.4520	0.1294	0.0305	0.3902	0.0156	0.3921	0.0249	0.0679	0.0487	0.0414	0.2790	1.3537	0.0906
Threshold	1.0126	2.7497	3.4031	1.1536	1.2214	2.6088	0.2231	0.3348	0.1353	2.9356	2.4322	3.0802	1.2701	2.7610	2.3243

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t- statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation. (1) EQ = Environmental Performance Index (EPI); (2) EQ = Temperature and (3) EQ = number of natural disasters occurrences.

Table B.6
Regression analysis based on distance approach [DV = *LFS*].

	FS DIFF-GMM	SYS-GMM	FSAVA DIFF-GMM	SYS-GMM	FSACC DIFF-GMM	SYS-GMM	FSUTI DIFF-GMM	SYS-GMM	FSSTA DIFF-GMM	SYS-GMM
Constant		1.063***		1.998***		1.017***		1.048***		0.640***
		[7.48]		[18.20]		[4.42]		[5.08]		[4.87]
LFS_{t-1}	0.800***	0.195***	0.3014***	1.998***	0.846***	0.846***	1.101***	0.991***	0.165*** [5.46]	0.482***
	[16.71]	[4.09]	[5.54]	[18.20]	[15.98]	[15.78]	[17.98]	[13.33]		[17.93]
LAL	0.008	0.057***	0.001***	0.082***	0.0455***	0.003***	–	–	0.986***	0.060**
	[1.63]	[5.03]	[2.68]	[5.32]	[5.41]	[4.25]			[6.65]	[2.00]
LEQ	0.015*	0.280***	0.073***	0.046***	0.069***	0.069***	0.053***	0.002***	0.741***	0.058**
	[2.04]	[5.54]	[2.76]	[7.48]	[2.59]	[2.50]	[2.78]	[5.59]	[3.31]	[2.34]
LPOP	−0.003***	−0.004***	−0.012***	−0.006***	−0.045	−0.045*	−0.021**	−0.001***	−0.1695	−0.055*
	[−6.75]	[−3.23]	[−1.84]	[−8.66]	[−1.50]	[−1.95]	[−2.28]	[−3.33]	[−1.20]	[−9.60]
LBP	−0.050***	−1.349***	−0.206***	−0.130***	0.047***	0.027***	−0.104*	−0.004***	−0.088***	−0.415***
	[−2.89]	[−2.91]	[−2.56]	[−6.82]	[3.73]	[3.43]	[−1.90]	[−3.57]	[−4.64]	[−2.83]
*LBP*LEQ*	0.059***	1.297***	0.212***	0.0948***	0.040***	0.020*	0.092**	0.009**	0.210*	0.455***
	[3.29]	[3.01]	[2.57]	[5.15]	[2.72]	[1.92]	[2.20]	[8.80]	[1.90]	[3.61]
LCA	0.012***	0.009***	0.132****	0.0167***	–	–	–	–	–	–
	[8.16]	[2.99]	[6.95]	[3.93]						
LGINI	−0.060*	−0.099***	–	–	−0.163***	−0.163***	–	–	–	–
	[−3.50]	[−3.51]			[−5.03]	[−5.08]				
LPRI	−0.040***	−0.030***	–	–	−0.051	−0.051***	−0.003***	−0.002***	–	–
	[−6.34]	[−4.25]			[−4.13]	[−4.43]	[−4.77]	[−4.13]		
LGDP	0.003*	0.219***	–	–	–	–	0.007***	0.006***	–	–
	[1.88]	[5.14]					[3.68]	[5.64]		
LUNE	−0.015**	−0.005	–	–	–	–	–	–	−0.076***	−0.054***
	[−2.04]	[1.52]							[−2.57]	[−4.80]
	Model criteria									
Hansen	0.723	0.296	0.543	0.471	0.587	0.792	0.691	0.498	0.558	0.287
AR(1)	0.030**	0.069*	0.010***	0.001**	0.038***	0.038**	0.005***	0.084*	0.082*	0.039**
AR(2)	0.425	0.369	0.203	0.262	0.638	0.638	0.613	0.349	0.758	0.117
Difference-Hansen	–	0.821	–	0.191	–	0.981	–	0.948	–	0.999
#instruments	33	33	33	33	33	33	33	33	33	33
#Groups	56	56	56	56	56	56	56	56	56	56
#Obs	336	336	336	336	336	336	336	336	336	336
	Marginal effect									
Mean	0.2141	4.4563	0.7429	0.2943	0.2260	0.1165	0.3078	0.0363	0.8520	1.6216
Min	−0.5286	−11.870	−1.9257	−0.899	−0.2775	−0.1352	−0.8503	−0.0770	−1.7915	−4.1059
Max	0.3219	6.8269	1.1304	0.4676	0.2991	0.1531	0.4759	0.0527	1.2358	2.45318
Threshold	2.3338	2.8292	2.6424	3.9404	0.3088	0.2592	3.0970	1.5596	1.5204	2.4895

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in [] stand for t- statistic. The values of the Hansen and AR tests stand for the p-value. The model is estimated using the two-step model with robust estimation.

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SUSTAINING FOOD SECURITY IN MALAYSIA

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CHALLENGES OF URBAN GARDEN INITIATIVES FOR FOOD SECURITY IN KUALA LUMPUR, MALAYSIA

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Abstract: Sustainable urban farming is a strategy to improve food availability and food access, and to support food security for the urban population in Malaysia. However, the development of these activities has been affected by several constraints. This article aims to identify the challenges faced by urban farmers in Kuala Lumpur. The challenges of practicing urban gardening were categorised into five groups (technical, resource-related, economic, social and environmental factors). Data were collected via a questionnaire survey distributed to 106 urban farming practitioners from 17 urban gardens in Kuala Lumpur and were analysed using descriptive analysis by tabulating the frequency and percentage. The result showed that highly fluctuating weather, problems with access to available land and financial problems were the main challenges faced by urban farmers in Kuala Lumpur. Furthermore, difficulty in access to a financial institution, lack of commitment and the increased number of pests were also the problems faced by the urban garden. Availability of technical factors is the least issue in this study. Correlation analysis was used to determine the relationship between the challenges of urban gardens and socio-demographics. The result showed that there was a weak correlation between technical factors of educational level (r = 0.225) and race (r = 0.210), respectively, as well as between race and social factor (r = 0.201), while there was a moderate correlation between age and environment factor (r = −0.410). There is a need for further work, and comprehensive research should be conducted to capture what actions can be taken to create a policy-making space for urban farmers.

Keywords: community, food security, obstacle, sustainable, urban agriculture

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Introduction

The World Food Summit in 1996 agreed that food security materialises when all people can access sufficient, safe and nutritious food that meets their dietary needs for active and healthy life (Pinstrup-Andersen 2009). However, many factors contribute to food insecurity. A study by

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Ihab et al. (2013) revealed that 83.9% of households in Bachok, Kelantan, faced food insecurity because of large household size, food expenditure and low monthly income. Food will become unaffordable, particularly for urban residents with lower income, and their daily diet will be affected and lead to hunger and malnutrition (Othman et al. 2018). Besides, the increased population and a decline in food products can have an impact on food security in cities (Muhamad et al. 2015). According to the Department of Statistics Malaysia (2016 a, 2016b), the Malaysian population is projected to rise from 28.6 million in 2010 to 41.5 million by 2040. This obviously will decline the availability of domestic food, which will increase the amount of imported food. For instance, the government needed to import food from China and Thailand in 2014 (Ministry of Finance Malaysia 2011), and the cost of imported food increased from RM 8.97 billion in 2012 to RM 17 billion in 2014 (Ministry of International Trade and Industry Malaysia, 2015).

Hence, according to the Ministry of Agriculture and Food Industries, Malaysia, in the 'Program Sentuhan Kasih Tani-Pertanian Bandar 2.0', urban farming is an initiative by the government to enhance food security and ensure a complete food supply chain (New Straits Times, 2018). Urban farming is a strategy for Malaysia's economic and food security (Othman et al. 2018). The urban garden is defined as the growing of food within cities (Ackerman 2012), and is one of the initiatives to ensure that all people in the world are fed (Mok et al. 2014). The engagement of people in urban garden practice ensures that the food sources can be accessed easily and are safe to consume (Alaimo et al. 2008). A previous study by Rezai et al. (2016) shows that availability and accessibility of fresh food among households in Putrajaya improved when they grew vegetables daily. Besides, the other highlighted benefits about this urban garden practice are that it helps in improving mental health and reducing stress and it allows people to plant something that can be consumed safely (Teig et al. 2009). A study in 15 countries by Zezza and Tasciotti (2010) shows that there is a positive change in the dietary diversity and calorie intake among urban people after being involved in urban farming. Furthermore, fluctuating food prices can contribute to food insecurity in cities. According to Mkhawani et al. (2016), the impact of the increase in food price caused 50.0% of households in South Africa to need to spend almost half of their money on food, and it affected their ability to access other important commodities required in the household. This study also states that 15.0% of households needed to borrow money from microlenders. Thus, an urban garden is important to overcome this issue.

Although the urban garden has the potential to support food security and provides many benefits to urban farmers, they should face many challenges, such as fluctuating weather that will have a negative impact on food sources. According to the Food and Agriculture Organization (2015), the most natural hazard affecting the agricultural crop sector is flood, and a study by Jega et al. (2018) shows that floods in Kelantan had an impact on almost all the crops, livestock and agricultural assets. Next is dryness of soil, which reduces soil fertility and stops root growth and causes decomposition of organic material (Ogwuche et al. 2018). Insufficient rainfall and temperature lead to food insecurity all over the world (Milan, Ruano 2014; Generoso 2015). It is in line with the findings of Solaymani (2018), showing that there is a direct correlation between changes in rainfall–temperature and the productivity of agricultural products. Thus, farmers adapt to rainfall variability through the choice of crop and planting dates, adjusting the levels of fertiliser, as well as resorting to cropping in areas with a high water table (Makuvaro et al. 2017).

According to a study by Pourjavid et al. (2013), the top constraint of urban farming in Tehran was high start-up cost and lack of knowledge among urban managers and authorities. Mostly, urban farmers need loans or subsidies to develop urban gardens because these require a large investment in terms of operational cost, infrastructure, energy and management (Valk 2012). Farmers also need to arrange the cost for purchasing fertilisers, pesticides and tools (Dimitri et al. 2016). A finding by Makuvaro et al. (2017) reveals that the shortage of pesticides among farmers is caused by a lack of capital. Besides, less access to loan facilities will increase the impact on farming activities, e.g. for small urban farmers in Africa, Asia and Latin America, in the context of scaling up their production (Cabannes 2012). The high cost of irrigation is one of the issues in urban farming (Kutiwa et al. 2010; Adedayo, Tunde 2013). Rainwater is another source of water in cities. A study by Moglia (2014) shows that farmers use water from the Kalkallo Stormwater Harvesting and Reuse facility. However, there are possibilities that it may be contaminated with pathogens, heavy metals, excessive nutrients and salinity (Norton-Brandao et al. 2013). Furthermore, the shortage of land in an urban area will affect the urban farmers involved in this practice (Beniston 2016). According to Low (2019), lack of space is one of the challenges for urban farming in Singapore because of the complex and restrictive regulatory legislative framework related to land use.

Other than that, the challenge faced by urban farmers is hard-to-access available land. The agricultural sector needs to compete for the available soil with the residential, industrial and commercial sectors (Duchemin et al. 2009) and most of the available land is owned by private owners (Barthel et al. 2013a). Land, particularly in urban areas, is valuable and highly competitive (Man et al. 2017). Half of the farmers in Accra cultivate their crops not on their land, and private owners only sell to those residential and commercial developers who are the highest bidders (Asomani-Boateng 2002). In addition, illegal urban gardens and recreational urban farming have created conflicts among the farmers, residents and local government (Razak, Roff 2007; Man et al. 2017). Meanwhile, the main challenges faced by urban farmers of nutrition gardens in Mucheke town, Masvingo, are difficulty in securing fertilisers/manure, pests and diseases, and theft (Chimbwanda 2016). Pests and diseases can be influenced by climate change because the rise in temperature and change in rainfall patterns increase the number of fungi and diseases that affect yield production in Malaysia (Rahim 2014). Furthermore, lack of information about market demands and pricing, sudden shortages of products and price instability can be seen as other challenges faced by urban farmers (Man et al. 2017). For instance, intensive training can improve the knowledge among farmers in Nepal, where less-literate farmers cannot use all the information without guidance from extension services (Karki et al. 2011).

In addition, several economic, environmental and social factors can be identified and categorised as the challenging constraints of the urban garden. The constraints are classified based on related factors. In terms of the economic factor, the location of the urban garden far from supermarkets and lack of marketing skills are the challenges faced by urban farmers. A previous study by Aarthi Dhakshana and Rajandran (2017) shows that 27.0% of farmers in Thanjavur faced problems due to lack of marketing techniques. Othman et al. (2017) reveal that the fewest participants are among people younger than 20 years of age because they have the perception that this activity is not profitable to them (Ramaloo et al. 2018). Thus, the aim of this study was to identify the demographic background of target respondents in urban gardens around Kuala Lumpur, to investigate the challenges of urban garden development and to identify the relationship between demographic background and the factors challenging the development of this urban garden practice in Kuala Lumpur, Malaysia.

Materials and methods

Study area

Kuala Lumpur is the capital city of Malaysia and the fastest-growing metropolitan area with 1.78 million people. Kuala Lumpur is located 54 m above sea level, and the annual rainfall in this city is 2,486 mm. Kuala Lumpur has abundant rainfall, especially during the northeast monsoon season from October to March. It has a tropical climate with an average temperature of 27.1°C. Due to rapid urbanisation and increasing population, this city is suitable for urban garden development and supports food security.

Data collection

This was a descriptive survey research carried out at urban gardens that are registered under Local Agenda 21 Kuala Lumpur (LA21 KL). The UN Local Agenda (LA21) was officially implemented in 2005 in Kuala Lumpur to encourage public, private and community partnerships to develop a better city vision. All urban gardens involved in this study are located around Kuala Lumpur (Fig. 1). The primary data were obtained using structured questionnaire surveys. Prior to the survey, a pilot test was conducted to improve the validity and reliability of the survey

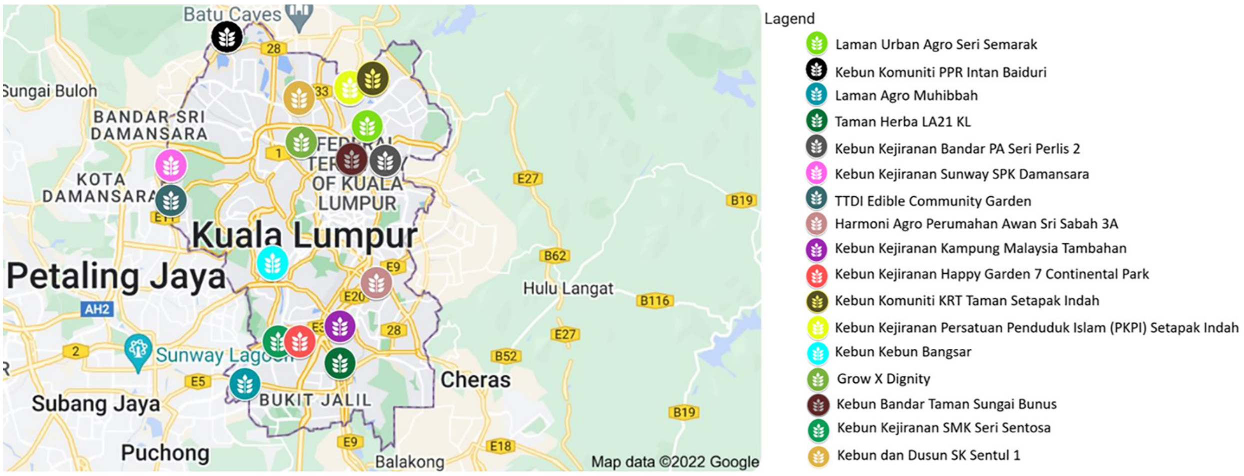

Fig. 1. Map of the locations of all the urban gardens in Kuala Lumpur for the years 2016–2020.
Source: Urus Setia Local Agenda 21 Kuala Lumpur, Dewan Bandaraya Kuala Lumpur, Malaysia.

question. The surveys were conducted between January and May 2020 by common survey methods, namely through field data collection (face-to-face interviews) and an online survey method (Kelley et al. 2003; Othman et al. 2018). Because of the movement restriction due to the coronavirus disease (COVID-19) pandemic, this study only involved 106 urban farming practitioners from only 17 urban gardens out of all the urban gardens listed under LA21 KL.

Measurement of variables

The questionnaire was composed of three sections. Section A consisted of the socio-demographic characteristics of the respondents (gender, age, race, educational level, number of households, household income and experience); Section B involved the perspective of the practitioner about the benefits of an urban garden; and Section C asked the questions related to challenges of the urban garden. All the identified constraints and challenges in the urban garden were categorised into five groups: technical, resource-related, economic, social and environmental factors. These constraints were rated by the respondents based on a five-point Likert's scale from '1' to '5', with '1' indicating 'strongly disagree' and '5' indicating 'strongly agree'.

Data analysis

The collected data from completed questionnaires were coded and analysed in Statistical Package for Social Science, IBM SPSS Software Version 26 (IBM corporation, Armonk NY, USA) and tabulated by using frequency and percentage. To assess the reliability of the questionnaire, Cronbach's alpha coefficient was calculated. This coefficient for the main sections of the questionnaire was in the range of $0.644 \leq \alpha \leq 0.848$. Spearman-rho analysis was used to determine the correlation between socio-demographic characteristics and the challenges for the urban garden.

Results

Socio-demographic characteristics of respondents

Table 1 presents the socio-demographic profile of respondents. They are composed of 39 males and 67 females, with percentages of 36.8% and 63.2%, respectively. In terms of the respondents' race, Malay urban farming practitioners constituted the highest percentage (78.3%), followed by the Chinese (14.2%), Indians (3.8%) and others (3.8%). Most of the respondents (48.1%) fell within the age group of 41–60, while 40.6% are in the age group of 15–40. Table 1 also indicates that most of the respondents (57.5%) have completed a tertiary educational level. The result also shows that 47.2% of the respondents are from the lower-income group with a monthly household income of ≤RM 3,000 per month, with four to six family members per household (50.0%). Most

(40.0%) of them have been only involved in this practice for three years.

Table 1. Socio-demographic profile of respondents.

Characteristics	Frequency	Percentage (%)
Gender		
Male	39	36.8
Female	67	63.2
Age		
<15	5	4.7
15–40	43	40.6
41–60	51	48.1
>60	7	6.6
Race		
Malay	83	78.3
Chinese	15	14.2
Indian	4	3.8
Others	4	3.8
Educational level		
Primary school	5	4.7
Secondary school	40	37.7
Tertiary school	61	57.5
Other	0	0.0
Number of people in households		
1–3	38	35.8
4–6	53	50.0
>6	15	14.2
Household income (RM)		
≤3,000	50	47.2
≤6,275	27	25.5
≤13,148	29	27.4
Experience (years)		
<1	26	24.5
<3	45	42.5
<5	19	17.9
>5	16	15.1

Source: own study.

Perspective of practitioners about the benefits of urban gardens

Table 2 shows the perspective of urban farming practitioners regarding the benefits of the urban garden. Based on the results, the majority (98.1%) of the respondents acknowledge that the urban garden is the government's initiative to sustain the urban environment, followed by the building of social relationships among farmers (97.2% of respondents). Meanwhile, the third-highest score (95.3% of respondents) was for the safe production of food sources in the garden, production of more nutritional food and easy access to vegetables and fruits for urban residents.

Prioritising constraints facing urban gardens

Constraints listed in Table 3 have been prioritised by the respondents. Overall, highly fluctuating weather was given the highest rankings by the respondents. Meanwhile, financial problems ranked as the most important constraint after the problems of access to available land. Constraints, such as difficulties with access to training and consultation from the government, difficulties in access to technical support from authorities and non-governmental organisations (NGOs) and limited access to local urban farming information online were among the lowest priorities facing urban agriculture development.

Challenges facing urban gardens

Technical factor

Based on Table 4, the technical factor is not the major challenge in this study: the majority of the

Table 2. Perspective of practitioners on benefits of urban gardens.

Statement	Frequency	Percentage (%)
It is one of the green initiatives by the government to sustain the urban environment.	104	98.1
Building social relationships among farmers	103	97.2
Safe food sources can be produced in the garden.	101	95.3
More nutritional food can be produced from the garden.	101	95.3
Urban people can easily access vegetables and fruits.	101	95.3
Encouraging farmers to do exercise for their health	98	92.5
Urban wastes can be reduced.	97	91.5
People can generate sources of income.	93	87.7
It helps urban poor save their money to buy food sources.	92	86.8
Price of food sources from the garden is cheaper than from the market.	83	78.3

Source: own study.

respondents disagreed about the lack of awareness and promotion programmes delivered to urban farmers (35.8%), and 45.3% of them also do not have difficulties in receiving technical support from the authorities or NGOs to improve their knowledge on urban gardening. The result also shows that 50.0% and 54.7% of them do not face any problems with access to training and consultation from relevant agencies and access to online information related to local urban farming, respectively.

Table 3. Prioritising challenges facing urban gardens.

	Mean	Standard deviation	Priority
Highly fluctuating weather will affect the yield	3.76	1.06	1
Access to available land is a major problem	3.65	1.07	2
Financial problems is the main issue	3.48	1.11	3
Increased number of pests	3.48	0.89	4
Shortage in the number of members to help in managing the garden	3.47	1.07	5
Price of pesticide in the market is too high	3.41	1.15	6
Flood will damage the yields	3.40	1.18	7
Hard to access financial institutions to lend money	3.40	1.03	8
Rain will reduce soil fertility	3.34	1.08	9
Lack of rain reduces water availability	3.29	1.01	10
I am afraid of my produce being stolen	3.25	1.29	11
Most of the available land belongs to private owners	3.19	1.08	12
Available land is contaminated	3.09	1.09	13
Hard to get volunteers to manage the garden	3.09	1.04	14
Need to compete for available land with industries	3.08	1.16	15
Lack of commitments from communities	2.99	1.02	16
Lack of marketing skills	2.97	0.99	17
Lack of cold storage	2.96	1.26	18
Difficult to access financial resources from the government	2.90	0.98	19
Hard to get regular customers	2.82	1.02	20
Hard to buy cheap fertiliser near the garden	2.81	1.14	21
Hard to find a leader	2.81	1.18	22
Hard to access water supply near the garden	2.80	1.23	23
Lack of equipment and tools	2.76	1.17	24
Price for the produce is too low	2.70	1.03	25
Lack of awareness and promotion programmes delivered to urban farmers	2.67	0.95	26
Inability and lack of supply of seed	2.61	1.13	27
Mostly selling produce to middlemen	2.49	1.16	28
Farm is located far from supermarkets	2.34	0.96	29
Difficult to get training and consultation from relevant agencies	2.28	0.86	30
Difficult to access technical support from authorities or non-governmental organisations to improve knowledge	2.12	0.86	31
Hard to access local urban farming information online	1.95	0.79	32

Source: own study.

Table 4. Technical constraints.

Constraint	SD freq., %	D freq., %	N freq., %	A freq., %	SA freq., %
Lack of awareness and promotion programmes delivered to urban farmers	11 (10.4)	38 (35.8)	32 (30.2)	25 (23.6)	0 (0.0)
Difficult to access technical support from authorities or non-governmental organisations to improve knowledge	26 (24.5)	48 (45.3)	25 (23.6)	7 (6.6)	0 (0.0)
Difficult to get training and consultation from relevant agencies	16 (15.1)	53 (50.0)	31 (29.2)	3 (2.8)	3 (2.8)
Hard to access local urban farming information online	29 (27.4)	58 (54.7)	15 (14.2)	3 (2.8)	1 (0.9)

SD – strongly disagree, D – disagree, N – neutral, A – agree, SA – strongly agree
Source: own study.

Resource-related factor

Table 5 shows the constraints on access to resources faced by urban practitioners. The majority (53.8%) of them agreed on facing problems with access to available land, and 35.8% of the respondents also agreed that the available land belonged to private owners. However, 28.3% of them had a neutral opinion regarding having to compete with industries for available land. Table 5 also shows that 33.0% of them agreed that the available land was contaminated, and 35.8% of the respondents do not have any problem with access to water supply. Besides, 31.1% of the respondents faced the problem of high price of pesticides. Access to fertilisers (31.1%), lack of seed supply (38.7%) and complete equipment for their gardening activities (36.8%) are not major problems in this study.

Economic factor

Table 6 shows that the majority of the respondents agreed that the financial problem was the main issue (39.6%) in implementing and managing the urban garden. However, 44.3% and 42.5% of them have a neutral opinion regarding easy access to financial resources from the government and lack of marketing skills. Besides, 40.6% of them face problems with access to financial institutions lending money. Table 6 also shows that the majority of urban farmers disagree on the price of produce being too low and whether it is hard to get regular customers, with percentages of 36.8% and 33.0%, respectively. The majority of them also do not agree about the need to sell the product to a middleman (35.8%) and on the farm being located far from the supermarket (38.7%). In addition, 38.7% of them have a problem with a lack of cold storage.

Social factor

Table 7 shows that most of the respondents (37.7%) have a neutral opinion about the shortage of members to help in managing the garden. However, 33.0% and 35.8% of the respondents have a problem accessing volunteers and lack of commitment from the public to help them in

Table 5. Resource-related constraints.

Constraint	SD freq., %	D freq., %	N freq., %	A freq., %	SA freq., %
Access to available land is a major problem	6 (5.7)	12 (11.3)	13 (12.3)	57 (53.8)	18 (17.0)
Most of the available land belongs to private owners	8 (7.5)	20 (18.9)	31 (29.2)	38 (35.8)	9 (8.5)
Need to compete for the available land with industries	10 (9.4)	25 (23.6)	30 (28.3)	29 (27.4)	12 (11.3)
Available land is contaminated	9 (8.5)	23 (21.7)	31 (29.2)	35 (33.0)	8 (7.5)
Hard to access water supply near the garden	14 (13.2)	38 (35.8)	21 (19.8)	21 (19.8)	12 (11.3)
Price of pesticide in the market is too high	7 (6.6)	16 (15.1)	30 (28.3)	33 (31.1)	20 (18.9)
Hard to buy cheap fertiliser near the garden	14 (13.2)	33 (31.1)	23 (21.7)	31 (29.2)	5 (4.7)
Inability and lack of supply of seed	16 (15.1)	41 (38.7)	23 (21.7)	20 (18.9)	6 (5.7)
No access to equipment and tools	13 (12.3)	39 (36.8)	23 (21.7)	22 (20.8)	9 (8.5)

SD – strongly disagree, D – disagree, N – neutral, A – agree, SA – strongly agree
Source: own study.

Table 6. Economic constraints.

Constraint	SD freq., %	D freq., %	N freq., %	A freq., %	SA freq., %
Financial problem is a main issue	9 (8.5)	7 (6.6)	31 (29.2)	42 (39.6)	17 (16.0)
Difficult to access financial resources from the government	9 (8.5)	24 (22.6)	47 (44.3)	21 (19.8)	5 (4.7)
Hard to access financial institutions to borrow money	3 (2.8)	21 (19.8)	26 (24.5)	43 (40.6)	13 (12.3)
Lack of marketing skill	8 (7.5)	23 (21.7)	45 (42.5)	24 (22.6)	6 (5.7)
Price for the produce is too low	11 (10.4)	39 (36.8)	31 (29.2)	21 (19.8)	4 (3.8)
Hard to get regular customers	9 (8.5)	35 (33.0)	32 (30.2)	26 (24.5)	4 (3.8)
Mostly sell produce to middlemen	22 (20.8)	38 (35.8)	26 (24.5)	12 (11.3)	8 (7.5)
Farm is located far from supermarkets	21 (19.8)	41 (38.7)	33 (31.1)	9 (8.5)	2 (1.9)
Lack of cold storage	16 (15.1)	29 (27.4)	12 (11.3)	41 (38.7)	8 (7.5)

SD – strongly disagree, D – disagree, N – neutral, A – agree, SA – strongly agree
Source: own study.

the garden. Besides, most of them (34.0%) do not have a problem finding a leader for their urban garden project. The result also shows that farm theft (25.5%) is not a major problem among urban farming practitioners.

Environmental factor

Table 8 shows that the majority of the respondents (36.8%) have a problem with highly fluctuating weather that affects their yield production. Thus, 39.6% of them agree that rain will reduce soil fertility, and 48.1% agree that lack of rain will reduce the availability of water for their uses. The majority (37.7%) of the urban farming practitioners agree that flood will damage their yields, and 49.1% of them agree that highly fluctuating weather will increase the number of pests.

Table 7. Social constraints.

Constraint	SD freq., %	D freq., %	N freq., %	A freq., %	SA freq., %
Shortage in the number of members to help in managing the garden	4 (3.8)	13 (12.3)	40 (37.7)	27 (25.5)	22 (20.8)
Hard to get volunteers to manage the garden	6 (5.7)	27 (25.6)	31 (29.2)	35 (33.0)	7 (6.6)
Lack of commitment from the public	10 (9.4)	23 (21.7)	33 (31.1)	38 (35.8)	2 (1.9)
Hard to find a leader	13 (12.3)	36 (34.0)	25 (23.6)	22 (20.8)	10 (9.4)
I'm afraid of having my produce stolen.	9 (8.5)	27 (25.5)	22 (20.8)	25 (23.6)	23 (21.7)

SD – strongly disagree, D – disagree, N – neutral, A – agree, SA – strongly agree
Source: own study.

Table 8. Environmental constraints.

Constraint	SD freq., %	D freq., %	N freq., %	A freq., %	SA freq., %
Highly fluctuating weather will affect the yield	4 (3.8)	8 (7.5)	26 (24.5)	39 (36.8)	29 (27.4)
Rain reduces soil fertility	7 (6.6)	16 (15.1)	29 (27.4)	42 (39.6)	12 (11.3)
Lack of rain reduces water availability	5 (4.7)	22 (20.8)	22 (20.8)	51 (48.1)	6 (5.7)
Flood will damage the yields	8 (7.5)	18 (17.0)	22 (20.8)	40 (37.7)	18 (17.0)
Increase in the number of pests	3 (2.8)	11 (10.4)	32 (30.2)	52 (49.1)	8 (7.5)

SD – strongly disagree, D – disagree, N – neutral, A– agree, SA – strongly agree
Source: own study.

Table 9. Correlation coefficient (r) between the socio-demographic background and the challenges of urban gardens.

		Technical	Resource-related	Economical	Social	Environmental
Gender	Spearman rho	−0.031	−0.173	−0.166	−0.058	−0.062
	Significance	0.750	0.077	0.089	0.552	0.527
Age	Spearman rho	−0.031	−0.131	−0.103	−0.164	−0.410**
	Significance	0.753	0.179	0.294	0.193	0.0
Race	Spearman rho	0.210*	−0.051	−0.112	0.201*	−0.149
	Significance	0.031	0.603	0.255	0.039	0.128
Education level	Spearman rho	0.225*	0.041	−0.088	0.021	−0.097
	Significance	0.021	0.674	0.370	0.830	0.323
Number of people in households	Spearman rho	−0.177	−0.047	0.111	0.072	0.109
	Significance	0.070	0.631	0.256	0.464	0.267
Monthly household income	Spearman rho	0.043	−0.126	−0.223*	−0.119	−0.197*
	Significance	0.660	0.199	0.021	0.226	0.043
Experience	Spearman rho	−0.143	0.018	−0.003	−0.052	−0.002
	Significance	0.143	0.857	0.979	0.594	0.981

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.
Source: own study.

Correlation analysis

Table 9 shows the correlation between socio-demographics and the challenges of an urban garden. The result reveals that there is a significant relationship between the age and the environment, with a value of −0.410. It also shows that there is a weak correlation between technical factors and race, with a value of 0.210, and the education level, with a value of 0.225 at a significant level of 0.05. The value of 0.201 for the correlation between the social factor and race at a significance level of 0.05 also shows that these have a weak correlation. The monthly household income also has a weak correlation with the economic factor, with a value of −0.223, and the environmental factor, with a value of –0.197 at a significance level of 0.05.

Discussion

Urban gardens play an important role in producing food sources, which makes it crucial in most developing countries. It is generally believed that the urban garden has the potential to enhance food availability, access and utilisation, especially among the urban poor. Besides, it also has the potential for improving the urban environment. As a result, from the socio-demographic profiles of respondents, this study has revealed that among urban farmers, females are predominant because there is a perception in societies that women have the responsibility to ensure safe food supply to their family members (Kutiwa et al. 2010), and also this activity meshes well with women's other household activities such as cooking and childcare (Islam, Siwar 2012). Besides, 48.1% of the urban farmers involved in this survey are within the age group of 41–60, and the majority have received tertiary education. This is in line with a study by Rezai et al. (2016), wherein young urban dwellers with higher education are more involved in urban farming activities. Furthermore, 50.0% of the urban farming practitioners have between four to six people per house, and 47.2% have a household income of ≤RM 3,000, which falls under the bottom 40% (B40) income group (Department of Statistics Malaysia, 2017). It is also in line with a previous study (Islam, Siwar 2012), where the urban garden is important for the urban poor to produce their own food.

Many benefits of gardening activities for urban farming practitioners towards food security are listed in this study. According to Table 2, the majority (98.1%) of the respondents are aware that the urban garden is the government's green initiative to enhance a sustainable urban environment because a high-density urban environment has an impact on the quality of city residents' lives, and increases the awareness of people living in cities to take action in creating a better environment to improve the current quality of life (Lau et al. 2017). According to Lovell (2010), an increasing amount of vegetation through the urban garden project in an urban area helps regulate humidity levels. Besides, the creation of green space in cities can reduce the number of urban wastes and urban heat island effects, in addition to improving the air quality of the surrounding area (Berhanu, Akola 2014). The second-highest benefit mentioned by 97.2% of the respondents is building a social relationship. It is in line with the study by Sanye-Mengual et al. (2016), where the purpose of involvement among urban farmers in Barcelona is more for leisure and social activity than for food production activity. This practice allows urban farming practitioners to meet their friends for four to five hours per day at the garden plot (Sauyah, personal interview, 14 March 2020).

Meanwhile, the perspective of urban farmers on the benefit of the urban garden for food security (the third highest: 95.3% of the respondents) is that safe and more nutritious food can be produced through the urban garden, and it can also help people in cities gain easier access to vegetables and fruits (Taylor, Lovell 2014). These three are related to the components of food security. According to Brüssow et al. (2017), the four components in achieving food security are availability, access and utilisation, underlined by stability. A study by Park et al. (2011) shows that the urban garden can make food accessible to residents and can also increase the consumption of fresh produce (Corrigan 2011). For instance, growing the vegetables daily helps improve the availability and accessibility of fresh food among households in Putrajaya (Rezai et al. 2016). Besides, the urban garden also helps produce food sources closer to consumers (Lovell 2010). Furthermore, most of the urban women farmers become involved in crop farming to cater to the family's demand for fresh, nutritious and agrochemical-free food (Gamhewage et al. 2015).

Table 3 reveals the prioritising challenges related to the urban garden faced by urban farmers in Kuala Lumpur. The results show that the main barrier to the urban garden in Kuala Lumpur is highly fluctuating weather. Highly fluctuating weather will affect the crop's yield. According to Alam et al. (2011), a low level of rainfall can be overcome by farmers with irrigation, but high rainfall will lead to damage to output and serious damage to crops at the end of the crop cycle. Besides, an increase in rainfall and temperature also causes agricultural production losses of between RM 37 and RM 48 per hectare in Peninsular Malaysia, Sabah and Sarawak (Zainal et al. 2012). The second major barrier in this study is the problem of access to available land. Findings by Hussain et al. (2019) show that planting in the pot is a popular method because of limited open spaces in some residential areas and it is also portable and easy to handle within a small compound. On the other hand, the lack of space for farming activities in Edible Garden City, Singapore, is due to the restriction of the legal framework on land use (Low 2019). Besides, contaminated land also contributes to limited land availability in cities. According to Nabulo et al. (2012), land contamination in Kampala, Uganda, is caused by the waste disposal practice, which has led to health concerns due to the presence of toxic elements in the vegetables grown in an urban area. The third major barrier is a financial constraint. It is similar to the finding by Ramaloo et al. (2018): farmers in Taman Desa Damai Community Garden at Bukit Mertajam face financial constraints to pay the rental fees on land use and domestic water supply. Besides, lack of capital causes difficulties among farmers in purchasing adequate amounts of fertilisers and pesticides (Makuvaro et al. 2017).

Table 4 shows the challenges faced by urban farmers related to technical factors. Most (35.8%) of the respondents in this study do not have any problem with urban garden knowledge because there have been enough awareness and promotion programmes related to urban gardens, such as an exhibition by Malayan Agri-Horticulture Association (MAHA) (Ali, personal interview, 14 March 2020). Besides, 45.3% and 50.0% of urban farming practitioners can access technical support and training and consultation services from the government and NGOs. It is in contrast with the findings by Adeoti et al. (2011), where 50.0% of farmers in Accra, Ghana, never receive advice facility from the authorities. According to Singh et al. (2015), training can provide more information related to agriculture activities. Thus, a study by Gamhewage et al. (2015) shows a lack of knowledge among women involved in urban farming in Sri Lanka, causing difficulty in identifying diseases, pest attacks and nutrient deficiencies. The role of knowledge is also important to increase the number of participants in this practice (Azman et al. 2013; Shamsudin et al. 2014) whereby knowledge builds a favourable attitude of the public towards the urban garden. In addition, 54.7% of urban farmers disagree that it is difficult to access online urban farming information because a lot of information about not only urban farming but also everything on agriculture has been provided by the government and NGOs online.

The data on resource-related constraints in Table 5 show access to available land is a challenge among 53.8% of the urban farmers involved in this study. It is similar to the study by Pearson et al. (2010), where the primary constraint in Australia is to protect and preserve land because of intense competition with other land uses. Besides, limited land is available in Singapore for farming activities because of the restricted legislative regulatory framework on land use, whereby no land is allowed for farming for social purposes, and the land that is set aside for community purposes cannot be used for farming (Low 2019). The high price of land in cities is also one of the reasons, as shown in a study by Moglia (2014), wherein the cost of available land for agriculture around Kalkallo is reported to be as high as AUS$ 100 000 per hectare. Furthermore, 33.0% of urban farmers in this study face problems with contaminated land. This phenomenon has been proved in a study by Säumel et al. (2012), where the vegetables produced in the city contain a high amount of trace metals. The contaminant can come from waste disposal practices similar to the occurrence in Kampala, Uganda, where the waste disposal practice contaminates the land and it affects human health because of toxic elements, such as cadmium, chromium and lead contained in the vegetable (Nabulo et al. 2012).

Table 6 also reveals that 35.8% of the respondents have agreed that the available land belongs to a private owner. According to Asomani-Boateng (2002), there are issues related to private owners, whereby they tend to sell their plots to residential and commercial developers, who are usually the highest bidders. The high price of pesticides is one of the issues reported by 33.1% of urban farmers. It is similar to the study by Makuvaro et al. (2017), where a shortage of pesticides used to control pests and diseases is faced by farmers in Lower Gweru due to lack of capital. However, the majority of urban farming practitioners in this study do not have difficulties in accessing seed, fertiliser and complete equipment. It contrasts with the finding by Gamhewage et al. (2015), where the third major constraint of urban farming in Sri Lanka is the poor quality of input, such as the unsatisfactory quality of planting material and poor soil fertility. The urban farming practitioner received the inputs such as seeds, fertilisers and some equipment from the Department of Agriculture during the early stages of involvement in this practice (Norizai, personal interview, 14 March 2020).

The data regarding economic factors reported in Table 7 revealed that the majority (39.6%) of urban farmers had to face financial problems similar to farmers in Kenya, who were affected by the financial constraint to adopt urban agriculture (Muriithi 2013). This is because urban gardens require a large investment in terms of operational cost, infrastructure, energy and management (Valk 2012). The difficulty in getting access to financial institution is agreed by 40.6% of the respondents in this study. This might be happening because of a lack of information among farmers about available sources of lenders and the type of credits offered in their area. Besides, commercial banks do not lend money to agricultural enterprises because it is risky (Adeleke et al. 2010). However, 35.8% of the respondents do not need to sell their products through a middleman because most of them (33.0%) have regular customers. All the vegetables are sold to the regular customer directly at the garden or at Farmer's Markets (Hamidah, personal interview, 14 March 2020). Next, according to Antwi and Seahlodi (2011), marketing constraints include limited knowledge, lack of access to high-value reliable markets, distance from markets, poor quality of products, lack of storage facilities, poor agricultural extension services and lack of financial support. It is in line with this study, where 38.7% of the respondents have a problem storing their produce in the absence of cold storage. The study by Aarthi Dhakshana and Rajandran (2017) shows that farmers in Thanjavur cannot afford to purchase cold storage due to lack of capital, which has an impact on farmers' marketing . According to Cong and Baldeo (2006), lack of storage facilities will lead to reducing the quality of the produce, increasing the humidity of the produce and increasing the produce loss.

According to Noriah Mat, Senior Deputy Director of Putrajaya Corporation Landscape and Parks Development, the challenge of Community Garden Programmes is attracting volunteers (*The Star* 2014). This is similar to this study based on the data for social constraints in Table 7, where 33.0% of urban farming practitioners face a shortage of volunteers, which is derived from a lack of commitment from the public, mentioned by 35.8% of the respondents. A finding by Gamhewage et al. (2015) shows that the constraint faced by women participants in this practice is insufficient time because they need to spend more time on household care and management. This study also shows that most women not participating in this practice were job holders. In a study by Othman et al. (2017), urban farming practitioners spent from four to five days per week in the garden after finishing work and during weekends. Furthermore, a study by Ramaloo et al. (2018) shows a lack of participation among young people in this practice because they considered community gardens as non-profit activities. It causes difficulty in managing such garden activities as weeding, watering, harvesting and replanting (Au Yong, personal interview, 1 May 2020). Moreover, finding a leader and farm theft are not major problems in this study, but are similar to the findings of Ober Allen et al. (2008) and Bradley and Galt (2014), where the implementation of community gardens in cities is less likely to support crime or vandalism. However, 23.6% of the respondents experienced this issue. The high-quality fences that were installed in the garden area (Yusof, personal interview, 12 March 2020) as well as the plants and machines that were used for farming activities were stolen in the night (Jamil, personal interview, 14 March 2020).

Environmental issues constitute one of the factors that can have a negative impact on farming activities and food supply. The data in Table 8 show that highly fluctuating weather is a challenge faced by 36.8% of the respondents in this study. A study by Alam et al. (2013) shows a decline in crop production in Malaysia because of the fluctuation of rainfall between –30.0% and +30.0%, which also leads to drought in many areas. Table 8 reveals that 48.1% of the respondents agree that lack of rain will reduce the water availability. According to Gornall et al. (2010), 80.0% of agriculture depends on rainwater. Thus, the poor rainfall pattern and the amount received in Lower Gweru and Lupane communal areas lead to poor production of crops, hunger, shortage of grazing and, finally, low animal productivity (Makuvaro et al. 2017). Moreover, warmer temperatures increase the plant stress, which require greater water input (Wortman, Lovell 2013). On the other hand, 37.7% of urban farmers agreed that flood disasters can damage the yield. It is shown in a study by Jega et al. (2018) that floods in Kelantan affected almost all the crops, livestock and some agricultural assets. Climate change also contributes to the increase of pests and diseases in the garden area, faced by 49.1% of the urban farming practitioners in this study. A previous study by Rahim (2014) shows that changes in rainfall pattern and increase in temperature will cause the quick spread of fungus and diseases, which affects the yield in the agriculture sector in Malaysia. Besides, another impact of the increasing number of pests is also the overuse of pesticides and reduction in biodiversity (Al-Amin and Siwar 2008).

Based on the correlation analysis results in Table 9, the value of the technical factor and race is 0.210, with a significance level of 0.05. It indicates there is a weak positive correlation between the variables. According to Carstens (2005), the Chinese have a better education than other races, which makes them more aware of the environment. This is because they have a long history of living in cities and are the first- or second-generation urban dwellers. Next, the value of the technical factor and education is 0.225, with a significance level of 0.05, which shows that there is a weak positive correlation. According to Singh et al. (2015), training can provide more information, knowledge and exposure of urban farmers to innovations related to agricultural activities.

The results in Table 9 also show that the value of the social factor and race is 0.201 at the significance level of 0.05, which shows that there is a weak positive relationship. The finding by Othman et al. (2019) shows that the Chinese have higher social motivations than the Malays and Indians in the context of urban farming. This is because the Chinese have higher physical and mental health motivation than Malays and Indians because they are predominantly employed as entrepreneurs and employees (Department of Statistics Malaysia, 2016). Table 9 also shows that there is a strong negative correlation between the environmental factor and age, with a value of –0.410 at the significance level of 0.01. According to Barthel and Isendahl (2013b), experience in farming is very important and it can be gained through years of practice. It means that young farmers have higher possibility of being vulnerable to the impact of climate change than older farmers because of a lack of experience in farming activities. This study also shows that monthly household income has a weak negative correlation between the economic factor (–0.223) and the environmental factor (–0.197) at the significance level of 0.05. This is because urban gardens require a large investment for operational cost, infrastructure, energy and management (Valk 2012). Besides, farmers also need a sufficient amount of money to overcome climate change. According to Makuvaro et al. (2017), farmers tend to apply fertiliser at higher rates than usual under high rainfall conditions and the number of pests will increase due to climate change. However, this study shows that most of the smallholder farmers are unable to purchase an adequate amount of commercial fertiliser because it is very expensive, and lack of capital causes a shortage of pesticides.

Conclusion

This study documented the challenges that urban farmers in Kuala Lumpur faced in managing their gardens in cities. In terms of the socio-demographic profile of the respondents, urban farmers are predominant among females. Most of the people involved in this urban garden practice are in the age group of 41–60 and have received tertiary education. Furthermore, most of the urban farmers in this study have from four to six people per house and have a household income of ≤RM 3,000. Prioritising challenges faced by urban farmers regarding urban gardens reveals that highly fluctuating weather, problems with access to available land and financial problems are at the top of the list. The main resource-related constraint faced by urban farmers was access to available land, while difficult access to financial institutions was the main economic constraint. Besides, in terms of social factors, the main challenge faced by urban farmers was a lack of commitment from the public due to many factors such as lack of time and lack of interest among young people. The increased number of pests due to highly fluctuating weather, which reduces the productivity and quality of crops was the main issue when it came to environmental factors. Meanwhile, the difficulty in getting training or technical support from the local authorities and NGOs and access to information online under technical factors were among the lowest priorities facing urban garden development. The technical factor has a weak positive correlation with race and the educational level. Besides, the social factor has a weak positive correlation with race, and there is a moderate negative correlation between the age and the environmental factor. There was also a weak negative correlation between household income-related economic factors and environmental factors.

Thus, the community should move towards urban farming—although it seems to be difficult to achieve with its limitations—which is crucial for urban farming to be sustainable. The government needs to publicise more about other alternative gardening practices, such as vertical farming and hydroponics. These alternatives can solve the problems related to contamination and lack of available land. On the other hand, the government and agencies should provide more financial resources to those who need economic help, which can allow them to buy inputs and cold storage to store their produce. The education and training about the choice of planting dates and other suitable crops, soil and water conservation, and regulating the amount of fertilisers should be enhanced to allow farmers to overcome the climate change problem. Besides, the government should plan and make policies specifically to overcome the challenges faced by urban farmers and also for the transformation of urban garden development, where the government should view this urban farming as a catalyst for supporting food security, achieving a better lifestyle for urban residents and the well-being of the natural environment. There is also a need to conduct further research more comprehensively to capture the actions that can be taken to create a policy-making space for urban farmers.

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ARTICLES FOR FACULTY MEMBERS

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Food access in crisis: Food security and COVID-19

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ABSTRACT

Disparities in food access and the resulting inequities in food security are persistent problems in cities across the United States. The nation's capital is no exception. The District of Columbia's 's geography of food insecurity reveals a history of uneven food access that has only been amplified by the vulnerability of food supply chains during the COVID-19 pandemic. This paper examines the history of food insecurity in Washington, D.C., and explores new opportunities presented by advances in urban agriculture. Innovations in food production can offer urban communities sustainable alternatives to food access that simultaneously address local food security and green infrastructure needs. They also bring persistent sociopolitical barriers into greater focus. The current COVID-19 pandemic and its imposed social isolation exacerbates these barriers, rendering conventional food access solutions inadequate to deliver on their well-intentioned aims. The ability to order groceries and home goods on mobile devices, for example, may seem fortuitous. Yet, it also exposes the deep disadvantages of marginalized populations and the isolating nature of structural racism. Contrary to the market-centered focus of traditional food access policies, such as public-private partnerships, this paper highlights community-centered strategies that help dismantle existing sociopolitical barriers in an age of crisis and help shift the food justice discourse from food access to the broader goal of community empowerment.

1. Introduction

Food access has never been more important. As the COVID-19 pandemic proliferates across the globe, identifying how to secure local access to the global supply chain of essential goods and services, such as food, water, and shelter, has come into sharp focus. Resolving the challenge of food access is imperative for two reasons: first, a lack of food can trigger deficiencies in critical nutrients and calories necessary to fight the onset of disease; and second, a surplus of nutrient-deficient food of poor quality can ignite health problems such as obesity, diabetes, and hypertension that can compromise immune systems. Accordingly, access to adequate supplies of nutrient-rich food is not only a social determinant of public health, but perhaps more important in an age of crisis, an indicator of vulnerable communities riddled with pre-existing health conditions and, consequently, a heightened risk of coronavirus infection.

In addition to raising concerns about pre-existing and food-related health conditions, the COVID-19 pandemic has exposed the vulnerability of global food supply chains. Government-imposed social distancing policies have impacted seasonal labor supplies to harvest crops. The virus has impacted the health of low-wage workers in meat processing plants and distribution centers. Workers at countless hand-off points along the food supply chain are exposed to infection risks. All this increases food security risks and amplifies public health dangers. Yet, food access is not simply a supply management issue; it is an expression of unresolved discriminatory practices embedded in culture and woven into local regulatory landscapes. In cities and metropolitan regions across the United States, full-service grocery stores are often conspicuously absent from low-income marginalized neighborhoods where black and brown populations constitute the majority of low-wage 'essential' workers who help secure fragile supply chains.

The current lack of food access in many black and brown low-income neighborhoods is not a recent development born of crisis, but an injustice that stems from a long history of governmental neglect. The United States is the world's largest food producer, exporting close to $73 billion worth of food annually, more than double that of the world's second-largest food exporter, Germany. Further, United States agriculture leads the world in market concentration with a food economy shaped by superstar agribusinesses and highly processed foods. Small Business Administration ("SBA") loans that favor fast food chains instead of small independent food vendors, and sugar subsidies that translate to high sugar snacks and beverages have cemented the lack of access to nutrient rich food alternatives in low income neighborhoods. As a result, food access remains uneven across socioeconomic and racial

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geographic lines.

As concerns about the fragility of food supply chains rise and worries about the pre-existing health conditions of low-income neighborhoods mount, the need for local food alternatives has become increasingly evident. To be sure, steady progress has been made. According to USDA data, local farmers markets have almost doubled in the last ten years. Notably, Washington D.C. boasts the largest number of farmers markets among cities nationwide (measured on a per 100,000 population basis), having grown from less than twenty to over fifty markets in recent years. Notwithstanding, the prices charged at local markets are often prohibitively expensive for low-income residents, undermining their transformative potential.

This paper traces the history of food access disparities in Washington, D.C., which remains a highly bifurcated city with significant income, health, and racial inequalities. Further, it describes more recent efforts to improve food access, including the urban agriculture initiatives of the University of the District of Columbia, the only public and land-grant university in the nation's capital. Despite some successes, food access policies in Washington, D.C. have struggled to overcome long-standing socioeconomic inequities, much less implement robust community-centered solutions. After examining the barriers to urban agriculture as a solution to food access disparities, this paper points toward innovations in urban food and agriculture policy that can help inspire a shift in food access discourse toward more sustainable and inclusive visions of food justice. The paper concludes by mapping the contours of alternative policy approaches that, we argue, are critical to addressing the long-standing food access problems of Washington D.C. and similarly situated cities across the United States. Not only will such policies help rebuild a food system whose growing disconnect from local residents has been laid bare by the current COVID-19 pandemic; even more, they will empower local communities to both shape and rebuild local food access across America.

2. Food Apartheid[1] – Entrenched Socio-Economic Disparities

Access to food in the capital of the United States is highly uneven. Of the approximately 520 businesses that self-identify as food retailers, 88% do not offer any fresh, unprocessed food, and only 12% offer an adequate variety of fresh food to support a healthy diet. These facets of D.C.'s geography of food access underscore a well-known phenomenon called *Food Desert* neighborhoods. The United States Department of Agriculture United States Dep. of Agri, 2016 ("USDA") defines Food Deserts as "urban neighborhoods and rural towns without ready access to fresh, healthy, and affordable food" (Urban Farming Land Lease Amendment Act of 2020, 2020). Eight census tracts in Washington D.C. qualify as Food Desert, or Food Apartheid neighborhoods. All are located east of the Anacostia River, which has long constituted a demarcation of D.C. neighborhoods along socio-economic and racial lines.

Administratively, Washington, D.C. is divided into eight Wards, each with approximately 80,000 residents. Wards 2 and 3 (and sections of Ward 4) encompass the northwest quadrant of the district, while Wards 7 and 8 (and sections of Wards 5 and 6) are located east of the Anacostia River. Population density varies between the eight Wards. Ward 1, which comprises the downtown area of Washington D.C., has both the highest population density and the smallest geographic area. Conversely, Wards 3 and 5 contain both the largest geographic areas and the lowest population densities. Since 2010, the population of Washington, D.C. has increased at an average rate of 2.2% per year. This renewed growth followed decades of population decline upon the heels of the historic civil rights protests of the late 1960s and the white flight to the suburbs that followed it. The recent population increase is consistent with national data revealing a steady trend toward urbanization and a reversal of the urban population declines of previous decades (O'Hara, 2018).

Economic trends have generally been positive for Washington, D.C. The median household income has increased by almost 20% over the past 25 years, which compares favorably to the slight decrease in national household income during that same time period. However, poverty rates have not followed the same positive trend. Indeed, the rate of poverty has remained at 18%, or 4% above the national average (US Census). This poverty persists, notwithstanding a considerable drop in the district's unemployment rate from 12 to 6% between 2000 and 2008. The persistently high poverty rates in Washington DC can be traced to the stark socio-economic disparities among its eight wards. For example, Wards 2 and 3 in the northwest quadrant of the city record the lowest unemployment rates, while Wards 7 and 8 in the southeast quadrant boast five times the unemployment rate of Wards 2 and 3. Household income has shown similar disparities with median household income in Wards 2 and 3 at roughly five times that of Wards 7 and 8 (Table 1; see also O'Hara, 2018).

These socio-economic disparities follow distinct racial lines. Wards 7 and 8 are home to the highest percentage of non-Hispanic black residents, and also report the highest percentage of female-headed single-parent households. Further, while approximately 24 and 30% of the predominantly black populations in Wards 7 and 8, respectively, are under the age of 18, the highest percentage of residents over the age of 65 live in Ward 3, where 78% of the population report as white. The fastest growing demographic, particularly in Ward 4, are Hispanics who also make up the largest percentage of foreign-born residents (Table 2; see also O'Hara, 2018).

Food access reveals a similar socio-economic divide. Ward 3 in the city's northwest quadrant reports the smallest percentage of non-Hispanic black residents across all Wards and has the highest number of full-service grocery stores per 1000 residents. Conversely, Ward 7 – reporting the highest percentage of non-Hispanic black residents – has the lowest number of full-service grocery stores per 1000 residents. Fig. 1 highlights the location of full-service grocery stores across Washington, D.C., with each dot indicating a store location (O'Hara, 2017). As the map illustrates, Washington, D.C.'s Food Apartheid neighborhoods are concentrated in Wards with the lowest percentage of white residents. These neighborhoods are home to 36% of the city's population yet house less than 10% of its full-service grocery stores.

Not surprisingly, food insecurity and food-related health problems are prevalent in the food apartheid neighborhoods of Washington, D.C. The Department of Agriculture defines food security as "access by all people at all times to enough nutritious food for an active, healthy life." (USDA, 2014). Low food security refers to a diet defined by reduced quality, limited variety, and low desirability. Food insecurity is driven by two factors: (1) an inadequate supply of food all or some of the time; and (2) a food supply with insufficient nutritional quality to sustain a healthy and active lifestyle.

In many neighborhoods across Washington, D.C., residents are considered food insecure by both measures. While some households do not have access to adequate food supplies, others lack access to nutrient-rich food options. According to a survey tracking food security in the nation's capital, 13% of households are food insecure and struggle with hunger, 19% of households experience food hardship and do not have enough food at least some of the time, and 37% of households with children struggle with food insecurity (USDA, 2012; O'Hara, 2015, 2017). Among the myriad damaging effects of food insecurity upon the lives of children are impaired cognitive development, reduced school readiness, lowered educational attainment, slower physical, mental, and social development, and overall health deficits (Cook et al. 2006).

At the other end of the spectrum, a lack of nutrient-rich food often triggers obesity, considered a lead indicator of food-related health problems. Beyond its own health effects, obesity is closely related to conditions like diabetes and heart disease. To be sure, this is a national problem. The national obesity rate in the United States is 36%, and 69%

[1] We use the term food apartheid to avoid the negative association with desert environments conveyed by the term food desert.

Table 1
Income and Unemployment by Ward.

Socio-Econ. Info.	Ward 1	Ward 2	Ward 3	Ward 4	Ward 5	Ward 6	Ward 7	Ward 8
Household Income	$113,972	$209,147	$257,224	$123,353	$82,425	$140,853	$56,759	$45,239
Unemployment	5.1%	3.8%	3.7%	9.8%	14%	6.2%	19%	22%

Table 2
Demographics of Washington, D.C. by Ward.

Demographics	Ward 1	Ward 2	Ward 3	Ward 4	Ward 5	Ward 6	Ward 7	Ward 8
Total population	82,859	77,645	83,152	83,066	82,049	84,290	73,290	81,133
Children under 18	12%	5%	13%	20%	17%	14%	24%	30%
People over 65	2%	6%	13%	3%	2%	3.3%	0.3%	0.2%
Single Parent Female Headed Households	10%	3.8%	4%	19%	22%	11%	33%	39%
Black (non-Hispanic)	33%	10%	6%	59%	77%	43%	95%	94%
White (non-Hispanic)	40%	70%	78%	20%	15%	47%	2%	3%
Hispanic	21%	9%	8%	19%	6%	5%	2%	2%
Asian	5%	10%	8%	2%	2%	5%	0.3%	0.5%

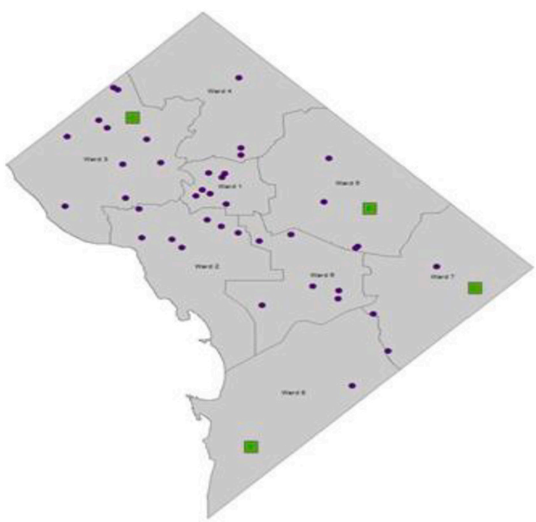

Fig. 1. Full Service Grocery Stores in Washington, D.C.

of the U.S. population are either overweight or obese. Yet, while average obesity rates for Washington, D.C. compare favorably to the national rate at 25%, four of D.C.'s eight Wards have obesity rates above the national average. Ward 8, which consists of 94% non-Hispanic black residents, reports the highest rate of obesity at 45%.

Overall diabetes rates in Washington D.C. are 2% higher than the national average, yet the rates across Wards follow the established racial divide. Ward 3 has the lowest rate of diabetes, and Ward 8 has the highest (Fig. 2; see O'Hara, 2018). Diabetes related deaths follow similar patterns. Death rates from diabetes in Wards 5, 7 and 8 (which contain the highest percentages of non-Hispanic black residents across all wards) are seven times higher than the rate in Ward 2 (70% non-Hispanic white), and 5 times higher than the rate in Ward 3 (78% non-Hispanic white) (Table 3).

Other health indicators mirror the same socio-economic disparities and racial divides. For example, while life expectancy in D.C. has improved substantially over the past 25 years, and D.C. residents have gained an average of 10 years to their lifespans, disparities between Wards persist. Ward 8 has a life expectancy of 70 years (94% non-Hispanic black) while the life expectancy in Ward 2 is 86 years (70% non-Hispanic white). Put another way, some non-Hispanic white residents in D.C. can expect to live 16 years longer than their non-Hispanic black peers in neighboring wards. Similar disparities are evident for maternal and infant health. At 7.6% infant deaths per 1000 live births, D.C.'s infant mortality is higher than the national average of 6.1%, and more than three times the rates of Finland (2.2%), Japan (2.3%) Sweden (2.4%) and many other Asian and European countries (Table 3; Xu et al. 2012; Woolf and Aron 2013; Sasson 2016; Aries and Xu 2019).

These statistics tell a compelling story of the close correlation between socio-economic status and preventable food-related illness. Even more, the demographic characteristics of the District of Columbia reveal the racial dimensions of this story and, thus, remnants of America's vicious legacy of racial injustice that have endured (Babey et al., 2008) Despite repeated efforts to address food access in the nation's capital through economic stimulus and regulatory policies, deep disparities remain.

3. Food Access in Washington, D.C. – A Brief History

The history of food access in Washington, D.C. is nuanced. In the early twentieth century, the city was home to a network of small grocery stores and an informal cottage industry of food carts called "hucksters" that sold produce, fish, and meat from door to door. Food choices offered by these local small businesses were tailored to the cultural and ethnic characteristics of the diverse, albeit segregated, neighborhoods of D.C. (Reese, 2019; Bockman 2016). In many ways, food access in Washington, D.C. prior to the Civil Rights Movement was born of necessity, characterized by a rich network of decentralized small businesses that served the diverse needs of black and brown neighborhoods divided by an ideology of racial segregation and white supremacy.

Indeed, the District's cottage industry "hucksters" and mom-and-pop stores often served their clientele from their own homes. Many of these food vendors experienced similar discriminatory treatment as their black and brown clients. For example, small grocery stores were often owned by Jewish and Asian families who experienced their share of discrimination. However, the goods and services they provided went well beyond food access. Food vendors were also knowledgeable about the cultural and ethnic characteristics of their clients, and many vendors extended credit to customers in need of temporary assistance (Reese, 2019). Thus, these small food businesses captured more than simply the monetary value of food. Their community-centered approach gave expression to a marketplace characterized by qualitatively differentiated products, services, cultures, and contexts, coupled with localized financial services to meet the credit needs of local populations (O'Hara, 2001, 1996).

The network of D.C.'s small stores and food carts was supported by cooperatives that consolidated purchasing power and community capital, facilitating a degree of economic autonomy, self-determination,

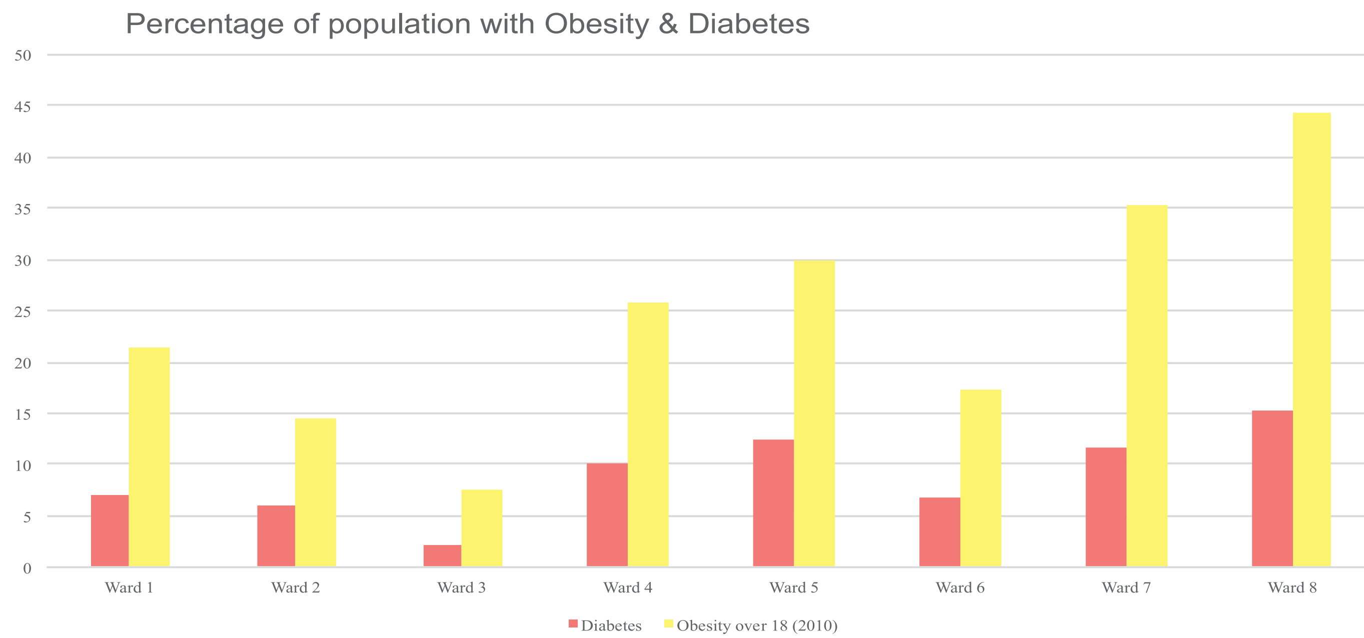

Fig. 2. Food Related Illness of Adults in Washington, D.C.

and collective upward mobility (Bockman 2016). Cooperative economics was leveraged as a tool to respond to the widespread racial and class oppression that excluded large segments of the population from the promises of democracy. By consolidating local food markets and pooling community capital, cooperatives forged a pathway to economic uplift. The cooperative business model thus made entrepreneurial endeavors possible for marginalized populations, ambitions that would otherwise have proven more difficult under the forces of racism and capitalism that persist even today.

One example of cooperative economics in action was the District Grocery Store ("DGS") cooperative which launched in 1921. DGS leveraged combined resources to maintain profitability and competitiveness. At its peak, DGS consisted of 300 member-grocery stores that served neighborhoods all over the District. However, in the wake of the 1968 race riots across the U.S., food access in D.C. changed. A trend of outmigration by white residents to the suburbs that began in the 1950s accelerated dramatically. Most of the DGS stores closed in the seventies and early eighties as supermarkets moved into affluent D.C. neighborhoods, offering an array of products that made it close to impossible for small stores to compete. The result was a rapid loss of purchasing power and jobs, followed by a steady divestment of food businesses, especially in neighborhoods east of the Anacostia River (Crowe et al. 2018; Jones, 1972).

As D.C. abandoned its decentralized small-scale food networks, the loss of face-to-face communication and the dismantling of strong ties of trust between community members resulted in various modes of disempowerment. Alongside a loss of food access, many black and brown D.C. residents lost the diverse expressions of cultural value and the financial support of localized sharing economies (Hossein). At the same time, the prominence of full-service grocery stores, better known as super-market chains, grew. These new super-sized grocery stores and their corporate hubs were designed to facilitate a more efficient, centralized system of food access. Instead, they perpetuated inequality in food access by serving predominantly higher-income white suburbs, while low-income black and brown neighborhoods in the urban core were neglected. The bias against urban marginalized neighborhoods was further exacerbated by marketing studies that associated *suburban* with middle class and civically engaged white citizens, and *urban* with low-income and drug-addicted black citizens (Pawasarat and Quinn 2001, Reese, 2019, Bell and Standish 2009). These biases, which embodied America's vicious legacy of white supremacy, have shaped political discourse concerning food delivery in D.C. for decades. As full-service grocery stores became the only remaining food access points in communities across the United States, the modern food apartheid neighborhood emerged along racial and socio-economic lines.

Despite D.C.'s racialized history of dismantling localized food access networks, modern efforts to address the persistence of food apartheid neighborhoods has focused largely on attracting new supermarkets to areas that lack them. This strategy ignores the business models that successfully served moderate to low-income communities in the past (Bell, 2010). There is also limited evidence that supermarkets are effective in reducing food-related illness (Cummins and Macintyre 2006, Cummins et al. 2014). Even more, many supermarkets lack involvement from neighboring residents and are inattentive to their neighbor's diverse food cultures and specific food access needs (Evans et al. 2015, O'Hara, 2018). Like many U.S. cities, studies of the District of Columbia indicate that the addition of full-service grocery stores during the past 20 years has ostensibly been driven by economic factors. Close to 40 grocery stores opened during that timeframe, yet none of them are located in the food apartheid neighborhoods of Ward 7 and 8 (D.C. Food Policy Council 2019). As noted above, these Wards house the largest percentage of non-Hispanic black residents across the district.

Some argue that profit margins for grocery stores in low-income neighborhoods are notoriously slim and therefore unable to absorb the

Table 3
Health indicators of Washington, D.C. by Ward.

Health Indicators	Ward 1	Ward 2	Ward 3	Ward 4	Ward 5	Ward 6	Ward 7	Ward 8
Life expectancy	78 yrs.	86 yrs.	85 yrs.	78 yrs.	75 yrs.	77 yrs.	73 yrs.	70 yrs.
Infant mortality	4	3	5	11	10	10	7	10
Diabetes deaths	3	3	4	15	21	12	21	20

hazards of doing business in high-risk neighborhoods. This is despite evidence that purchasing power in low-income neighborhoods is often underestimated (Bell, 2010; O'Hara, 2001). Yet, such arguments merely suggest that, despite the perceived benefits of full-service grocery stores, a broader community-centered strategy is needed to revive the many connections between local food systems and social sustainability, lifestyle choices, technology, land-use options, and more. The value of these social and environmental metrics exceed the market value of food itself and are not captured in the present-day centralized and increasingly digital food marketplace (O'Hara, 2020).

4. Disembedding Food

The dismantling of Washington, D.C.'s decentralized network of small grocery stores and local hucksters is but one expression of a larger trend – the continued disembedding of economic activity and the associated loss of power suffered by local communities, especially in urban America and the global south. As grocery stores have grown larger and food systems have become increasingly centralized, consumerism has risen throughout the body politic. Like the supermarkets that replaced small mom-and-pop grocery stores, retail moved to the suburbs in the form of massive shopping malls. Victor Gruen, the architect credited with inventing the shopping mall, had a benevolent vision of the mall as a social focal point in the artificial, community-deprived environment of American suburbia. Malls were intended to provide a meeting place to foster social solidarity, with shopping options unencumbered by the mood swings of nature due to the mall's heated and air-conditioned indoor environment that protected shoppers from the elements. The message to American consumers was clear: shop until you drop! The economy depends upon you!

Some malls did become places for teenagers to meet and senior citizens to walk. Yet, the culture of malls never evolved into the organic communal spaces that Gruen envisioned. In fact, he ultimately considered them a failure. This failure, however, appears mild in light of the evolving sociology of the virtual marketplace. Sandburn writes, "But for all its flaws, the mall did manage to bring people together in ways that, in the era of personal devices, even Gruen might appreciate." (2017). The advent of virtuality has led to even greater social isolation and a growing disconnect between our daily lives and the social/cultural and physical/environmental context that sustains our interactions. Shopping in malls and supermarkets has given way to the computer screen and mobile devices. Amazon, the most prominent example of the rapidly unfolding virtual marketplace, went from $89 billion in sales and a net loss of $241 million to $232 billion in sales and a net income of almost $10 billion in just five years.

The boon of digital technology may appear fortuitous amidst the imposed social isolation of the COVID-19 pandemic. From ordering groceries on mobile devices to browsing home goods on e-commerce platforms to logging into zoom chats for remote workplace functioning, the virtual marketplace feels like a lifeline to an economy drowning under the weight of the coronavirus. Yet, the amplification of social isolation is but one aspect of the new virtual economy; labor implications are another. As one third of U.S. malls closed their doors over the past two decades, 450,000 jobs were eliminated, and only half of them have been replaced by jobs in the virtual economy. Additionally, these new jobs are not only fewer, but different. Services traditionally performed in-house have been outsourced to contracting firms and freelancers. Many job functions, including clerical, financial, procurement, and logistics services, can be provided on-line from almost anywhere (Autor et al. 2017).

As a result, a growing segment of the new labor force works in low-wage jobs without traditional benefits, while their new workplace is rife with safety risks. At Amazon, for example, the pressure to fill orders and meet efficiency goals runs up against the physical limits of workers who need rest and care (Atlantic 2019); and while the physical, mental, and emotional needs of workers go unmet in their new virtual workplaces, their labor is being supplanted by robots. Amazon prides itself on improving its safety record through an increased reliance on robotics, rather than an increased respect for the regenerative and restorative needs of its workers.

The net result has been not only the erosion of work, but also the crippling of social support systems designed to absorb the everyday pressures associated with working two and three jobs to make ends meet, much less struggling to navigate a battered benefit system (O'Hara, 1997, 1998, 1999, 2004). Feminist scholars have long called attention to systemic biases against biological and ecological functions associated with the fluctuating cycles of the female body (Price and Shildrick 1999; Griffin). Yet, the continued de-contextualization of work in the virtual economy now renders even the less cyclical male body as unreliable, replacing the once heralded patriarch with the time- and biologically-independent mechanical and digital automaton.

The costs of the externalities associated with the growing virtual marketplace have never been more visible than during the current COVID-19 pandemic. The long supply chains that characterize the industrial scale, centralized U.S. food system have been rendered highly vulnerable to disruption. Workers in meat packing plants and distribution centers are burdened with low wages yet face some of the highest exposure risks to the coronavirus. Indeed, fatality rates in some of the meat packing plants in small-town America are higher than those in the densely populated inner-city neighborhoods of New York City (CDC, 2020). With many restaurants and hotels now closed due to the COVID-19 pandemic, millions of hospitality sector jobs have vanished, and food banks around the country are struggling to meet the demand of hungry Americans seeking help. Yet, part and parcel of the supply disruption, food has gone to waste on farms and along other segments of the distribution chain. These realities lay bare the dehumanizing effects of virtual markets. Even more, they hide the deep material disadvantage of marginalized populations who provide the very foundation for the virtual marketplace by putting their physical bodies on the line as so-called 'essential' workers (Van Dorn, 2020).

These insights add a new dimension to the well-established depletion of biophysical systems necessary for the sustained growth of an increasingly virtual economy (O'Hara, 2020; Rees, 2020). The around-the-clock and around-the-globe access it demands relies not only on enormous amounts of biophysical energy to feed the computer servers that store supply chain data, such as on-demand orders and customer demographics; it also demands an around-the-clock and around-the-globe supply of low-priced labor to stock supply chains and distribution centers. The new reality of COVID-19 exacerbates the isolating nature of poverty and structural racism that has rendered countless distressed neighborhoods as Food Apartheid communities. At the same time, virtual superstar firms like Amazon and Facebook have yet to resolve the historic dematerialization of socio-economic life in low-income black and brown communities across the United States (a Massey and Denton, 1993; Squires and Kubrin, 2006). This emerging paradigm calls for new solutions and new policies that do more than simply attract supermarkets and big box stores to poor marginalized neighborhoods. It calls for a community-centered and grassroots movement for food justice, along with the policies to support it.

Food justice activities have long exposed the layered connections between our globalized food ecosystem and its complex geopolitical network of production, distribution, and consumption (Shiva, 1991; Altieri, 2009; Bell, 2010; Alkon and Agyeman, 2011). The concentration of disadvantage in black and brown urban ghettos across the U.S. not only reflects America's legacy of white supremacy and enchantment with capitalist logic (Reese 2019); it underscores the social determinants of health inequity that explain why black Americans represent the highest percentage of deaths from COVID-19 with 88 deaths per 100,000 compared to 54 deaths per 100,000 among Latino populations and 40 deaths per 100,000 among whites (Gallagher, 2006; Babey et al., 2008; McClintock, 2011; Benfer, 2015). Food insecurity thus emerges as both a cause and symptom of COVID-19 and its swelling death toll, lending renewed urgency to the call of food justice activists for decentralized, localized, and culturally resonant food systems (Perfecto et al., 2009; Mares and Alkon, 2011).

As the economist Nicolai Georgescu-Roegen argued decades ago, what matters is not merely the flow of inputs, outputs, and waste associated with the production and consumption of goods and services, but also the very process of their conversion (Georgescu-Roegen 1984; see also Daly, 1996 Daly, 1996, Gowdy and O'Hara, 1997, O'Hara, 2016). There is no sustainable rate at which non-renewables can be processed; there is no sustainable rate of substitution without material and energy consequences; and there is no substitution for time-dependent processes of reproduction and restoration without personal, social, and environmental costs. All conversion processes utilize energy, create entropy, and deplete energy funds, regardless of the material flows involved. Accordingly, attention must be aimed at resolving: (1) what conversion and distribution processes minimize energy use, and thus, minimize entropy creation; (2) what conversion and distribution processes place the least amount of pressure on the absorptive, buffering, and regulating capacities of the ecosphere of local communities; and (3) what conversion and distribution processes preserve the resilient knowledge of marginalized communities and their cultural roots (O'Hara, 1996, 1999, 2016, 2000). Women, the poor, black and brown people, and people living in the global south have always carried a disproportionate share of the burden of overused and undervalued physical, social, human, and environmental capital (O'Hara, 2010, 1997, 2014; Mellor 2002). A "radical reconstruction of society," as Dr. Martin L. King, Jr. urged, requires new policies that call into question default solutions with an eye toward leveling the playing field.

5. Rethinking Food Access – The Role of Urban Agriculture

Following the demise of the DGS cooperatives, Washington, D.C. saw its first legislative efforts to address eroding food access in Wards east of the Anacostia River. In 1986, D.C. Council Chairman, David A. Clarke, introduced The Food Production and Urban Gardens Program Act of 1986. The Act required that "…the Mayor establish a Food Production and Urban Gardens Program, which would include maintenance of an inventory of vacant city lots, development and promotion of policies to encourage the donation and cultivation of vacant lots for use in the Food Production and Urban Gardens program, the encouragement of food buying clubs and produce markets in the District, and the creation of incentives and outreach to promote the availability of such vacant lots."

As a result of the legislation, the District implemented "the University of the District of Columbia's provision of technical assistance for gardening and food production efforts and coordination with the Office of the State Superintendent of Education on using buildings and grounds for urban gardens and creating instruction regarding science and gardening to prepare students for related careers." Despite these early efforts, disparities in food access across Washington, D.C. did not improve. In 2010, the Board of Trustee of the University of the District of Columbia created its newest college, the College of Agriculture, Urban Sustainability and Environmental Sciences ("CAUSES"). CAUSES reasserted the land-grant mission of the University and sought to focus attention on research and practical skills to address the capacity-building needs of Washington, D.C., especially related to food systems and green infrastructure. The mission of CAUSES speaks to this commitment, offering "…research-based academic and community-outreach programs that improve the quality of life and economic opportunity for people and communities in Washington, D.C., the nation, and the world."

To support local food initiatives and their capacity-building linkages to green infrastructure and health, CAUSES launched its Urban Food Hubs initiative in 2013 (O'Hara, 2015, 2017). According to the USDA, "Food Hubs" represent an effort to scale small and local food businesses by pooling resources to reduce costs and aggregate production, distribution, and marketing services (USDA 2016, Barham et al. 2012). The CAUSES model expands the USDA definition beyond the core concept of small-scale food production and food processing operations by incorporating "food distribution" and "closing the loop through waste and water management" as the core components of its Urban Food Hubs model. All four components – (1) production, (2) processing, (3) distribution, and (4) waste & water management – constitute a unique model that furthers the CAUSES mission of improving the quality of life and economic opportunities of D.C. residents, and marginalized peoples more generally.

While all UDC food hubs integrate the four components of the CAUSES model, the specific characteristics of each Food Hub vary based on the physical, environmental, social, and cultural context stemming from the community where it is located. Four UDC food hubs are currently in various stages of implementation in Wards 5, 7 and 8, with the Ward 3 Urban Food Hub serving as a demonstration and training site on the main campus of the University. A fifth one is located at a public charter school in Ward 7. The locations of the food hubs are indicated as green squares in Fig. 1. The adaptive approach of the CAUSES Urban Food Hubs model has allowed it to incorporate community goals, context conditions, and resources that are unique to the location of each hub.

At the same time, the UDC model bridges other critical sectors. The cutting-edge technology applied in the soil-less hydroponic and aquaponic systems, for example, links food production to water and energy-saving technology by utilizing a unique aerator that is based on molecular spin rather than compressor systems. The food processing component links the model to the hospitality and food retail sectors, while nutrition education through recipe sheets and cooking classes seek to reduce food-related health problems by changing eating habits through culturally appropriate diets. The waste and water management component of the model links to a host of green infrastructure and green building sector initiatives, from mitigating flooding by reducing storm water runoff and increasing permeable surfaces, to mitigating heat island effects by growing food on green roofs, improving soil health through composting, and generating energy from organic waste through bio-digesters. Taken together, the four components of the UDC Urban Food Hubs model demonstrates that food systems are complex and can contribute multiple social and environmental benefits when they are decentralized and adaptive to specific social and environmental context conditions.

All four components of the UDC Urban Food Hubs model offer opportunities for training, job creation, and local business development. (1) Food production can take place on rooftops, in raised beds, in hydroponics and aquaponics systems, on parking lots, in small greenhouses and in decommissioned factory buildings. (2) Food processing education can engage diverse methods, from cooking classes, to catering, to hot sauce, pesto and smoothie production launched in incubator kitchens and food trucks. (3) Food distribution can draw on a range of models from farmers markets to direct marketing contracts with local restaurants and food stores (especially ethnic markets), and community-supported agriculture networks that supply weekly deliveries of fresh food, rather than selling by the pound. (4) The waste-and–water management component of the Food Hubs model engages an array of activities, from composting food waste and selling the compost for soil enhancement, to water capture and reuse, to energy generation through bio-digesters. All offer opportunities for creating jobs, launching green innovations, and turning negative environmental and public health impacts into positive outcomes that empower marginalized neighborhoods.

The wide-reaching ambition and radical vision of the UDC Urban Food Hubs model is guided by an important ethic – upfront investment is needed to build the capacity necessary to ensure future success. In the case of the UDC urban food hubs, funding to build the Hubs came from private and public sector grants, in addition to the University's own resources. In his recent book, *Food Town USA*, Mark Winne (2019) documents the ability of local food economies to become the motor that revitalizes communities across the United States. These local food economies challenge the standard view of economic development, which assumes that external demand is the primary driver of the production of goods and services. However, demand that is internal to a region can play an equally important role in fueling local economies. In fact, considerable benefits can accrue when residents and businesses are incentivized to spend their money at home rather than leaving the region. Further, when necessities are produced within a region, residents are not forced to rely upon complex supply chains to ensure their subsistence. As money is recycled within a community, a multiplier effect ensues, turning every dollar spent locally into more than a dollar's worth of economic benefits. The reduced need for transportation associated with local food networks also has positive environmental impacts, including reduced energy use and a smaller carbon footprint.

Beyond their commercial potential and infrastructure benefits, the UDC urban food hubs also help dismantle the isolating effects of food apartheid neighborhoods. Each food hub location features a community garden where residents can obtain a small plot of land to plant fresh food at no cost. Free gardening classes and cooking demonstrations reintroduce lost skills and yield positive effects. Growing even a small plot of vegetables has been shown to supplement income, catalyze healthier eating habits, and stimulate multi-layered benefits that can empower cash-poor households with limited family networks and personal assets to navigate times of crisis. The cheap and highly processed food produced in highly-centralized industrial-scale farms are therefore exposed as not cheap at all; rather, they may come at the expense of social stability, human health, and ecosystem resilience.

While the comprehensive, circular design of the UDC Urban Food Hubs model may be new, small-scale urban agriculture is not. In the decades following the Civil War, formerly enslaved black Americans acquired land to provide for themselves and their communities (Daniel, 2013). Despite the obstacles they faced, they numbered 14% of the overall U.S. farming population by the 1920s (). Washington D.C., Philadelphia, and Detroit had especially active black farming communities that provided food access to farm families and consumers, often in close proximity to urban areas. Similarly, in Germany, Holland, Austria, Switzerland, and several other European countries, small garden plots provided food, outdoor space, and sometimes housing to low-income families during times of rapid urbanization and industrialization in the 19th century. These small gardens served as buffers against food insecurity through social upheavals. Even today, almost 1 million garden colonies remain at the outskirts of German cities (Bund Deutscher Kleingaerten, 2020BDG, 2020). In contrast, 95% of the small farms established by black Americans disappeared between 1920 and 1990, chiefly due to racially biased lending practices and discriminatory policies that excluded small farms from the efficiency increases enjoyed by their large counterparts (Willingham 2019). Recreating a small-scale, decentralized, and resilient food systems in the U.S. context will require not only creative designs that wrestle with modern socioeconomic barriers, but also financing to support its implementation.

6. The struggle for food access policies

A resilient local food system has the potential to reduce vulnerability to natural and social disasters. The Washington, D.C. Food Production and Urban Gardens Program Act of 1986 ("1986 Urban Gardens Program Act"), and its associated food buying clubs and produce markets, sought to achieve this goal by supporting localized food access programs especially east of the Anacostia River. However, the implementation of the 1986 Urban Gardens Program Act has made limited progress in the three and a half decades since its passage.

The Supermarket Tax Exemption Act of 2000 ("STEA"Supermarket Tax Exemption Act of 2000) and the Food, Environmental, and Economic Development in the District of Columbia Act of 2010 ("2010 FEED-DC Act") sought to advance matters with tax-based incentives to encourage the market to drive new supermarkets into Washington, D.C.'s food apartheid neighborhoods. However, while twenty-two grocery stores have qualified for tax exemptions under the STEA between 2000 and 2015, "…only two of these supermarkets located in the highest need areas east of the Anacostia River – and one of the two closed shortly after opening." (Lieber 2019). The 2010 FEED-DC Act sought to correct this record by (1) improving access to healthy foods in low-income neighborhoods; (2) encouraging green technology; and (3) creating good jobs in areas with high levels of unemployment.

Four years later, the D.C. Council passed the Urban Farming and Food Security Act of 2014 ("2014 Urban Farming Act 2014") in response to the "lack of food options, vacant properties, and blight in [the] communities." Specifically, the legislation sought to "build on the legacy of the Food Production and Urban Gardens Program Act of 1986" by recognizing that "despite the Act being part of the District's laws for the past 30 years…the Food Production and Urban Gardens program was never implemented." (Urban Farming Land Lease Act of 2019). The 2014 Urban Farming Act went into effect in March of 2015, establishing an urban farm land-leasing initiative for district-owned land. Additionally, it specified criteria for applicants to participate in the urban farming initiative and carved out a tax exemption for privately-owned land used for agricultural purposes under certain conditions.

Also, in 2014, the D.C. Council introduced the Food Policy Council and Director Establishment Act ("Food Policy Council Act"). The Food Policy Council Act created a 13-member "coalition of food leaders and government staff appointed by the Mayor to promote a more equitable, healthy, and sustainable food system in the District." Further, the council established a goal to ensure D.C. residents have access to "reliable, affordable, nutritious food near their residence." he Act was adopted subject to budget appropriations and, like its predecessors, has not been fully implemented.

The most recent legislation, the Urban Farming Land Lease Amendment Act of 2019 ("2019 D.C. Urban Farming Act"), which took effect in November of 2019, followed a series of amendments to the 1986 Urban Garden Program Act seeking to finally implement the late city council chairman David Clarke's urban farming initiative (Urban Farimg Land Lease Act of 2020). Specifically, it seeks to clarify the land-leasing program under the 2014 Urban Farming Act, and define the conditions under which the District may enter into a lease with a qualified applicant to create and maintain an urban farm on vacant land. It also seeks to address liability concerns about potentially contaminated soils by authorizing the Department of Energy and Environment to waive soil testing requirements for a lessee who agrees to grow produce in raised beds, greenhouses, or hydroponically, with related amendments for rooftop and indoor farming.

The long line of amendments to D.C.'s urban farming legislation illustrates that even progressive strategies geared toward food sovereignty – placing greater control of globalized food systems into the hands of marginalized community members – can be distorted. Chief among such distortions is the market logic of neoliberalism that ultimately subverts the well-intended aims of food policies (Alkon, 2014; Holt-Giménez and Shattuck, 2011; Figueroa and Alkon, 2018; Harris, 2009). Indeed, the market-based design of Washington, D.C.'s urban farming program conveys at least three interconnected, yet discrete aspects of neoliberal rationality that have invaded, and continue to overwhelm the District's food justice discourse.

First, the language of the 2019 D.C. Urban Farming Act reflects an *ethic of American exceptionalism,* which sustains false hope in the meritocratic ideals of the American Dream and its rhetoric of self-determination without systemic reform. This ethic belies the structural barriers that hinder social progress for marginalized citizens and low-income communities (Lefebvre, 2002; Figueroa, 2015; Silver, 2019). Notions of equality before the law, and liberty within the free market, support the supposed fairness of an urban farming program designed as a "land lease" for "a base period of 5 years… not to exceed 14 years" to an eligible applicant with "experience in agricultural production." The program does not include any preferences for low-income farmers, places no restrictions on where or to whom the produce is sold, and does not identify a need for education and training to equip residents of distressed neighborhoods with the food production, processing, and distribution skills or business acumen necessary to compete in the urban food systems arena.

Second, by establishing a private marketplace for the creation of urban farms via tax-based incentives, the 2019 D.C. Urban Farming Act reflects the *privatization of public goods*. In so doing, it undermines the public welfare role of the government sector and cements long-standing wealth gaps while discounting the many non-market factors that disadvantage distressed communities (Toussaint, 2018). Eligible participants who win a competitive bidding process are rewarded with exemptions "from real property taxation and possessory interest taxation," enabling savvy and well-funded entrepreneurs to reap financial benefits from the usage of public land near poor neighborhoods. Even more, by framing ideals of public interest in the language of a laissez-faire economic marketplace, the program degrades longstanding civic norms of democratic citizenship, reducing residents from democratic co-creators in the public decision-making process to individualistic consumers in a competitive marketplace (Greenwood, 2005).

Third, provisions in the 2019 D.C. Urban Farming Act that seek to limit governmental liability for the environmental risks associated with urban farming reflect a *delegation of public accountability*, made more problematic by historic land contamination in many low-income neighborhoods nationwide linked to inequitable zoning policies (Agyeman 2016; Tabuchi et al.). The law clarifies, in relevant part, that nothing "shall be construed to create governmental liability … related to the safety of food produced on land leased from the District." It also waives soil testing requirements for farmers that capitalize on food production methods that do not require the usage of potentially contaminated soils – e.g., raised beds, hydroponics and aquaponics, vertical agriculture, and green roof production. Not only will the low-income residents of distressed neighborhoods struggle to garner the high startup costs of such farming techniques (USDA 2016), they will likely remain exposed to the risk of contamination from unanticipated events not contemplated by the law, such as flooding, erosion, or pest infestations after vacant lots have been repurposed for urban farming (Vogel 2019).

Taken together, the politics of neoliberal rationality evident in the 2019 D.C. Urban Farming Act have fashioned a distortion effect that masks discriminatory systems with entrepreneurial opportunity. This impact obscures the concentration of disadvantage with a delegation of public accountability that perpetuates a toxic narrative of poverty through the rhetoric of self-determination. Under this approach, food justice is in danger of becoming yet another ploy for the private market to profit from poverty (Shelby, 2021), while marginalized citizens remain vulnerable in the face of crises like the COVID-19 pandemic. These same forces confront the full implementation of the UDC Urban Food Hubs model, which is associated with time consuming efforts of training for local residents, shared ownership models that bring uncertainty with navigating land conditions, and complex communal objectives that go far beyond individual profit or utility-based models.

What is needed then is a new course between the corporatized food system and neoliberal food justice strategies that espouse the rationality of private markets on the one hand, and the dichotomy of a centralized public sector food system that stifles empowerment and initiative in marginalized communities on the other. As Corrine Blalock suggests, neoliberalism has not only influenced the debate about food justice, but has more generally fostered a notion of community development that relies upon "the creation of stable and well-protected property rights, enforcement of private contracts, and limitation of the arbitrary exercise of government power—enabling a particular ideal of entrepreneurial liberty, not visions of society." (Blalock, 2014; Harvey, 2005). Charting a new course requires serious discourse on the nature of neoliberalism embedded in food justice activism and its political rationality, especially at a time when the economic impact of the COVID-19 pandemic is raising questions about the viability of strategies that espouse a 'consume your way out of the crisis' or 'pick yourself up by your own bootstraps' approach. Similarly to Philip Mirowski's analysis of the great recession of 2008, we may stand at another threshold where neoliberal ideas are employed to solve a crisis they are inherently ill equipped to address (Mirowski, 2014).

7. Toward the urban commons

A supportive and reliable legal environment is crucial to the success of a resilient local food system. Equally important is the creativity of such a legal environment and a willingness to challenge traditional economic theories of growth and sustainability. Drawing upon insights from ecological economics (Sheeran 2016), feminist economics (O'Hara, 2004; Yuille, 2015), critical legal scholarship (Lobel, 2004), and the rich legacy of democratic theorizing within the black radical tradition (Blalock, 2014White, 2018), we point toward the alternative valuation framework of the Social and Solidarity Economy, or SSE (Toussaint 2019;). The SSE framework is rooted in a variant of embedded liberalism that offers an alternative perspective to the prevailing, crisis-ridden capitalist economic regime. It focuses instead on community embeddedness, empowering people-centered organizations, and leveraging progressive societal norms. Further, SSE emphasizes redistributive justice, participatory democracy, and alternatives to a financial system that has moved from being a means to value creation to being an end in itself (Mazzucato 2015). Taken together, the SSE offers a progressive approach to community economic development that transcends the dogma of market fundamentalism by re-conceptualizing the city as a Commons (Foster and Iaione, 2016; Ostrom, 1990). By affirming the primacy of public good over private profit, ethics over efficiency, and democratic citizenship over governmental power, the SSE framework advances a participatory, inclusive, and equitable conception of socio-ecological and economic life. It reveals at least three legal tools for food justice activists that straddle common notions of private markets versus public interventionism: (1) land banks; (2) community land trusts; and (3) cooperatives.

Mariana Mazzucato points to the false dichotomy between laissez-faire markets and public intervention (Mazzucato, 2015, 2020). She argues that the unchecked power of free markets does not result in value creation, but instead in value extraction. The intervention of the public sector can help to ensure overall value creation by mitigating market failures and inefficiencies. In the case of urban food systems in rapidly urbanizing cities, a critical role of the public sector may be to secure long-term reliable access to land. For urban farmers in high land-value cities like Washington D.C., securing access to affordable land is a crucial concern (O'Hara, 2015, 2017; Hagey, 2018, Cooper, 2018). Not only does urban agriculture require considerable time, energy, knowledge, and capital; vacant land in distressed neighborhoods often requires costly soil remediation due to historic contamination linked to governmental neglect or environmental justice infractions. While the 2019 D.C. Urban Farming Act encourages high-efficiency systems like aquaponics and hydroponics, which can overcome the soil quality challenges of urban environments, it does not address the structural barriers that hinder many low-income residents from competing (Alkon, 2012). Land banks are quasi-governmental entities that take title to vacant and tax-delinquent properties through eminent domain and repurpose them for the benefit of the community. They have been successfully used in cities like Cleveland OH, Flint MI, Philadelphia PA, Atlanta GA, and Louisville KY to ensure equitable access to land (Owley and Lewis, 2014; Alexander, 2005). For example, in 2009, Cleveland established the Cuyahoga Land Bank to reserve the city's approximately 15,000 vacant and abandoned properties for the public interest

(Reconnecting America 2008; Re-Imagining a More Sustainable Cleveland, 2008). Community-based organizations, churches, schools, and local residents can apply for funding and technical assistance to build community gardens and green space, replacing an ethic of American exceptionalism with a spirit of social solidarity.

A related strategy to the land bank is the conservation easement. It too straddles free market rationality and public sector interference by placing permanent limitations on the permissible uses of land. The easement imposes obligations on the property owner to ensure the availability of the property for agricultural, forest, recreational, or open space purposes. For example, the L'Enfant Trust, founded in 1978 with the goal of protecting D.C.'s historic structures and neighborhoods, holds conservation easements on over 1100 historic properties and protects these properties from demolition, neglect, and any alterations that would erode their historic aesthetic (Goldchain 2018). Similar strategies can ensure the reliable availability of land for community gardens and agricultural purposes.

A second legal strategy that enables community members to collectively own urban farms in their neighborhood is the community land trust ("CLT"). A CLT is a legal entity that acquires and retains permanent ownership of land by holding it in trust in perpetuity and leasing the land to other entities through long-term ground leases (Kelly, 2010). As the name implies, CLTs facilitate community empowerment, typically featuring a place-based membership, a democratically elected board, and a commitment to the use and stewardship of land on behalf of community members (Yuen, 2014). The CLT institutes a communal entity that falls outside of the individual interest based rationality of free markets. In Chicago, IL, for example, a CLT called NeighborSpace operates as a city-funded land trust authorized to purchase tracts of land and protect them from commercial development on behalf of the community (Ignaczak, 2013). NeighborSpace does not control or manage the agricultural projects on the land. Rather, they are focused on providing land preservation, environmental assessment, liability insurance, and legal defense for residents. By advocating for a local right to control land, and by prioritizing healthy and culturally appropriate food, CLTs replace the delegation of public accountability with the communitarian ideals of a solidarity economy (Krinsky and Segal, 2019; Edmund 2009).

Finally, the SSE framework points toward cooperatively owned business entities as a third legal strategy to democratize the ownership of assets in response to the privatization of public goods (McCarthy 2019). Collective worker-ownership has long been a strategy for marginalized citizens to pool capital and productive resources to combat structural barriers to individual advancement (Gordon Nembhad, 2014; Gilbert et al., 2002). The cooperative business model – typified by the democratic principle of "one-person-one-vote" – challenges the privately-owned and hierarchically-managed business models typical of capitalist market rationality. For example, in Jackson, MI, Cooperation Jackson thrives as a grassroots movement for social liberation and economic justice for marginalized black citizens, exposing the duality of power in the ongoing struggle for food justice (Smith II, 2019; Brown-Hayat, 2018). Employing the principle of participatory democracy and social solidarity through community land trusts, cooperative business entities, and food hubs, the group has taken over abandoned buildings and vacant lots to produce healthy and culturally appropriate food for local residents. Even more, building upon the black radical tradition of Fannie Lou Hamer, who organized the cooperative Freedom Farm in 1969 to secure food sovereignty for marginalized black farmers in the South (Nembhard 2014; McCutcheon, 2019), Cooperation Jackson embodies Mayor Chokwe Antar Lumumba's bold plan to make Jackson the "Mondragón of the South."

To be sure, scholars have expressed reservations about the ability of cooperatives to overcome the challenges of neoliberalism, especially when low-income neighborhoods lack adequate funding and technical support (Zitcer, 2017). However, the experience of the University of the District of Columbia demonstrates that public institutions can provide resources to test the viability of management models that leverage community resources. After investing in its Urban Food Hubs model to create productivity through bio-intensive soil based and high-efficiency soilless aquaponics and hydroponics systems, the University is now in the process of testing two business models at its Urban Food Hubs locations in Wards 5 and 8 (O'Hara, 2018). A key aspect of the model is not only the upfront investment in productive capacity, but the ongoing investment in training, workforce development, and community engagement to sustain the capacity. Given the continued need for capacity-building and the development of complementary skills in the neighborhoods where the Urban Food Hubs are located, the cooperative model may prove the most viable platform when bolstered by public support services to not only combat the politics of neoliberalism, but educate vulnerable citizens on how to achieve liberation through food access (Nuri, 2019; Penniman, 2018).

8. Conclusion

As the COVID-19 pandemic continues to disrupt supply chains and claim lives across the globe, the need for secure access to food, water, and shelter, has come into sharp focus. Food access is especially critical for two reasons: first, a lack of food can trigger nutritional deficiencies; and second, a surplus of nutrient-deficient food can ignite health problems such as obesity, diabetes, and hypertension. Both types of deficits translate into food insecurity that manifest as pre-existing health conditions and compromised immune systems. Accordingly, consistent access to nutrient-rich local food characterized by short supply chains is more than a social determinant of public health; in light of the COVID-19 pandemic, it is also an indicator of vulnerability that places communities riddled with pre-existing health conditions at heightened risk of coronavirus infection (Cimons, 2020; Popkin et al., 2020).

In addition to raising concerns about pre-existing and food-related health conditions, the COVID-19 pandemic has exposed the vulnerability of global food supply chains. Shelter-in-place and social distancing policies have impacted seasonal labor supplies to harvest crops. Low-wage workers in meat processing plants and distribution centers comprise the new essential workforce that bears enormous exposure-risks. Even more, the added hand-off points associated with virtual demand and delivery systems constitute added food safety risks that have exposed the inherent conflict between fragile global food supply chains and human well-being. Yet, food access is not simply a supply management issue; it is an expression of unresolved discriminatory practices that are woven into local regulatory landscapes as well as global markets.

We trace the history of these structural determinants in Washington, D.C., and document the dismantling of food access in low-income marginalized neighborhoods where black and brown populations constitute the majority of residents. We further describe more recent efforts to improve food access in the capital of the United States by introducing several policy efforts, as well as the urban agriculture initiatives of the University of the District of Columbia, the only public and land-grant university in Washington D.C. W. Despite some successes in recent years, food access policies in D.C. have struggled to overcome long-standing socioeconomic and racial inequities.

We argue that some of the well-intentioned food access initiatives we review disregard persistent policy barriers that stand in the way of their implementation. Specifically, we highlight how D.C.'s urban agriculture initiatives remain firmly rooted in neoliberal market narratives and reiterate the false dichotomy between private market productivity and public sector inefficiency. We point to innovations in urban food and agriculture policies that can help inspire a shift in the food access discourse toward more sustainable and inclusive visions of food justice. We conclude by mapping the contours of alternative policy approaches that are essential to addressing long-standing food access problems in Washington, D.C., and cities elsewhere. Three legal strategies that can help steer food justice policies toward a new course between the current highly centralized corporatized food system, neoliberal food access strategies, and public sector dominance are: (1) landbanks and conservation easements, which help to preserve vacant land for community purposes; (2) community land trusts, which foster community ownership of urban agricultural spaces; and (3) cooperative business models, which transcend isolating narratives of individualized success through a shared productivity and profit model. Collectively, these community-centered strategies help to reimagine cities as the urban commons that seeks to decentralize and democratize food access. Food access policies aligned with this new course achieve more than improved food security and reduced public health exposure. They also serve as a model for overcoming entrenched cultural narratives of poverty and neoliberal ideals of market logic. In so doing, they move us toward a socially and ecologically just economy that sustains people, communities, and the planet far beyond the food sector.

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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Food Innovation Adoption and Organic Food Consumerism—A Cross National Study between Malaysia and Hungary

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Abstract: In order to meet the rising global demand for food and to ensure food security in line with the United Nation's Sustainable Development Goal 2, technological advances have been introduced in the food production industry. The organic food industry has benefitted from advances in food technology and innovation. However, there remains skepticism regarding organic foods on the part of consumers, specifically on consumers' acceptance of food innovation technologies used in the production of organic foods. This study measured factors that influence consumers' food innovation adoption and subsequently their intention to purchase organic foods. We compared the organic foods purchase behavior of Malaysian and Hungarian consumers to examine differences between Asian and European consumers. The findings show food innovation adoption as the most crucial predictor for the intention to purchase organic foods in Hungary, while social lifestyle factor was the most influential in Malaysia. Other factors such as environmental concerns and health consciousness were also examined in relation to food innovation adoption and organic food consumerism. This paper discusses differences between European and Asian organic foods consumers and provides recommendations for stakeholders.

Keywords: organic foods consumerism; food innovation adoption; food security; circular economy; health consciousness; environmental concern

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1. Introduction

The human population is still growing fast. Today, the global population is around 7.8 billion. This number is expected to increase by 10% (8.5 billion) by 2030, 26% (9.7 billion) by 2050, and 42% (10.9 billion) by 2100, according to the U.N. Department of Economic and Social Affairs [1]. The growing population increases the demand for food, sometimes leading to the irresponsible use of natural resources which are becoming scarce [2]. This rising demand exerts pressure on the environment, resulting in massive deforestation and the deterioration in biocapacity and marine ecosystems [3]. Due to the emergence of biological hazards that affect quality of life, health concerns are more prevalent among consumers now than ever before. Meeting food supply challenges and feeding the growing global population with good quality food, has emerged as the new global food security agenda.

The increasing demand for organic food may reflect consumers' concerns regarding the devastating effects of conventional agriculture on people's health and the environment [2]. Rimal et al. [4] and Saba and Messina [5] found that consumers purchased organic food as they perceived that the risk of pesticide contamination is relatively low in organic food and the growing of organic food is perceived as harmless for the environment. Growing buyers' interest in quality food, wellbeing, better health, and sustainable living make organic food a viable choice [6]. Organic food that is regulated is produced with less negative impact on nature as compared to the conventional food production process. The demand for organic food initiates the establishment of various organic farming techniques around the world, utilizing a minimum of synthetic inputs or none at all [7].

Besides health reasons, moral thought and responsibility towards the environment motivate some consumers to purchase organic food [8,9]. Hence, organic food has gained popularity and is seen as a way of life for some consumers [10]. Although organic food is positioned as a better food choice for health and the environment, the issue of its relatively higher cost is a hindrance to purchase for some. Surveys conducted in the United Kingdom, Japan, India, and Indonesia in 2015 revealed that consumers were willing to pay up to 30% more for fruits and vegetables as an act of social responsibility [11]. However, Timmins [12] noted that the advantages related to organic food were not sufficient for some purchasers to make the final decision to purchase organic food. Besides pricing concerns, the technology of producing organic food also draws consumer skepticism [13].

Overall, the demand for organic food globally is shaped by a number of economic, sociological, and psychological factors, which can vary from country to country and from type of commodity to food group [14]. Cross-national studies could aid in a better understanding global consumers' similarities and differences and pave the way forward towards a more sustainable food and future for all. A recent cross-national study by Boobalan et al. [15] compared Indian and American organic food consumerism and found key differences between consumers in these two large countries regarding the psychological benefits they acquire when purchasing organic food. Against this backdrop, this study aims to investigate the factors contributing towards the intention of consumers from Asia (Malaysia) and Europe (Hungary) to purchase organic food, taking into consideration the role of the food innovation adoption behavior of consumers.

To this end, this paper is presented in sections, as follows. This introduction addresses the aim and focus of this research. Section 2 presents the literature review and subsequently the conceptual framework based on the critical secondary research review. This is followed by the description of the research methodology in Section 3. The research findings and discussion are highlighted in Section 4. Section 5 demonstrates the cross-national comparison of the findings between consumers in Malaysia and Hungary. Section 6 presents the conclusion of the study and Section 7 the limitations of the research and suggestions for future study.

2. Literature Review and Theoretical Framework

According to the Oxford Dictionary, 'organic' simply means something that is derived from living matter. In the food and agricultural industry, the word 'organic' is a labeling term that is given by the regulators indicating the approval of methods for the production, handling, and processing of organic foods sold. Organic food cultivation integrates cultural, biological and mechanical practices that lead to resource conservation and recycling of resources which promote ecological balance and biodiversity conservation [16].

In Malaysia, organic certification is regulated under the Malaysian Quality Standard 1529:2015 which ensures that the practice of organic farming is based on the four principles of Health, Ecology, Fairness and Care. The Malaysian organic standard emphasizes the health of soils, plants, animals, and humans, and the well-being of the ecological system, the environment, as well as balance and fairness to the ecological system [17]. In Hungary, the procedures of organic products' certification, production, labeling and marketing are governed by the [18]. The EU Regulation 2018/848 (Article 1) describes organic production as *"an overall system of farm management and food production that combines best environmental and climate action practices, a high level of biodiversity, the preservation of natural resources and the application of high animal welfare standards and high production standards in line with the* *demand of a growing number of consumers for products produced using natural substances and processes. Organic production thus plays a dual societal role, where, on the one hand, it provides for a specific market responding to consumer demand for organic products and, on the other hand, it delivers publicly available goods that contribute to the protection of the environment and animal welfare, as well as to rural development".*

'Organic labelled' foods are produced without the use of pesticides and artificial nitrogen composts, antibiotics, synthetic hormones, genetic engineering, or other detrimental practices prohibited in the regulation [19]. The entire organic food value chain is regulated to ensure that it is environmentally safe and free from irradiation, industrial solvents and synthetic food additives [20]. Based upon the stringent regulatory framework for producing organic food, the 'organic' label thus gives assurance to buyers that it the food is produced without harming the environment and without chemical residues in food. It serves as an assurance that the food is free from toxic and harmful substances.

To obtain an organic certification, farmers need to ensure that their fields are processed naturally, and free from prohibited materials for at least three years [19], as healthy soil has a profound impact on the quality of crops. Organic farmers are also expected to use ethical practices in farming such as hand weeding, mulching, intercropping, using mechanical control against pests, spread yields, crop revolution, and thick planting, instead of using conventional pesticides, herbicides, and engineered nitrogen manures, in order to enhance soil health [21].

There is an increased interest in the study of organic food production as it is also linked to food security and the sustainable supply of food to promote the circular economy. Previous studies have shown that consumers were motivated to purchase organic food due to health and environmental concerns [20,22,23]. Studies also found that consumers' health consciousness predicted their consumption of organic food [24–26]. Subjective norms including the influence of family and friends, compounded with lifestyle trends, also show a significant influence on the intention to purchase organic food [27,28].

In this cross-national study, five determinants of organic food consumerism were measured to assess their impacts on consumers' purchase intention towards organic food. These factors were found to have common interest in research into organic food consumerism for both European and Asian consumers in recent literatures. The first four factors are health consciousness, environmental concern, perceived quality of organic food, and social lifestyle factors. The fifth factor that this study introduces to the literature is the impact of consumers' adoption of food innovation technologies on their organic food purchase intention. Food innovation adoption is introduced as both an independent variable and a mediating variable in this study in order to examine its wider role in organic food consumerism.

2.1. Organic Food Consumption Trends in Hungary and Malaysia

Despite the excellent agricultural conditions in Hungary and Malaysia, the proportion of land used for organic production is relatively low compared to conventional farming (4.0% of total agricultural land in Hungary according to the Central Statistical Office [29] and 0.1% in Malaysia according to Willer et al. [30]). Consumer spending on organic food is still lower than conventional food products and it is believed that by increasing the demand for organic food, better food sustainability can be achieved via a transformation of the food value chain [30].

Within the Asia-Pacific region, people consume organic produce because of its health benefits and its advanced biological farming techniques. Demand for, and the consumption of, organic foods and beverages in the Asia-Pacific region are predicted to grow from 2020 to 2025 [31]. In the Asia-Pacific region, Malaysia is one the countries offering great opportunities for organic food to flourish. Recently, Malaysian shoppers have become more cognizant of well-being, and hence have increased their consumption of organic substitutes for conventional food. Nevertheless, the supply of organic produce in Malaysia is unable to meet the local market demand, causing a nationwide shortage of organic food. Malaysia still vigorously imports organic food from Europe and North America [32]. In Europe, Christos and Athanasios [33] predicted a lack of supply of organic food, not a lack of demand for it.

The United States recorded the largest sales of organic food (43%) in 2017, followed by the European Union member states (38%) [34]. Among Central and Eastern European countries, Hungary ranked as the third largest market volume of organic foods in 2010 [35]. Hungary is among the largest exporters of organic food in Central Europe. In 2018, there were 3929 producers who cultivated a total of 209,382 hectares of organic-farming land in Hungary [36].

As regards the domestic consumption of organic food, studies found that European consumers were driven by health consciousness, environmental concern, quality of life, and technological development [24,37]. Although environmental and health consequences can influence organic consumerism, the affordability of organic food was significant in determining consumers' food choices, particularly those in Italy and Hungary [25]. In Hungary, innovation in the food industry has been evaluated favorably by consumers [38]. This implies the significance of technological innovation in the food industry in satisfying consumers' needs [38]. Interestingly, food-technology was found to be related primarily to environmental concern among Hungarian consumers [39]. Similarly, in Malaysia, the creation of organic food has turned into an inventive methodology for the food sector to meet the rising consumer demands for healthier food choices.

2.2. Consumers' Purchase Intention towards Organic Food

Consumers' purchase intention is explained simply as the possibility that a consumer will acquire a product [22]. This variable is used in social science and business literature to indicate the actual consumption behavior of consumers towards a product or service [40]. It represents the likelihood that a purchase would take place as a result of "the interaction between customer needs, attitude and perception towards the product" [41]. Purchase intention acts as a measure of consumers' attentiveness in acquiring a product and the possibility of actually purchasing it [42]. According to Park and Kim [43] and Shin [44], purchase intention can be treated as a predictor of the actual purchasing decision due to its inclination to approximate to the actual conduct of a consumer. Although having an intention to purchase would more likely lead to actual purchase, it cannot be assumed that all predictors used would lead to actual purchasing action. Behavioral intention is formed based on an individual's motivation to perform that behavior, taking into account alternative options and his or her currently active goals [45]. With the limitation of observing the actual purchase behavior of consumers, purchase intention is used in this study to measure the potential of consumers' purchases.

Gifford and Bernard [46] employed a two-limit Tobit model and found that purchase intention towards organic foods among consumers may be influenced by the perceived benefits of organic agricultural methods, and the perceived risk of purchasing food grown using conventional procedures. In addition, Verhoef [47] posits that consumers are not only motivated by their rational economic motives, but also by emotional motives when purchasing organic food. The study found that consumers were willing to pay premium prices for organic food due to emotional motives, such as fear, guilt and empathy towards the environment.

Based on the relevant previous works, this study identified five variables to form an organic consumerism framework to compare Malaysian and Hungarian consumers as regards their organic food purchase behavior. They comprise food innovation adoption, health consciousness, environmental concern, perceived quality, and social lifestyle.

2.3. Health Consciousness

Health consciousness means that an individual's orientation toward his or her efforts to prevent illness and improve overall well-being [48]. Iversen and Kraft [49] defined health consciousness as "a tendency to focus attention on one's health" (p.603). An individual's level of health could be assessed through how one searches for health information and incorporates it into daily life. Homer and Kahle [50] posit that there is a relationship between consumers' intrinsic motivation, such as self-fulfillment, and a sense of accomplishment in purchasing nutritional food.

Health-conscious consumers are cognizant of their wellness and this health concern drives them to continuously improve their health and quality of life. To measure health consciousness, Ellison et al. [51] used behaviors such as food consumption, exercise, and substance use as indicators. Since the concept of health consciousness is linked more to personal attributes, measuring one's health consciousness on a psychological basis would better predict diverse health behaviors and result in greater construct validity.

Health consciousness has been relevant in predicting purchase intention and behavior regarding organic food production since buyers are aware that their food intakes impacts on their health. Previous research done by Shaharudin et al. [52] identified that consumers' attention to their health was a primary motive for the purchase of organic food. From another study, 87% of consumers believed that organic food was a healthier choice as compared to conventional food [10]. Similarly, Michaelidou and Hassan [53] highlighted health consciousness as the most important motive in explaining consumers' attitudes and behavior towards organic foods.

Shaharudin et al. [52] found the most popular motive to purchase organic food was consumers' perception of organic food as a healthier option for them. They also identified that consumers' interest in health was their primary motive to purchase organic food. Although the inherent evidence of the health benefits of consuming organic food have not been validated by Meemken and Qaim [2], a positive relationship between consumers' health consciousness and their purchase intention has been frequently identified in previous studies. Thus, this study hypothesized that health consciousness would positively influence consumers' intention to purchase organic food (Hypothesis 1 (H1)).

2.4. Environmental Concern

Consumers who are environmentally conscious prefer to use certain products because they believe they can reduce ecological impacts [54]. Similarly, consumers of sustainable wines were willing to change their consumption behavior to minimize the negative impact on the environment [55]. This type of consumer, also referred to as green consumers, often determine their purchase behavior for the benefit of the environment. The more consumers are concerned about the environment, the more positive are their attitudes toward organic food [56].

Seventy-five percent of respondents in the study by Petrescu and Petrescu-Mag [8] believed that organic food contributes to environmental protection. Congruently Basha et al. [57], found consumers' attitude towards purchasing organic food was strongly influenced by their concern for the environment. Sogari et al. [55] investigated consumers' environmental concerns and their intention to purchase sustainable wines and found it was important for consumers to believe that sustainable wines truly benefitted the environment in order to form a positive attitude towards purchasing sustainably.

In this study, a positive impact of consumers' environmental concern on their intention to purchase organic food is presented for testing in Hypothesis 2 (H2).

2.5. Perceived Quality

Perceived quality has gained popularity in marketing studies as a predictor of purchase intention and consumers' satisfaction. It is considered a crucial key for business sustainability, especially in competitive markets [58]. Perceived quality is defined as the personal judgment of the quality and benefit of a product or service that consumers establish in their minds [26]. The value of a product, also known as product utility, is often evaluated based on its ability to meet consumers' needs, resulting ultimately in their satisfaction. Consequently, the higher the value a product has is in consumers' minds, the higher the price they are willing to pay for it.

Consumers who purchase organic food often appear to be particularly concerned about the quality of the foods they consume. Half of the consumers who participated in a survey conducted by Timmins [12] agreed that organic food had better quality and taste. However, the major barrier to organic consumption was still the higher price. Some consumers perceived that the benefits of organic foods were not sufficient to justify its higher price [12]. Although value-for-money is found to be important for some consumers, one previous study finds this does not translate into anti-organic attitudes [12]. The affordability of organic foods played a major role in influencing consumers' food selection, particularly those in Hungary [25].

The locality of the organic food supply could potentially off-set the high price concern linked to organic foods. Consumers believe that locally produced greens produce a smaller carbon-footprint and are thus more environmental friendly and sustainable [59,60]. Timmins [12] found that 60% of his respondents were interested in locally sourced crops. Although affordability could influence consumers' food selection, the perceived quality of organic foods was found to be significant in predicting consumers' purchase intentions. This study predicts a positive relationship between perceived quality and consumers' intention to purchase organic foods (Hypothesis 3 (H3)).

2.6. Social Lifestyle

Studies in psychosocial theories and health behaviors explore how cognitive and social factors affect human health and disease [61]. Social and lifestyle factors relate to how peers and the people who surround a person affect his or her decision making. Additionally, messages through the media as well as reference groups and celebrities can also influence an individual's decision making [45]. Previous studies have shown the strong impacts of social factors on an individual's decision making in a wide variety of situations including business, social and health decisions [62–64].

Petrescu and Petrescu-Mag [10] explain the positioning of foods as fashionable items and their consumption as a social phenomenon that can generate consumers' interest and in turn become a part of their lifestyle. The trend and image factors may also influence consumers' decision to purchase organic foods despite the higher price. For instance, trendsetters in Vietnam who enjoy cooking pay greater attention to healthy food and prefer organic foods [27]. Specifically, a study involving youngsters by Vermeir and Verbeke [28] found a strong impact of social influence on sustainable food consumption behavior among young adults in Belgium.

The media often broadcasts programs showing the enjoyment of food and cooking in such a way that boosts the importance of food in representing power, pleasure, cleverness, and beauty. Often, people strongly believe that "who you are" to some extent is reflected in "what you buy". Social status was often found to be a determinant influencing people's decisions to consume green products rather than their more luxurious, non-green counterparts [65]. Similarly, Sahelices-Pinto et al. [66] showed that the consumption of organic foods was influenced by both social factors and self-esteem, revealing the impact of organic consumption on boosting one's social identity. Thus, hypothetically, a positive relationship may be established between social lifestyle and consumers' intentions to purchase organic foods (Hypothesis 4 (H4)).

2.7. Food Innovation Adoption

Food security has become a vital point of focus globally [67,68]. It is included as being of paramount importance in the United Nation's Sustainable Development Goals, as Goal 2 [69]. Goal 2 calls on all the nations of the world to work together to end hunger, achieve food security and improve nutrition, and promote sustainable agriculture. Altogether, the SDG Goal 2 proposes 8 targets to be achieved globally by the year 2030. The third target in the goal (Target 2.3) aims to double agricultural productivity, while the sixth target (Target 2.a) specifically mentions increased investments in technology development. In order to meet these two targets, the pivotal role of technology and innovation in food production is highlighted.

Fortunately, innovations in digital technologies such as advanced data analytics, predictive modeling, robotics, and the Internet of Things (IoT) have increased the efficiency of modern farming. Biotechnology advances in food technology also assist in increasing the food supply. By utilizing food innovation technologies that provide timely and accurate data, farmers can significantly improve their farming processes and eventually improve productivity. The new application of digitization and IoT in farming makes it possible to assess the soil moisture level, temperature, and many more agricultural matrices in real time to facilitate farmers' timely and accurate interventions.

The EU Regulation 2018/848 (Article 24) reads: "In order to support and facilitate compliance with this Regulation, operators should take preventive measures at every stage of production, preparation and distribution, where appropriate, to ensure the preservation of biodiversity and soil quality, to prevent and control pests and diseases and to avoid negative effects on the environment, animal health and plant health. They should also take, where appropriate, proportionate precautionary measures which are under their control to avoid contamination with products or substances that are not authorized for use in organic production in accordance with this Regulation and to avoid commingling organic, in-conversion and non-organic products". Based on this article, organic farmers can still use preventive measures to ensure their crops are safe from pests and diseases. However, if unauthorized substances are used in any of these activities, the products can no longer be considered organic. Hence, technology-based preventive measures would be ideal in order not to contravene this article and lose the organic product label.

As consumers' food preferences move towards fresh and whole foods, food-processing technology is also forced to meet the highest environmental standards with minimal alteration in the qualities and original flavors of the foods. As a result, organic farmers and their distributors spearhead the trend towards sustainable food production and a more transparent value chain [70]. This move towards a sustainable cycle of production is also referred to as the circular economy where the main goal is to reduce waste in the food production lifecycle [71].

The adoption of food innovation technology may influence consumers' purchase of organic foods, as food innovation technologies are rapidly being introduced into organic farming. Accordingly, this study proposes the fifth hypothesis to measure the impact of food innovation adoption of consumers on their intention to purchase organic foods (Hypothesis 5 (H5)).

2.8. Food Innovation Adoption Behaviour as Mediator in Organic Foods Purchase Intention

It is crucial for the food sector to identify the important drivers of consumers' preferences for foods in these modern times [72]. Consumers have become increasingly conscious of what they eat for various reasons, including skepticism as to whether food technology really produces better quality foods that warrant the higher price. As the biggest stakeholder in the food supply chain, consumers' preferences and decision making in foods purchase make them a formidable force for the food industry to reckon with. Mindful consumers are looking for the move towards sustainable food production. Health consciousness, environmental concern, perceived quality of organic foods, and social lifestyle would hypothetically impact their food innovation adoption behavior.

This study postulates that food innovation adoption would have both a direct impact on the intention to purchase organic foods (Hypothesis 6, 7, 8, and 9), and mediate the impact of health consciousness, environmental concern, perceived quality and social lifestyle on consumers' intention to purchase organic foods (Hypothesis 10, 11, 12, and 13).

The following list presents Hypotheses 6 to 13 which are put forward for testing in this study:

Hypothesis 6 (H6). *There is a positive impact of consumer health consciousness on food innovation adoption.*

Hypothesis 7 (H7). *There is a positive impact of consumer environmental concern on food innovation adoption.*

Hypothesis 8 (H8). *There is a positive impact of consumer perceived quality of organic food on food innovation adoption.*

Hypothesis 9 (H9). *There is a positive impact of consumer social lifestyle on food innovation adoption.*

Hypothesis 10 (H10). *The impact of health consciousness on consumers' purchase intention is mediated by food innovation adoption.*

Hypothesis 11 (H11). *The impact of environmental concern on consumers' purchase intention is mediated by food innovation adoption.*

Hypothesis 12 (H12). *The impact of perceived quality on consumers' purchase intention is mediated by food innovation adoption.*

Hypothesis 13 (H13). *The impact of social lifestyle on consumers' purchase intention is mediated by food innovation adoption.*

The research variables and corresponding hypothesis are shown in Figure 1.

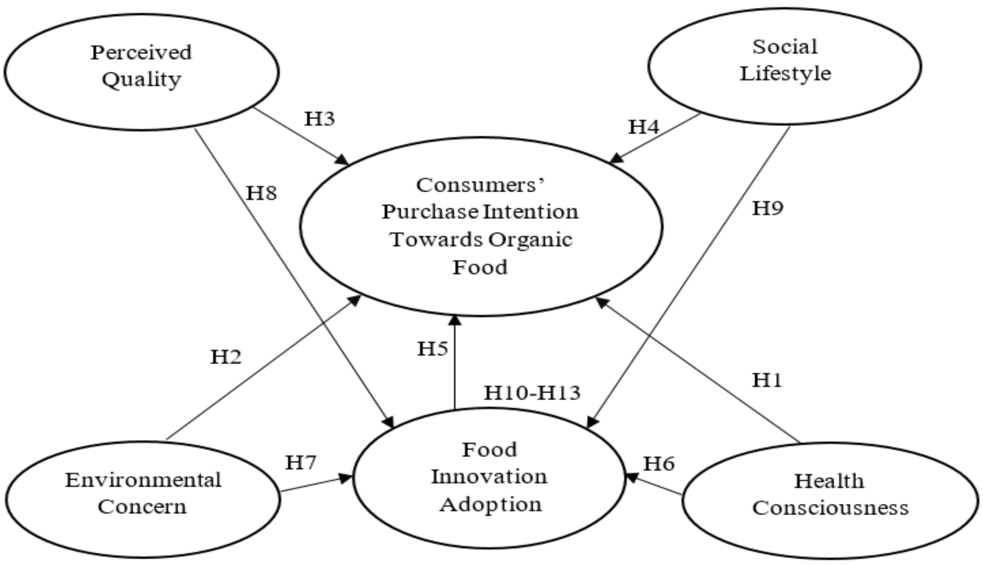

Figure 1. Research theoretical framework.

3. Methodology

According to Roitner-Schobesberger et al. [73], there have been numerous debates on buyers' views of organic foods in the United States and Europe; however, less has appeared in Asia despite the growing market for organic foods. For this reason, an analysis of organic foods consumerism in Malaysia—one of the leading contributors of agriculture in Asia—is selected for this study. Hungarian consumers in this study were chosen to represent organic consumerism in Europe. Although at this juncture, this comparison does not provide a holistic comparison between European and Asian consumers, in this pioneering cross-national study of organic foods consumerism, these two countries were chosen due to the proximity of the researchers to both countries to facilitate insightful data collection and to provide preliminary insights into this area of research. The findings of this research could warrant more comprehensive work in the future between Asia and Europe.

To conduct a cross-national comparison analysis of organic food consumerism in Malaysia and Hungary, this study utilized a research questionnaire as the data collection instrument for gathering primary research data. The participants in this study from both countries were approached randomly using the purposive sampling methodology and the classic mall-intercepted survey technique. The availability of organic food products in the areas where the respondents were approached was confirmed before administering the questionnaire to potential participants. Only participants who had prior experience of purchasing organic foods were selected as respondents. The survey was administered face to face among respondents in Malaysia and Hungary. Hardcopy questionnaire forms were used for data collection, which was carried out between June 2019 and March 2020 in both countries.

In total, 300 usable responses were obtained in Malaysia and 372 in Hungary. The filled questionnaires were carefully screened for missing data and mistakes in responses such as multiple responses for single response questions. Verified questionnaires were coded in the statistical software IBM Statistical Package for Social Sciences (SPSS), version 27, for descriptive analysis. Hypothesis testing and path modelling was done using Partial Least Square Structured Equation Modelling (PLS-SEM) using ADANCO PLS Software, Version 2.0. PLS-SEM was selected as the data analysis technique as the research model of this study is geared towards predictive modelling and testing the relationship between new constructs. Kline [23] pg. 286 recommends PLS-SEM as "well suited for where: (1) prediction is emphasized over theory testing and (2) it is difficult to meet the requirements for large samples or identification in SEM." Based on these criteria, the PLS-SEM technique was selected as the appropriate technique for hypotheses testing and path modelling for this study.

All measurement items of the research variables were measured using a five-point Likert scale based on the extent to which respondents agree or disagree with the particular indicator (item) statement in the questionnaire on a scale of 1 to 5; where (1) is Strongly Disagree, (2) is Disagree, (3) is Neutral, (4) is Agree, and (5) is Strongly Agree. This scale design is commonly used as measurement for social science studies. Churchill and Iacobucci [20] noted questionnaires using the Likert scale could provide appropriate measurements that would ease the process of tabulation and statistical analysis.

The indicators for Food Innovation Adoption (FIA), were self-developed for this study. These indicators were expert reviewed by two professors at the Multimedia University, Malacca Campus, Malaysia, who are specialists in technology adoption studies. Furthermore, the indicator statements were validated through a pilot study with data collected at the Multimedia University Malacca Campus among undergraduate students. The data from 200 samples showed the high reliability and internal consistency of the self-developed indicators, hence the indicator statements were incorporated in the final questionnaire for the productive phase of data collection in Malaysia and Hungary.

4. Results

Table 1 shows the respondents' demographic details.

Of the 300 respondents in Malaysia, 59% were females, and 71.3% were between 21 and 40 years old. Most of the respondents (83%) were single. In Hungary, 60.2% of the total respondents were males. As for ages, they had almost an equal number of respondents who were 21–40, 41–50 and 51–60 years old, with 36.8% between 21 and 40 years old. Lastly, more than half of the respondents in Hungary were married with children (53.2%), while in Malaysia this figure was about 15%.

Table 2 shows the research variables, indicator sources, aggregate means and standard deviations for both Hungarian and Malaysian data.

Table 1. Respondents' demographic information.

Demographic Factor	Options	Malaysia		Hungary	
		Freq.	Percentage (%)	Freq.	Percentage (%)
Gender	Male	123 (16.820 *)	41.0 (51.45)	224 (4.680 *)	60.2 (47.91)
	Female	177 (15.880 *)	59.0 (48.55)	148 (5.088 *)	39.8 (52.09)
Age	Below 20	65	21.7	4	1.1
	21–40	214	71.3	137	36.8
	41–50	13	4.3	123	33.1
	51–60	4	1.3	87	23.4
	Above 60	4	1.3	21	5.6
Marital Status	Single	249	83	108	29
	Married with children	46	15.3	198	53.2
	Married without children	3	1	28	7.5
	Single with children	2	0.7	20	5.4

Note: * Numbers in bracket represent national populations in millions. The Hungarian population statistics are obtained from [74]. The Malaysian population statistics are obtained from [75].

Table 2. Research variables and indicators with mean and standard deviation.

Research Variables	Indicators	Malaysia		Hungary	
		Mean	SD	Mean	SD
Health Consciousness (HC) Yang et al. [76]; Shaharudin et al. [52]	HC1—Healthy diet is an important factor when choosing what I eat	4.230	0.775	3.867	0.786
	HC2—I give a lot of attention to my health	3.826	0.837	4.11	0.745
	HC3—A healthy body is important to me	4.421	0.626	3.045	0.993
	HC4—Health concern is the reason for consuming organic food	3.919	0.874	3.140	1.00
	HC5—Proper nutrition is a key factor for purchasing organic food	3.909	0.848	4.196	0.909
Environmental Concern (EC) Yang et al. [76]	EC1—I am concerned about the state of our environment	3.993	0.798	3.457	1.065
	EC2—Environmental concerns affects my food choice	3.692	0.926	3.370	1.165
	EC3—Organic food is environmentally friendly	3.916	0.876	3.869	1.103
	EC4—Chemical fertilizers are harmful for the environment	4.143	0.910	4.382	0.8663
	EC5—Everyone should be concerned for our environment	4.568	0.707	3.471	1.067
Perceived Quality (PQ) Aulia et al. [58]	PQ1—Organic food is a healthier food option	4.220	0.788	3.353	1.078
	PQ2—Organic food has great nutritional benefits	4.153	0.880	3.251	1.059
	PQ3—Organic food has better quality due to its advanced cultivation methods	4.016	0.849	3.252	1.104
	PQ4—Though I may have to pay more, I get better quality organic food	3.879	0.926	3.225	0.9942
	PQ5—I am satisfied with organic food quality	3.923	0.939	3.733	0.9866

Table 2. *Cont.*

Research Variables	Indicators	Malaysia		Hungary	
		Mean	SD	Mean	SD
Social Lifestyle (SL) Basha et al. [57]; Falguera et al. [65]	SL1—Organic food is a trend in society	3.493	1.01	2.175	1.104
	SL2—My family influence me to consume organic food	3.177	1.14	2.046	1.036
	SL3—My peers influence me to consume organic food	2.959	1.04	2.754	1.22
	SL4—Celebrities often promote organic food consumption	3.214	1.09	3.807	0.935
	SL5—The lifestyle of consuming organic food is healthy	3.953	0.861	3.549	0.9742
Food Innovation Adoption (FIA) Self-Developed for this Study	FIA1—The way organic food is grown and processed influence me to consume organic food	3.721	0.908	2.843	1.132
	FIA2—The advantages of GM (genetically modified) foods outweighs potential disadvantages	3.476	0.931	3.495	1.036
	FIA3—Advances in food technologies have produced better quality food for the world	3.845	0.825	3.769	0.8930
	FIA4—Technologically superior organic food production improves food yields	3.815	0.860	3.939	0.9062
	FIA5—Innovation in food production is to be welcomed by all	3.922	0.796	3.877	0.9858
	FIA6—I support technology and innovation in food production	4.000	0.794	2.695	1.155
Consumer Purchase Intention Towards Organic Food (CP) Shaharudin et al. [52]	CP1—I purchase organic food frequently	2.966	1.12	2.587	1.143
	CP2—I will continue to purchase organic food	3.391	0.985	2.791	1.165
	CP3—I am willing to pay more for organic food than conventional food in the store	3.351	1.03	2.887	1.186
	CP4—I will recommend organic food to family and friends	3.738	0.918	2.195	1.194
	CP5—I consider myself a loyal organic food consumer	3.023	1.24	3.34	1.011

The measurement model is assessed via construct validity, convergent validity, and discriminant validity analyses. Before conducting hypotheses testing, it is essential to investigate the indicators' factor loadings. According Hair et al. [77], indicators with loadings below 0.50 should be removed from the path model due to the low predictability of the relevant variable. Thus, HC5, EC4, PQ5, SL1, FIA1, FIA3, and CP5 were removed from both the Hungarian and Malaysian path models in order to make identical comparison of path modelling for both countries (refer to Table 3).

For factor loadings that were above 0.50 but below 0.70, their variable's composite reliability (CR) and AVE are confirmed to exceed thresholds of 0.70 and 0.50 (Hair et al. [77] and Bagozzi and Yi [78]), assuring the path models' Reliability and Convergent Validity. As for the Cronbach Alphas, all values are above 0.70, fulfilling the satisfactory values, except for SL 0.673 (Malaysia) and 0.671 (Hungary), which were slightly below the 0.7 threshold; however, their CR and AVE are above threshold levels, hence fit for path modelling [79]. The statistics of all constructs and indicators are presented in Table 3.

Table 3. Internal consistency, composite reliability and convergent validity.

Variable	Indicator	Factor Loadings		Cronbach's Alpha		Composite Reliability		AVE	
		MD	HD	MD	HD	MD	HD	MD	HD
Health Consciousness (HC)	HC1	0.754	0.627	0.786	0.725	0.860	0.821	0.607	0.537
	HC2	0.768	0.655						
	HC3	0.650	0.809						
	HC4	0.801	0.820						
	HC5	0.720	-						
Environmental Concern (EC)	EC1	0.707	0.684	0.749	0.729	0.841	0.825	0.570	0.546
	EC2	0.720	0.815						
	EC3	0.766	0.607						
	EC4	0.635	-						
	EC5	0.767	0.826						
Perceived Quality (PQ)	PQ1	0.778	0.863	0.828	0.888	0.885	0.922	0.660	0.748
	PQ2	0.780	0.873						
	PQ3	0.817	0.890						
	PQ4	0.797	0.832						
	PQ5	0.843	-						
Social Lifestyle (SL)	SL1	-	0.673	0.673	0.671	0.787	0.752	0.515	0.513
	SL2	0.799	0.652						
	SL3	0.712	0.773						
	SL4	0.553	0.665						
Food Innovation Adoption (FIA)	FIA1	0.696	-	0.813	0.724	0.876	0.753	0.640	0.524
	FIA2	0.725	0.554						
	FIA3	0.739	-						
	FIA4	0.817	0.600						
	FIA5	0.798	0.603						
	FIA6	0.750	0.845						
Consumer Purchase Intention Towards Organic Food (CP)	CP1	0.847	0.919	0.896	0.914	0.923	0.919	0.706	0.796
	CP2	0.841	0.883						
	CP3	0.830	0.904						
	CP4	0.805	0.861						
	CP5	0.878	-						

Note: MD stands for 'Malaysian Data' (n = 300); HD stands for 'Hungarian Data' (n = 372).

A high inter-relationship and multi-collinearity between variables can lead to misleading findings, magnified standard errors, or weaker power of regression coefficients. According to Henseler et al. [80], when all the values of the Heterotrait-Monotrait Ratio of Correlations (HTMT) are lower than 0.85, this implies that the variables are conceptually distinct from each other. HTMT 0.85 is used in this study as the conservative criterion to assess discriminant validity [80]. From Table 4, it is observed that all HTMT values among the variables in this study are lower than the thresholds of 0.85, indicating the models are free from multi-collinearity.

Table 4. The Heterotrait-Monotrait ratio of correlations (HTMT).

	Malaysian Data						Hungarian Data				
	HC	EC	PQ	SL	FIA		HC	EC	PQ	SL	FIA
HC						HC					
EC	0.7260					EC	0.6272				
PQ	0.7212	0.7012				PQ	0.5968	0.8143			
SL	0.5757	0.3903	0.7851			SL	0.5162	0.7971	0.7720		
FIA	0.6335	0.6632	0.6631	0.6067		FIA	0.4229	0.5024	0.5512	0.5965	
CP	0.5099	0.3945	0.6405	0.6544	0.5104	CP	0.6738	0.7666	0.6357	0.8427	0.5773

Additionally, to assess the goodness of fit of the research model, the Standardized Root Mean Square Residual (SRMR) was calculated. The results show SRMR values of 0.0670 for Malaysia and 0.0541 for Hungary. The SRMR values for the Malaysian and the Hungarian models are within the threshold level of 0.08 (Hu and Bentler [81]), assuring the goodness of fit of the research models for both countries. The R square values for Malaysia are CP = 0.408 and FIA = 0.458; while R square values for Hungary are CP = 0.725 and FIA = 0.493. The research variables show a high variance explained in both models; especially with the Hungarian consumer purchase intention of organic foods, the model shows that the research variables account for approximately 73% of the variance.

Hypotheses Testing

For testing the hypotheses, bootstrapping with 5000 iterations was applied. The significance of the path coefficient is assessed to validate each hypothesis. The structural model for Hungary and Malaysia with the R square values, path coefficients, and factor loadings are presented in Table 5.

Table 5. Results of hypotheses testing for Malaysia and Hungary.

Hypothesis	Relationship	Malaysian Data		Hungarian Data	
		Path Coef.	*p*-Value	Path Coef.	*p*-Value
H1	HC → CP	0.600	0.107	0.185	<0.001 ***
H2	EC → CP	−0.011	0.860	0.117	0.014 **
H3	PQ → CP	0.271	<0.001 ***	0.187	0.002 ***
H4	SL → CP	0.306	<0.001 ***	0.113	<0.013 **
H5	FIA → CP	0.109	0.035 **	0.414	<0.001 ***
H6	HC → FIA	0.110	0.0402 **	0.188	<0.001 ***
H7	EC → FIA	0.341	<0.001 ***	0.014	0.852
H8	PQ → FIA	0.134	0.036 **	0.313	0.031 **
H9	SL → FIA	0.187	<0.001 ***	0.329	<0.001 ***

*** Significant at 1%; ** Significant at 5%

Based on the results of the Malaysian and Hungarian path analysis, it was found that the relationships between Health Consciousness (HC) and Environmental Concern (EC) regarding Consumer's Purchase Intention Towards Organic Foods (CP) are insignificant for Malaysia; however, these paths are significant for Hungary (Hypotheses 1 and 2 are partially supported—true only for Hungary). Perceived Quality (PQ), Social Lifestyle (SL) and Food Innovation Adoption (FIA) each show a significant impact on CP in both countries (Hypotheses 3, 4 and 5 are supported).

Among these five independent variables (H1 to H5), SL has the highest impact on CP (0.306) for Malaysia. However, for Hungary, FIA shows the highest impact on CP (0.414). It is interesting to note that the same factor (FIA), though significant, shows the lowest impact on CP in the Malaysian context (0.109). This indicates the difference in perception and role that FIA plays in these two countries.

On the other hand, PQ is found to be the second most important factor leading to CP in Malaysia and in Hungary. This finding highlights the consistent perception of users in both countries who tend to relate the perceived quality of organic foods with their purchasing intention.

As for the impact of the research variables on FIA as mediating variables, HC, PQ, and SL were found to be significant predictors of FIA in Malaysia and Hungary (Hypotheses 6, 8 and 9 are supported). Testing the impact of EC on FIA shows differing results for the two countries, where EC on FIA is significant in Malaysia but not in Hungary (H7 is partially supported). This shows that although EC leads to CP in Hungary, it does not significantly predict Hungarians' FIA behavior.

To further investigate the mediating effect of FIA in the relationships between each of the predictors HC, EC, PQ, and SL to CP, the significance of these indirect paths was tested. The results of the indirect effects are presented in Table 6.

Table 6. Indirect effects of factors towards CP through FIA.

Hypothesis	Relationship	MD		HD	
		Path Coef.	*p*-Value	Path Coef.	*p*-Value
H10	HC → FIA → CP	0.012	0.253	0.078	0.003 **
H11	EC → FIA → CP	0.037	0.082 *	−0.004	0.890
H12	PQ → FIA → CP	0.014	0.212	0.129	<0.001 **
H13	SL → FIA → CP	0.020	0.057 *	0.136	<0.001 **

** Significant at 1%; * Significant at 10%

The result of the indirect effects analysis reveals several significant paths. According to Hair et al. [77], it is necessary to evaluate indirect effects in order to determine whether a mediating effect is present. When both direct and indirect effects are significant, a partial mediation is observed; if the indirect effect is significant but the direct effect is insignificant, a full or indirect-only mediation is identified. However, when the indirect effect is insignificant, but the direct effect is significant, it indicates that a direct-only effect or no mediation effect is present [77].

From the mediation results above, it is observed that FIA is a significant mediator for EC and SL impacts on CP for Malaysia. However, it is not a significant mediator for PQ and HC. Reading this finding together with the earlier finding of the direct effect of HC on CP, it was also found not to be significant for Malaysia, while the direct effect of FIA on CP was significant. From these three findings, it can be deduced that for Malaysian consumers, health consciousness is an important reason that makes them consider accepting innovation in food production; however, health consciousness in itself is not the reason for purchasing organic foods.

As for the Hungarian data, the finding shows FIA as a significant mediator for HC, PQ and SL on CP. However, FIA is found not to be a mediator for EC. Compounding this finding with the direct impacts of EC on CP (significant) and FIA (not significant), it can be deduced for Hungarian consumers that environmental concern is an important factor of consideration for them when purchasing organic foods; however environmental concern in itself is not a reason for adopting innovation in food production. Based on this finding, Hypotheses 10, 11 and 12 are partially supported, while Hypothesis 13 is fully supported.

5. Discussion

The data obtained in both countries revealed that consumers in both countries have some commonalities and some key differences in their adoption of food innovation, as well as in the purchase of organic foods. This section presents a critical discussion of these findings for Malaysia and Hungary.

When it comes to the purchase of organic foods, both countries show different crucial determining factors that affect their decision making. To assist with visualizing the findings, Table 7 is based on the statistical results of path modelling coefficients in Table 5.

Table 7. Visual representation of Path Modelling Results showing the relative importance of the constructs.

Constructs	Malaysian Consumers		Hungarian Consumers	
	Food Innovation Adoption	Organic Food Purchase	Food Innovation Adoption	Organic Food Purchase
Health Consciousness	Important (4)		Important (3)	Important (3)
Environmental Concern	Important (1)			Important (4)
Perceived Quality	Important (3)	Important (2)	Important (2)	Important (2)
Social Lifestyle	Important (2)	Important (1)	Important (1)	Important (5)
Food Innovation Adoption		Important (3)		Important (1)

Note: Numbers in bracket show the ranking and relative importance of factors within the column.

For Malaysian consumers, SL is the most crucial factor, followed by PQ and FIA, in determining their organic foods purchase intention. Comparing this with Hungarian consumers, the result shows that FIA is the most crucial determinant for Hungarians, followed by PQ, HC, EC, and finally SL.

The social lifestyle factor is found to be the most important factor that contributes to the intention to purchase organic foods in Malaysia. The social lifestyle variable measures buyers' concerns regarding status and peer influences. Malaysian consumers demonstrate a greater tendency that social lifestyle will be a reason to purchase organic foods, which are more expensive than conventional foods. Social influence was also found in previous studies to impact on consumers' intention to purchase organic foods in Malaysia by Ayub [77,82] and in Pakistan [83]. In particular, peer pressure was found to be a significant determinant in persuading young Malaysian consumers to purchase green products in a previous study [84]. Malaysian consumers appeared to purchase organic products with the intention of fulfilling and expressing their social identity [85] which is found to be consistent with the findings of this study.

Other findings from the region, such as Nguyen et al. [86], reveal that organic foods label significantly contributed to buyers' favorable attitude to buying organic foods among urban Vietnamese consumers, while Fogarassy et al. [71] found that highly educated young people who are very conscious and live on good incomes may be the target group for circular innovation in Hungary. The study found that young consumers, the internet savvy, and software users living in cities buy organic foods and follow healthy lifestyle trends. Hence, having access to a more expensive food selection may be seen as a social symbol and a differentiator from the masses, as well as a sustainable lifestyle trend.

The perceived quality of organic foods is found to be the second most important factor that drives the intention to purchase organic foods in Malaysia. Malaysian consumers seem to compare conventional foods with organic foods based on this perceived main difference—its quality. In previous studies by Lee and Yun [87] and Lockie et al. [88], consumers were found to be committed to foods they perceived to be natural, nutritional and free of unnecessary processing as well as artificial additives. Organic plants contain lower levels of pesticide residues and minimum concentrations of nitrate and cadmium. Besides, organic animal products were also found to contain higher levels of omega-3 fatty acids. Overall, organic foods were associated less with allergies, eczema, and obesity. Although there was insufficient evidence to draw conclusions on the positive health outcomes of consuming organic foods in the study by Meemken and Qaim [2], the study found that consumers from Malaysia and Hungary do associate organic foods with higher quality.

Although health consciousness was expected to be an important reason for purchasing organic foods, this finding is contrary to the conventional wisdom. According to [84,89], health concerns were found to be more important than environmental issues for Indian consumers while they make purchasing decisions for organic foods. However, this study finds Malaysian consumers do not significantly associate health consciousness with their intention to purchase organic foods, but they do associate health consciousness with food innovation adoption, which is an important finding. FIA seems to fit the missing piece of the puzzle, in that it explains the inter-relationship between the health consciousness of consumers and their intention to purchase organic foods, as a mediator.

Food innovation adoption is the most crucial reason for the intention to purchase organic foods in Hungary. Hungarian consumers seem to show greater awareness of food innovations compared to Malaysian consumers. This is perhaps due to the greater usage of technology in the agricultural sector in Hungary and Europe in general, as compared to Asia where most countries still rely on human labor for agricultural output [90–92]. The labor intensity in Asian agricultural production could also be related to the type of crops they harvest. Rice cultivation is purportedly more labor-intense as compared to wheat production, contributing to the greater demand for human labor in Asian agriculture (Vollrath [93]).

A lesser emphasis on human labor in agriculture possibly allows European countries such as Hungary to focus more on food innovation technology. As a result, both capacity and performance in ecological innovations are found to be better in European countries, as compared to Asian countries [94]. The Hungarian data analysis shows the distinctly high impact of FIA (Beta Coefficient = 0.414) on consumers' intention to purchase organic foods. While FIA is a third important factor for Malaysian consumers, this finding shows a significant difference between European (Hungarian) and Asian (Malaysian) consumers. Food innovation adoption is an important determinant of intention to purchase organic foods among buyers in Europe, but not a strong determinant in Asia.

Although environmental concern was significant in determining Romanian consumers' eating habits (Oroian et al. [95]), this study finds environmental concerns do not have a substantial effect on Malaysian consumers' intention to purchase organic foods, and it is also the second least important factor that predicts the intention to purchase organic foods in Hungary. This inferior result of EC could be due to current consumers' motives in consuming organic foods, which is not primarily driven by their intention to protect the ecological environment. Rather, their motives are based on social lifestyle factors and perceived quality (for Malaysia) and food innovation, perceived quality, and health concerns (for Hungary). This finding is consistent with recent research that found health factor and maintaining social status in society take priority in consumers' minds over environmental safety [96].

The results for FIA reveal peculiar findings. EC is the most crucial determinant of FIA in Malaysia, while it is not significant in Hungary (but significant on CP in Hungary). Environmental concerns or ecological consciousness are seen as important determinants for FIA among Malaysians. There is a strong association between environmental protection and food innovation technology in Malaysian consumers' minds. These two dimensions are seen as highly connected. Conversely, for Hungarians, EC is seen as a 'distant factor' that has no direct impact on their food innovation adoption behavior. EC, although significant for Hungarians in their organic food purchases, is not something they associate with FIA. Perhaps Hungarian food consumers do not look at innovation in food technology as something that is truly protective and conserving the environment. This suggests a possible skepticism towards food innovation technology and production, which are perhaps not viewed as environmentally friendly albeit perceived to be producing good quality foods [97,98]. It is worth noting this major difference between Asia (Malaysian) and Europe (Hungarian) where Asian food consumers in this context associate environmental concerns with FIA, while European consumers seem not to associate the two.

Although Hungarian consumers do not associate EC with FIA, they strongly associate SL with FIA. Although social factors and status were not strong determinants of their intention to purchase organic foods, they are significantly more important in their FIA. This suggests Hungarian consumers consider social and lifestyle factors as trends that go together with innovation in the food sector. This possibly indicates that in their mind, innovation in food technology is just another social and lifestyle trend [99]. Social lifestyle trends are also found to be equally important elements in the Malaysian context which drive their adoption of food innovation. This could indicate a global trend of innovation in food technology being perceived by consumers as a social and lifestyle trend.

Hungarian consumers also show the high impact of PQ on CP, which indicates their high trust in food innovation technologies which are perceived to produce high quality foods, although they were skeptical about the environmental impact of FIA.

It was considered meaningful to include food innovation adoption as an important construct in the modelling of this study and to provide an understanding of the wider ecosystem of organic food consumerism. The indirect effect results show that food innovation adoption seems to significantly mediate the relationships between the independent and dependent variables for both countries in most relationship paths. For Malaysian consumers FIA effectively mediates the impact of EC and SL on CP, while for Hungarian consumers FIA effectively mediates the impact of HC, PQ and SL on CP. For an elusive construct such as the FIA which had previously been less understood, the findings of this research show its pivotal role in understanding the ecosystem of organic food consumerism.

6. Conclusions

Consumer consciousness towards a more natural lifestyle and consumption behavior has led to various attempts to incorporate technology and trends in food production innovations. Various studies have discovered that buyers were increasingly troubled about the kind of foods they consume daily [100,101]. The rising interest in nutritious foods is reflected in consumers' demand for organic food alternatives that promise better quality foods through the innovative use of technology and innovation in production. Food innovation serves the twin-role of providing high quality foods, as well as increasing the production of foods to meet rising global food demand.

Cross-national studies are gaining popularity as they are meaningful ways to provide new insights into consumer behavior by comparing consumer choices and actions in different cultures [87]. To add to this body of literature, this study measured important factors that influence the intention to purchase organic foods in Hungary and Malaysia, both countries that are strong in agricultural output in their regions. Additionally, this study identified food innovation adoption as an important variable to be included in the model as evidenced in recent food technology literatures, to better understand the organic food consumerism ecosystem impacted by food innovation technologies. We found food innovation adoption plays a critical role in explaining consumers' organic foods purchasing behavior in Hungary and Malaysia.

The marketing of organic foods could emphasize the quality of organic foods as this is found to be the biggest driver of the intention to purchase organic foods in both countries. Social and lifestyle factors are highly significant in driving purchasing intentions. Consumers associate organic foods with trends in society and see it as a lifestyle choice. This could be a persuasive narrative for governments, policy makers, organic food producers, and retailers in improving engagement with consumers to promote sustainable consumption behavior. This could also lead to greater involvement of organic food buyers in the organic foods value chain, which is desirable for consumers [102]. Organic food growers and retailers may provide more information and transparency regarding their cultivation process, which is often invisible to final consumers. This lack of transparency may be leading to skepticism towards food innovations that are utilized in the production of organic foods.

7. Limitations of the Study and Future Directions

Although the sample size obtained in this study was statistically significant, the demographics of the respondents from both countries were not similar. A more proportionate sampling of respondents based on national population statistics may provide more comparable data. Future studies could investigate demographic control variables as well as assess their moderating effects on food innovation adoption and the intention to purchase organic foods.

The purposive sampling methodology was used to select respondents in this study, due to the absence of a sampling frame. Future studies could collaborate with retailers to create a list of organic foods purchasers through customers' purchase records to target actual customers who have purchased organic foods to be included for data collection.

This study is also limited in measuring the consumer purchase behavior related to organic foods. We used purchase intention as a measure to estimate actual behavior. Future studies can address this limitation by measuring the actual purchase of organic foods.

There seems to be a higher level of skepticism, especially in Europe, regarding the relationship between environmental conservation and food innovation. More work is needed in this area to discover the reasons behind the skepticism and to further assess the impact of food technology and innovation on environmental protection and preservation in the context of organic foods.

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SUSTAINING FOOD SECURITY IN MALAYSIA

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Article

Patterns and Causes of Food Waste in the Hospitality and Food Service Sector: Food Waste Prevention Insights from Malaysia

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Abstract: Food waste has formidable detrimental impacts on food security, the environment, and the economy, which makes it a global challenge that requires urgent attention. This study investigates the patterns and causes of food waste generation in the hospitality and food service sector, with the aim of identifying the most promising food waste prevention measures. It presents a comparative analysis of five case studies from the hospitality and food service (HaFS) sector in Malaysia and uses a mixed-methods approach. This paper provides new empirical evidence to highlight the significant opportunity and scope for food waste reduction in the HaFS sector. The findings suggest that the scale of the problem is even bigger than previously thought. Nearly a third of all food was wasted in the case studies presented, and almost half of it was avoidable. Preparation waste was the largest fraction, followed by buffet leftover and then customer plate waste. Food waste represented an economic loss equal to 23% of the value of the food purchased. Causes of food waste generation included the restaurants' operating procedures and policies, and the social practices related to food consumption. Therefore, food waste prevention strategies should be twofold, tackling both the way the hospitality and food service sector outlets operate and organise themselves, and the customers' social practices related to food consumption.

Keywords: food waste; food loss; hospitality; food service sector; food waste prevention

1. Introduction

One third of food produced globally for human consumption is lost or wasted, which amounts to approximately 1.3 billion tons per year [1]. Food waste's formidable economic, environmental and social impacts have been recognised at the highest levels of global governance. The UN's sustainable development goal for responsible consumption and production urges the world to "halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" by 2030 [2]. The FAO recently launched the 'Global initiative on food loss and waste reduction' aiming to reduce food wastage throughout the food system by facilitating collaboration, coordination, and research and by raising awareness [3].

Food waste is produced along the various stages of the food supply chain [4]. The hospitality and food service (HaFS) sector (for the definition of the HaFS sector refer to [5]) has been identified as a sector with significant potential for food waste prevention, hence food waste from this sector has recently received increased attention in research [6,7]. Recent studies are building an understanding of the drivers giving rise to food waste [8,9] offer suggestions for food waste prevention strategies targeting consumers' attitudes and behaviours [10,11] or alternative approaches drawing from social practice theory [12]. The majority of research on food waste provides evidence from developed countries such as Scandinavia and Norther Europe [6,13,14], Northern America [15], and Southern Europe [16] with only few studies providing a developed country/ emerging economy perspective [17–19]. Despite their different perspectives, methodological approaches, and contributions, all of the above studies highlight the lack of sufficient evidence on how, why, how much and what type of food is wasted in the HaFS sector, and what could be done to prevent it. This is the research gap that this study seeks to address.

Therefore, this research aims to determine the patterns and causes of food waste generation in the hospitality and food service sector, in order to identify the most promising measures for food waste prevention. This paper presents a comparative analysis of five case studies from the HaFS sector in Malaysia, providing much needed evidence from a developing country perspective [7]. The study positions itself in the interface between quantitative and qualitative research, drawing on methods from ethnography and grounded theory, complemented with concepts and tools from industrial ecology.

2. Literature Review

Food waste is a growing issue due to its environmental [1,20–23], economic [24–27] and social implications [28–30]. Food waste has high carbon, water and ecological footprint [31–33] as well as negative impacts on cropland and fertiliser use [34]. Most importantly, it is recognised that food waste reduction has an important role to play in the quest for global food security [4,35,36].

Academic research on food waste has focused on developed countries [37,38] and households [39]. The material and social contexts of food waste practices [12,40] and in particular awareness around food and waste matters [41,42], lifestyle [43], technology and innovation [13,44], food shopping, preparation and consumption behaviours [45–47] are central in understanding household food waste. Discussions on household food waste centre around waste separation behaviour, especially in highly density housing areas [48,49], waste prevention [50,51], the perspective of the consumer, namely how consumers experience aversion when they waste food [52,53], how food consumption practices influence waste generation [54,55], and the role of social media campaigns in food waste prevention [56,57].

Outside the household focus, studies have examined the scale and nature of food losses and waste in the entire food chain expressed in weight, calorific content and economic value [4,58,59]. In hospitals case studies have highlighted the scale of the food waste problem [25], shown how catering practices and public procurement impact food waste generation [60], and how reduced portion sizes, bulk meal delivery systems, improved forecasting, and provision of dining rooms can be effective food waste minimisation strategies [61,62]. Research focusing on the retail sector highlights the complex and varied causes of food waste and suggests multifaceted prevention approaches [61,62] including social media campaigns with mixed results [57]. In the food industry, studies argue that clearer communication and stronger cooperation amongst the main actors in the food supply are essential for food waste reduction, through waste avoidance and donations of edible fractions to charitable organisations [63,64]. Case studies in universities have explored food waste reduction interventions such as tray-less delivery systems [65], written messages encouraging pro-environmental behaviour [11,66] and a social media-based food sharing tool [67] with mixed results.

Finally, in the HaFS sector research has focused on quantifying and monitoring food waste [6,9,14,68], other studies suggested that food buffet services and overproduction are two of the main causes of food waste [15,69], and revealed that 'nudging' techniques can lead to food waste minimisation [11,70]. Other studies have attempted to quantify food waste and understand the processes that give rise to it in order to propose recommendations for food waste reduction [12,15,71–73]. Food waste prevention has been recognised as the most advantageous option for addressing food waste [74], and food surplus management identified as essential in achieving prevention [75]. Food surplus management includes the redistribution to people affected by food poverty as a means of achieving food waste reduction and urban food security [76,77]. However, the role that food surplus redistribution can play towards realising sustainable food is questioned [28,78]. It is argued that food surplus donations though civil society organizations, in fact, depoliticise food issues, focus on individual personal responsibility, and fail to address structural poverty [79,80]. Most studies acknowledge the need for more holistic understanding of the problem, and call for interventions at the individual, organisational, and policy levels [8].

3. Methods

Five case studies from the hospitality and food service sector in Malaysia were selected based on access, availability, type of food service (such as buffet style, *a la carte*, combination of the two), price range, type of cuisine, type of customers, primary function (such as work place canteen, hotel restaurant, banquet facility, standalone restaurant), and size (number of meals served per day) (for more details on the case studies please refer to Table 1). The selected case studies did not aim to give a comprehensive picture of the whole HaFS sector, but instead to offer opportunities to test how these variables affect food waste generation and prevention. Food waste generation was studied from the time of purchasing raw food supplies, throughout food storage, preparation and cooking, customer consumption and finally discarding food waste. It did not include waste collection and final disposal at the landfill or other waste treatment facilities, as these stages were outside the remit and control of the HaFS operations.

Table 1. Case studies summary table.

	Description	Size (Av. No. of Meals served Per Day)	Average Meal Price (RM[1]/USD[2])	Type of Service	Type of Customer & Function
HaFS Operation 1	Banquet facility	560	RM80–250 (USD22–68)	Buffet (all you can eat) Full table service Lunch, dinner, mid-morning and mid-afternoon coffee breaks	Local families/weddings, professionals on conferences, workshops, annual dinners, promotional events
HaFS Operation 2	Chinese cuisine restaurant	210	RM60–150 (USD16–41)	*A la carte* Lunch, dinner	Local families, professionals in meetings, work colleagues
HaFS Operation 3	Malay cuisine restaurant	160	RM40–100 (USD11–28)	Buffet (all you can eat) *A la carte* Lunch, dinner	Local families, work colleagues, professionals in meetings
HaFS Operation 4	Five-star hotel restaurant	170	RM80–130 (USD22–35)	Buffet (all you can eat) *A la carte* Breakfast, lunch, dinner	Tourists, professionals in meetings, local families
HaFS Operation 5	University food court	6,440	RM5–20 (USD1–4)	Canteen buffet (pay what you eat) Breakfast, lunch, dinner	Students and university staff

[1] RM: Ringgit Malaysia; [2] USD: United States Dollar.

Mixed methods were used for data collection and analysis based on the methodological framework developed by Papargyropoulou et al. [81] (pp 328-330). Figure 1 presents the methodological framework and the following sections elaborate on the individual methods used.

Quantitative data collection methods used in the case studies aimed to identify processes and activities within the HaFS operations that give rise to food waste [82]. They were used to measure the amount of food waste generated from these processes in order to prioritise the most promising measures for waste prevention. The quantitative data collection methods comprised of a food waste audit, photographic records, and collation of financial records and inventory of food purchases. During the food waste audit, the amount and type of food waste were measured and recorded continuously throughout the day and for a sufficient length of time (continuously for one week) in order to account for daily variation [83]. The length of the waste audit exceeded the recommended 3 days duration by WRAP and the Sustainable Restaurant Association, in order to improve data reliability [5,84]. Building on previous research [84] three types of food waste were monitored. 'Preparation waste':

produced during the food preparation stage, due to overproduction, peeling, cutting, expiration, spoilage, overcooking, etc. 'Customer plate leftover waste': food discarded by customers after the food has been sold or served to them. 'Buffet leftover waste': excess food that has been prepared but has not been taken onto the customer's plate or consumed thus left on the buffet or a food storage area and later on discarded. The ingredients of the food waste were also recorded to categorise food and food waste into nine food commodity groups (Table 2) and produce detailed Sankey diagrams of Material Flow Analyses (MFA). In addition, in-situ estimates of the edible fraction of food waste were made based on visual observations, in order to understand how much of the food waste was avoidable or unavoidable (for definitions of avoidable and unavoidable food waste refer to [5].

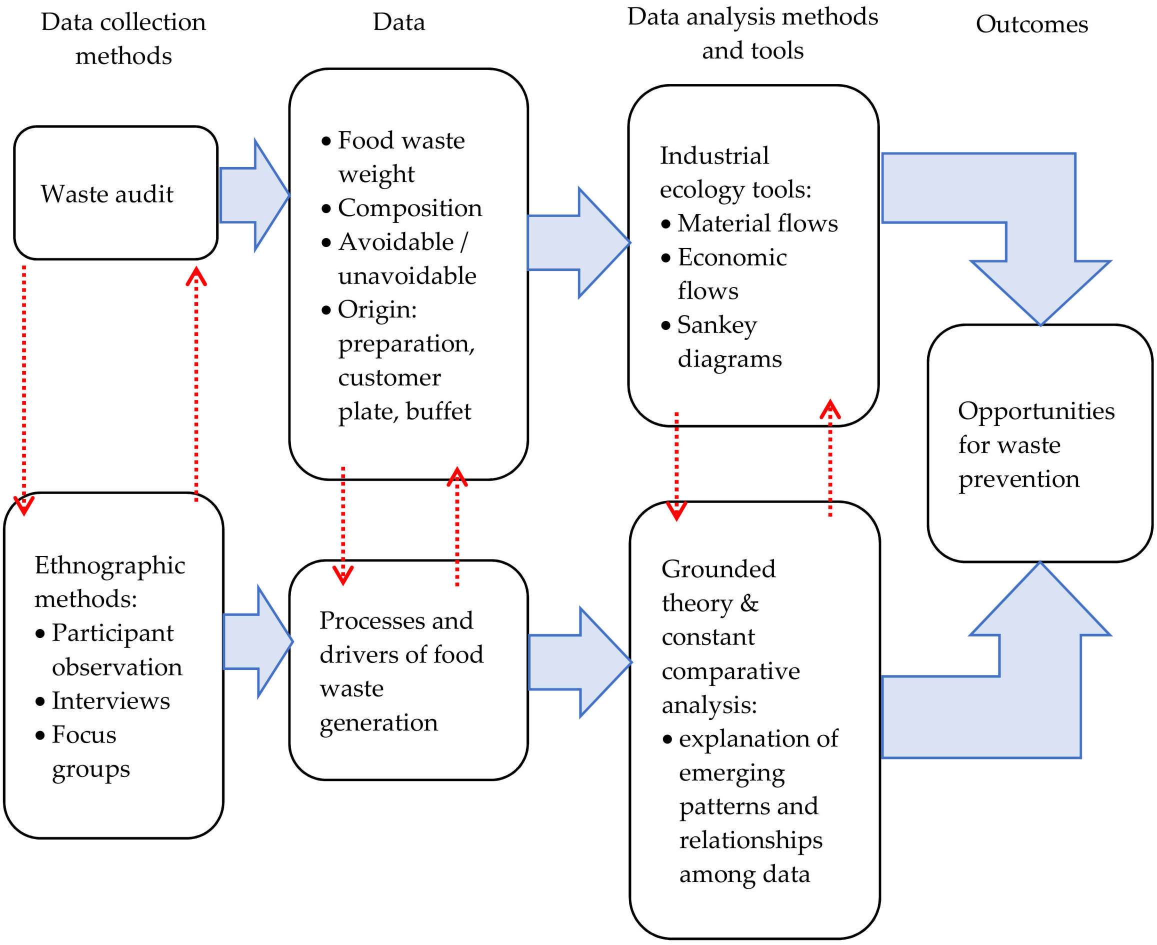


Figure 1. Conceptual framework for the study of food waste generation and prevention in the hospitality and food service sector (Adapted from [81]).

Table 2. Food commodity groups used in this study to categorise incoming food and waste.

Food Commodity Category	Type of Foods Included in the Category
Cereal and grains	Rice, pasta, noodles, bread, flour, pastries, other wheat, barley, maze, oats products
Dairy	Milk, cheese, yogurt, ice cream, and other dairy products
Eggs	Eggs
Fish and seafood	Fresh water fish, demersal fish, pelagic fish, other marine fish, crustaceans, other aquatic animals, and plants
Fruits	All fruits
Meat	Bovine meat, mutton/goat meat, pig meat, poultry meat, other meat, offal
Oils and fats	Olive, palm, vegetable oils, butter other animal and vegetable oils and fats
Sauces incl. liquid fraction of dishes	All premade and in-situ prepared sauces, including tin tomatoes, salad dressing, canned soup, and all other liquid fractions within dishes
Vegetables, roots, and pulses	All vegetables, potatoes, and pulses

The weight and composition of the food waste were combined with the food purchasing inventory to calculate the economic losses due to food waste. Sankey flow diagrams were used to visualise the magnitude of the material flows taking place within the HaFS operations. The thickness of each link represented the amount of flow from a source to a target node, on this occasion from food provisioning to food consumption. The flows are presented in % rather than kg/day to facilitate comparison amongst the case studies.

Qualitative data collection and analysis methods complemented the quantitative methods. Qualitative data were collected via interviews, participant observation, and focus groups. In-depth structured and informal non-structured interviews of the employees and customers from across the five restaurants and representatives of the National Solid Waste Management Department (NSWMD) were carried out (25 interviews with staff and 2 customers across all HaFS operations and 3 interviews with representatives of the NSWMD). Following the initial round of in-depth interviews, participant observation combined with informal non-structured interviews with the restaurant employees were conducted while collecting quantitative data. The observations were recorded through field notes in the form of a diary [85]. Three focus groups with employees from the participating HaFS operations were also undertaken following some preliminary data analysis. The participants of the focus groups comprised members of the management, procurement, sales, finance, food preparation, and operations teams (for stakeholder engagement methods see [86,87]). The first focus group included staff from 3 HaFS operations 1, 2, and 3. The second focus group included staff only from Operation 4, and the third included staff only from Operation 5. The focus groups allowed for verification of the data collected through the other data collection methods and offered an opportunity to seek clarification on behaviour recorded during the participant observation. It offered further insights as to where, how, why food waste was produced, and recommendations on how to prevent it.

Qualitative data were analysed with the use of the constant comparative method, an inductive and iterative data coding process used for categorising and comparing qualitative data for analysis purposes [88]. The constant comparative method is a key principle in Grounded Theory [89,90]. This coding process allowed for key themes to emerge from the qualitative data, and for relationships between these themes to become apparent. It allowed to again a better understanding of why and how food waste was produced in the participating HaFS operations, and what can be done to prevent it.

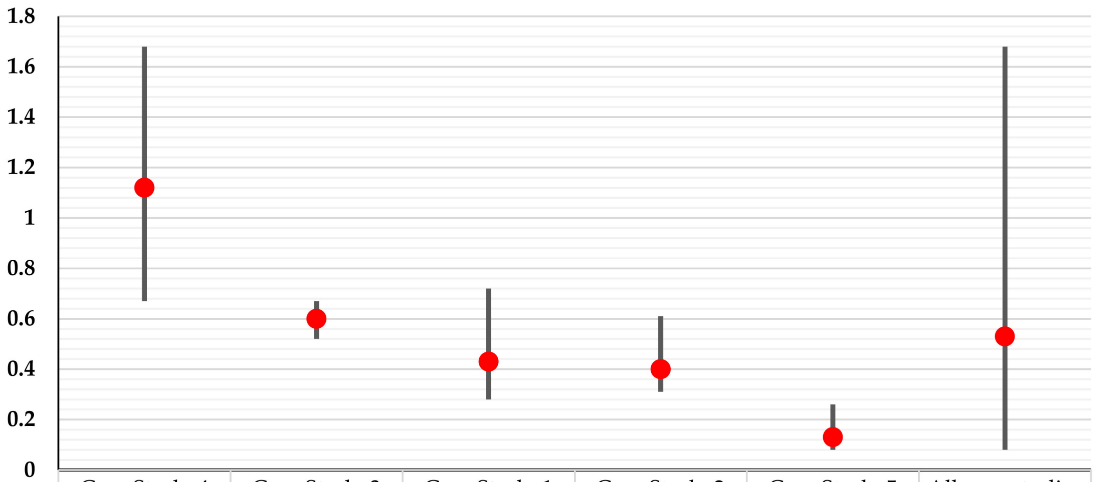
The quantitative methods identified the type and measured the amount of food waste generated, whereas the qualitative methods built a better understanding of the causes and patterns of food waste generation. Gaining an understanding of how much, what type, why and how food waste was generated, ultimately helped to identify the most promising measures for food waste prevention. The proposed waste prevention measures target the causes of food waste generation identified, and draw on insights from the interviews conducted in this study, as well as recommendations from the wider literature.

4. Results and Discussion

The characteristics of the five case studies presented in this paper are summarized in Table 1. Case Study 1 (HaFS Operation 1) was a high-end banquet facility, serving food for a number of events every day such as conferences, meetings, weddings, promotional events, workshops, and annual general meetings. It served on average 560 meals throughout the day, either buffet style or full table service to a variety of customers. Case Study 2 (HaFS Operation 2) was a mid to high-end standalone Chinese restaurant, serving *a la carte* lunch and dinner to approximately 210 customers a day. Case Study 3 (HaFS Operation 3) was a mid-range, buffet or *a la carte* style, Malay restaurant, serving approximately 160 meals a day. Case Study 4 (HaFS Operation 4) was a mid to high-end restaurant operating within a five-star hotel, and serving approximately 170 meals throughout the day, with buffet or *a la carte* service. Case Study 5 (HaFS Operation 5) was a university canteen comprising nine independently ran food outlets operating within the same ’food court’ space. It serves more than 6000 affordable meals throughout the day to university students and staff.

4.1. Patterns and Causes of Food Waste Generation

Food waste generation varied substantially amongst the HaFS operations studied. Figure 2 compares the HaFS operations according to their average food waste generation per customer. On average 0.53kg of food waste was produced for every meal/ customer served, however the most wasteful restaurant (Operation 4) produced over eight times more waste per customer compared to the least wasteful restaurant (Operation 5). This result highlighted how case-specific conditions can have a very significant impact on food waste generation, as suggested by other studies [6,14,18,58,91]. The top three restaurants in Figure 2 offered buffets where the customer could enjoy unlimited food for a fixed price. In the least wasteful restaurants, the customers paid according to what they consumed. These results indicate that 'all you can eat' buffets are more wasteful compared to the *a la carte* food service. Several reasons were behind this result and are elaborated on below.



	Case Study 4	Case Study 3	Case Study 1	Case Study 2	Case Study 5	All case studies
Min.	0.67	0.52	0.28	0.31	0.08	0.08
Max.	1.68	0.67	0.72	0.61	0.26	1.68
● Average	1.12	0.6	0.43	0.4	0.13	0.53

Figure 2. Food waste per customer (kg/ customer).

Preparation waste was 15–55%, buffet leftover 22–50% and customer plate waste 23–35% of total food waste, showing significant variation across the HaFS operations studied (Figure 3). Operation 2 did not offer a buffet, therefore did not generate any buffet leftover waste. This led to the other two waste types, e.g., preparation and customer plate food waste to appear seemingly higher as percentages of the total food waste. Significant variation has been reported in other studies where preparation waste was 5-31%, buffet leftover 7-44%, customer plate waste 4–37% [68]. Customer plate was the smallest fraction of the food waste produced, contrary to the opinions of the restaurants' staff and management as revealed during the interviews and focus groups. As the porter in Operation 3 explains while he is washing the dishes:

> I see the plates when they come back here to be washed. The stuff that people waste is so much. And good food too. We need to educate them [customers] but it's hard because they don't see all the work that goes on back here, just the finished dish. I tell you, this is where the problem is.

The customer was often blamed for the high food waste generation rates (for blaming the consumer see [40,92,93]). The restaurant staff and management were surprised by the results of the study showing that a significant potential for food waste prevention was within the scope and power of the restaurant itself, e.g., reducing preparation and buffet leftover waste.

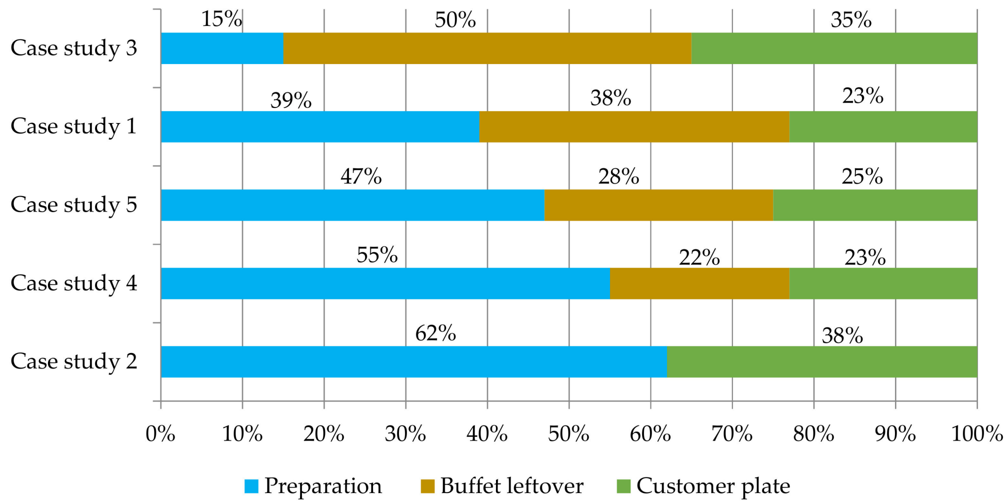


Figure 3. Percentages of preparation, customer plate, and buffet leftover waste fractions.

Customer plate waste showed the least variation across the HaFS operations, however, preparation and buffet leftovers were significantly different across the restaurants studied. The highest preparation waste percentage was observed in Operation 2, followed by Operation 4, Operation 5, Operation 1, and finally Operation 3. The order of the HaFS operations in terms of buffet leftover waste percentage from highest to lowest is the reverse i.e. Operation 3 has the highest percentage of buffet leftover, followed by Operation 1, Operation 5 and finally Operation 4 (Operation 2 did not offer a buffet, therefore is excluded from this analysis). These patterns are explained below: Operation 3 (Malay restaurant) is attached to Operation 1 (banquet hall) and operated by the same company. Buffet leftover from the banquet hall that had not been served was directed to the Malay restaurant and included in their buffet. This method reduced buffet leftover waste from the banquet hall and preparation waste from the Malay restaurant. It also made Operation 3 preparation waste percentage seemingly appear low and buffet leftover percentage to appear high.

Preparation waste percentage was the highest in Operation 2, Operation 4 and Operation 5. These were the restaurants where meals were prepared from scratch using fresh ingredients, leading to higher preparation waste rates. Observations and interviews identified poor cutting skills during food preparation as one of the contributing factors for high food wastage. For example, as the Head Chef in Operation 4 suggested:

> Some of the younger cooks don't know how to and they don't care. They have no training and they learn on the job, but they rush things to go faster and you see what they do [he points to a discarded watermelon skin with a lot of the ripe, red edible part of the fruit still on the skin]. That's why I only trust my experienced staff to cut the expensive stuff like meat and fish.

Avoidable food waste was 32–63% of total food waste across all HaFS operations, illustrating the substantial potential for waste prevention (Figure 4). The avoidable fraction measured in this study is comparable to that reported by Beretta et al [58] (p 771) at over two thirds of the total food waste. Preparation waste primarily consisted of unavoidable waste, such as inedible fruit and vegetable peelings, fruit stones, and bones. Customer plate waste had both inedible (unavoidable) and edible (avoidable) parts, whereas buffet leftover waste primarily consisted of edible (avoidable) parts.

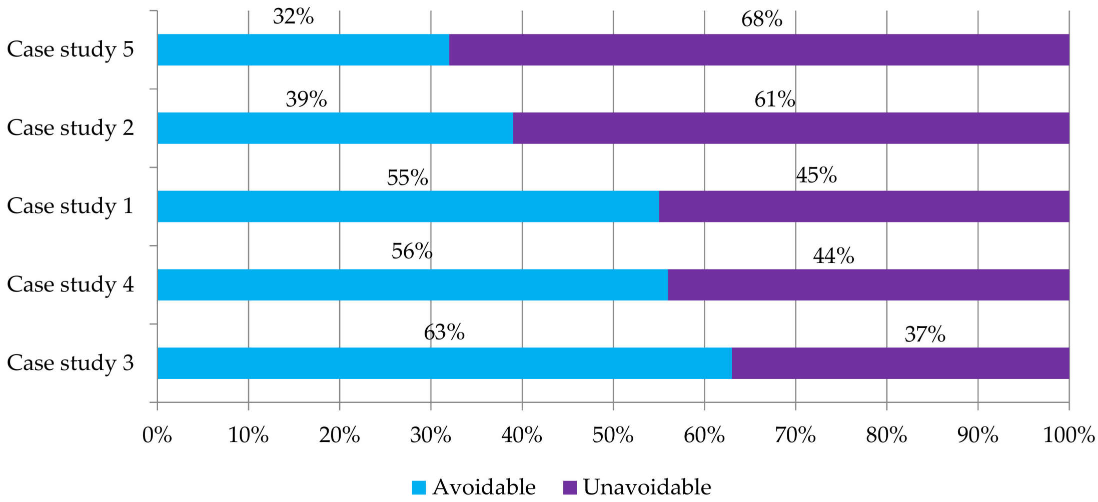


Figure 4. Avoidable and unavoidable food waste fractions.

Operation 3 (Malay restaurant) had the highest avoidable food waste fraction, due to the high buffet leftover rate. Operation 4 (hotel restaurant) had the second highest avoidable food waste fraction. Observations suggested that this was linked to the high preparation waste generated by the hotel restaurant due to high aesthetic standards (e.g. shaping a whole watermelon into a flower for buffet decoration) and cooking from scratch using fresh ingredients. Customer expectations for high aesthetic standards is potentially influenced by local culture. Although this study did not focus on this aspect, cultural factors can play a role in the way food is prepared, consumed and disposed of, as acknowledged in studies across different cultural contexts [15,16,19]. Operation 4 had in place a company-wide food safety policy stipulating that no food should remain on the buffet for a period longer than four hours. As a member of the kitchen staff in Operation 4 explained, this is a point of friction between the management team and the operations team:

> Look at this [pointing at food items on the buffet that have to be thrown away because they need to 'change over' the buffet]. This is bad, there's nothing wrong with this food, it could last for another 2 hours. We have to throw it away because they [pointing at the manager's office] are worried about HQ [headquarters].

As a direct result, every four hours staff would clear the buffet by throwing away all the food, and then replace it with a new batch of freshly prepared food. This practice generated quite substantial quantities of buffet leftover waste.

Although Operation 1 (banquet hall) diverted some of the buffet leftover waste (primarily avoidable waste) to Operation 3 and therefore practiced waste prevention, it still had the third highest avoidable fraction at 55%. Observations, discussions during the focus group, and the interviews revealed the following reasons behind food waste generation in Operation 1. As a banquet hall, Operation 1 catered for large functions such as weddings, conferences, workshops and marketing events. In many cases, the number of customers that turned up to these events was significantly lower than the number that the food was prepared for, for example as a waitress in Operation 1 explained:

> They [the customer] make a booking for 200 people and 100 turn up. They don't care, they have paid for 200 so we have prepared for 200. But it's such a waste, and we can't tell them off because you know, they are paying.

On other occasions, changes in the booking details, such as the menu and the number of participants, were made right up to the day of the event, as the Head Chef in Operation 1 stated:

> The booking department don't understand, they think we can change the menu and number [of meals prepared] last minute. I can't, I need at least a week, I need to put my order in purchasing [department] so I have the right ingredients and quantity.

In addition, the banquet hall had a policy of preparing 30% more food than what was required based on the reservations, in order to avoid running out. This practice led to a systematic production of food surplus that eventually caused food waste. Finally, there were instances where the menu that was selected was not appropriate to a specific event and layout, causing food waste. For example, a very 'heavy' and 'rich' menu comprising curries, stews, and rice, was selected for a marketing event where the layout of the dinner aimed to encourage networking amongst participants and as such did not have chairs. Participants could not easily eat the type of food offered without sitting down, which led to substantial buffet leftover waste. As a member of the staff from the Bookings department in Operation 1 describes, 'Finger' food would have been a more appropriate menu for this type of event [94]:

> I told them [the customer] this is not the best menu for the type of event he picked, but he didn't listen. He wanted 'proper' food you know, not 'finger' food. But the layout was set up for networking, no chairs, so people couldn't eat the curry standing up. And he had all these models and actresses coming, celebrities, you know they didn't eat anything!

Operation 2 (*a la carte* Chinese restaurant) had the second lowest avoidable food waste percentage, due to the fact that it only offered *a la carte* service. Operation 2 had no buffet leftover food waste and food was prepared for the correct number of customers, rather than the estimated number of customers such as in the case of the buffet restaurants. Observations revealed that the waiting staff of Operation 2 had the opportunity to consult customers on the right amount of food to be ordered and explain the items on the menu so that the customers could avoid ordering too much or food they did not like. A waiter in Operation 2 explained how he learned to do this during his training:

> At training they always tell us how to explain the menu to customers. They tell us to give advice if they start ordering too much. Tell them things like 'this dish is enough for 2 people', or 'this is a big portion'. Sometimes they [customers] listen. But sometimes they want to show off, you know, when business people take big clients out.

Operation 5 (university canteen) had the lowest avoidable waste percentage and the lowest food waste generation overall, making it overall the least wasteful HaFS operation. The meals at Operation 5 were very affordable compared to the other HaFS operations. The quality and variety of food reflected the low price in Operation 5, nonetheless, the profit margins were considerably lower compared to the other HaFS operations. Interviews with staff and management of the university canteen revealed that the low profit margins were the main driver for using food more efficiently and minimising food waste. For example, a food stall operator in Operation 5 described how and where she sourced, planned for and prepared the food she sold on her stall:

> Each food stall makes one dish so we know what we need. I buy everything I need from the Dato Karamat market [the nearest fresh produce market], in the morning then cook it here. I don't make much, so I don't have much 'balance' [leftover food] when I finish up. When it's gone, it's gone. The students know that, so they come early before I ran out. I know when the students go back home so I cook less then, enough only for staff.

The canteen prepared only enough food for the number of customers expected even if that meant that the last customers did not enjoy the same variety as the first (unlike Operation 1 and Operation 4 where 30% more food was prepared in order to ensure the buffet never ran out).

There was a correlation between the total amount of food wasted, and the proportion of avoidable food waste. For example, Operation 4 the most wasteful HaFS operation, and had one of the highest proportions of avoidable food waste, whereas Operation 5 was the least wasteful operation and had the lowest proportion of avoidable food waste. The order of the most wasteful operations was Operation 4, followed by Operation 3, Operation 1, Operation 2, and finally Operation 5, as expressed by the food waste per customer rate (Figure 2). The order of the highest avoidable food waste percentage was Operation 3, followed by Operation 4, Operation 1, Operation 2, and finally Operation 5, almost the same as the order for the food waste generation. The correlation between food waste generation and avoidable waste suggests that the restaurants that ensured avoidable food waste was reduced also practiced food waste prevention overall. The least wasteful (in terms of avoidable food waste and of overall food waste) operations Operation 5 and Operation 2 had one thing in common: the customer paid according to what they ordered and not a flat rate like in the other HaFS operations where 'all you can eat' type of buffet operated. They also avoided food surplus and thus prevented food waste (for the transition of food surplus into food waste see [95]). Operation 1 (banquet hall) practiced some food waste prevention by diverting buffet leftover to Operation 3 and to their staff's canteen.

The consumers' expectations of a continuously full buffet with an excessive number of different items on offer were given as the main reason behind the restaurants' practice of producing 30% more food than what was required. Observations of food consumption practices in buffets highlighted the link between food waste generation, in particular customer plate food waste, and the customers' perceptions of 'value for money'. Discussions with customers and staff revealed that the notion of 'value for money' closely related to quantity not necessarily quality of food. For example, when asked whether they were satisfied with the buffet in Operation 1, a customer referred to the variety and abundance of the buffet, not whether the food was tasty:

> Researcher: Are you happy with the buffet?
>
> Customer in Operation 1: Yes, the buffet is good value for money. It has so many items, a lot of choice, and it was full even towards the end. I tried them all.

Observations illustrating this point include customers taking too much food on their plate, consuming only a small fraction of it, leaving a considerable amount of uneaten food on their plate, before going back to the buffet to take another plate. This cycle was repeated numerous times. These examples demonstrate how food waste generation was affected by the type of service provided such as 'all you can eat' buffets, the customers' expectations such as the social norm of buffet abundance, and food consumption practices such as binge eating (for consumption practices see [12,96]).

The Mass Flow Analyses for Operation 1, Operation 2 and Operation 4 illustrate that food waste accounted for 16–28% of the total food (Figures 5–7). Operation 3 and Operation 5 did not provide sufficient data to carry out analysis of the material and economic flows. The average food waste rate was higher than the average 18% reported by Beretta et al [58] (p 771), 20% reported by WRAP [5] (p 4), and Engström et al [97] (p 206); however, lower than the maximum food waste Beretta et al encountered during their study, of 45% at a gourmet restaurant. Cereal was the most wasted food commodity across all HaFS operations, followed by fruits and vegetables for the operations that offered buffets. This result corresponds with WRAP's study that encountered 40% of all waste was carbohydrates such as pasta, rice and bread [5]. These patterns can be explained by the fact that the HaFS operations wasted a lot of rice as buffet leftovers due to overproduction. In addition, rice as a component of plate waste was often linked to customers perceiving rice as a 'cheap filler' rather than a main component of the meal. As the waiter in Operation 2 stated:

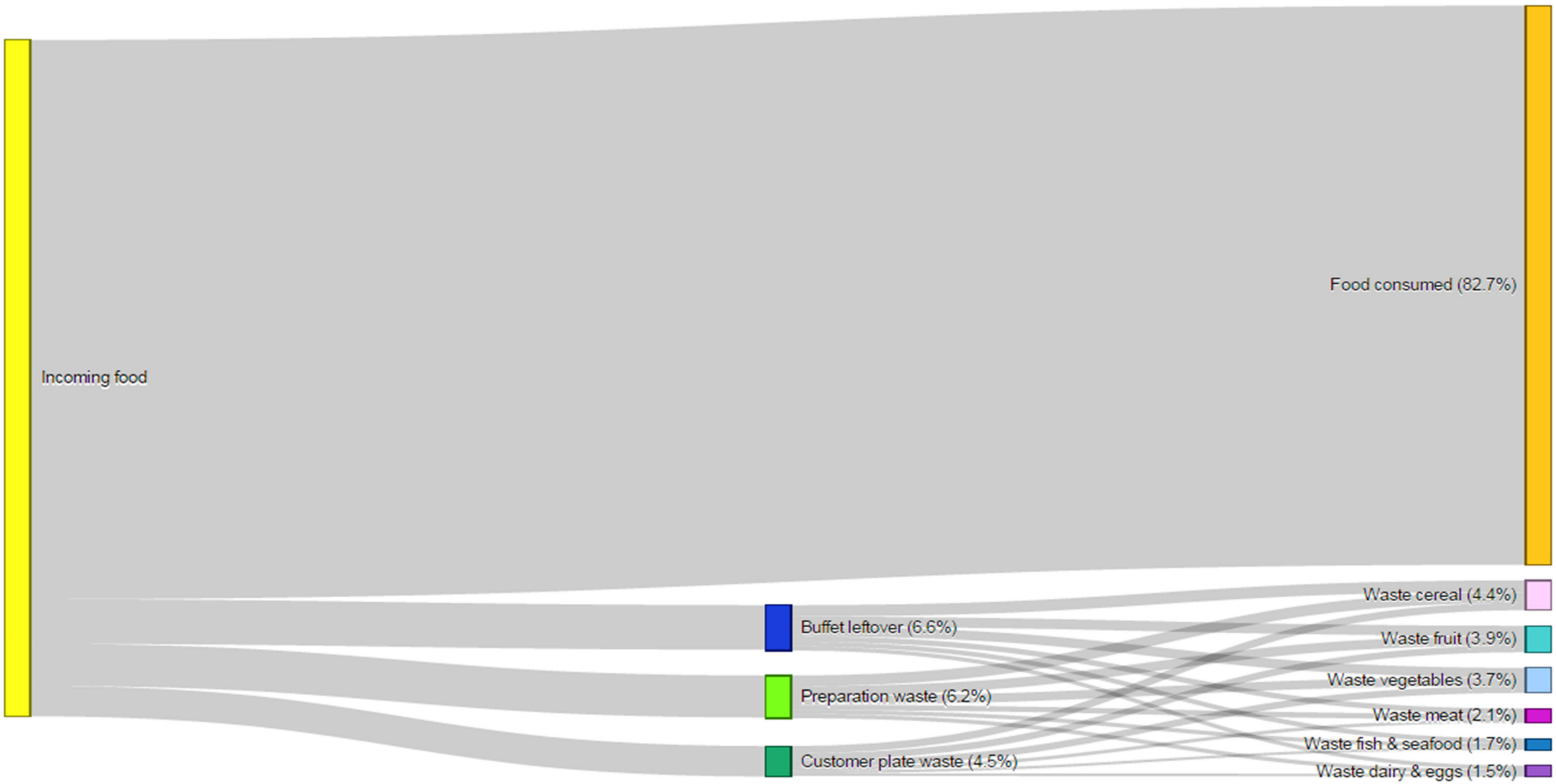


Figure 5. Material Flow Analysis for Operation 1 (banquet facility).

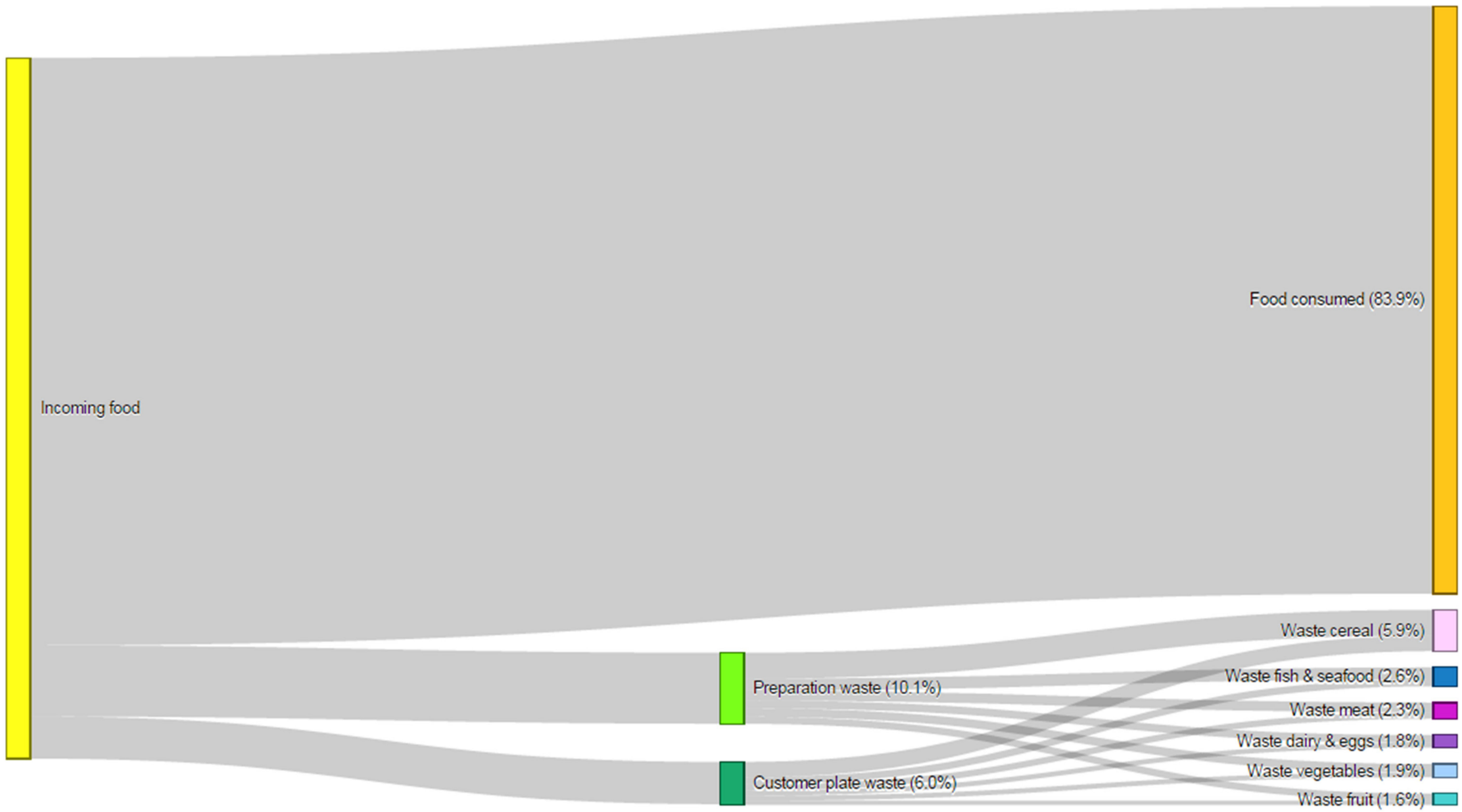


Figure 6. Material Flow Analysis for Operation 2 (Chinese restaurant).

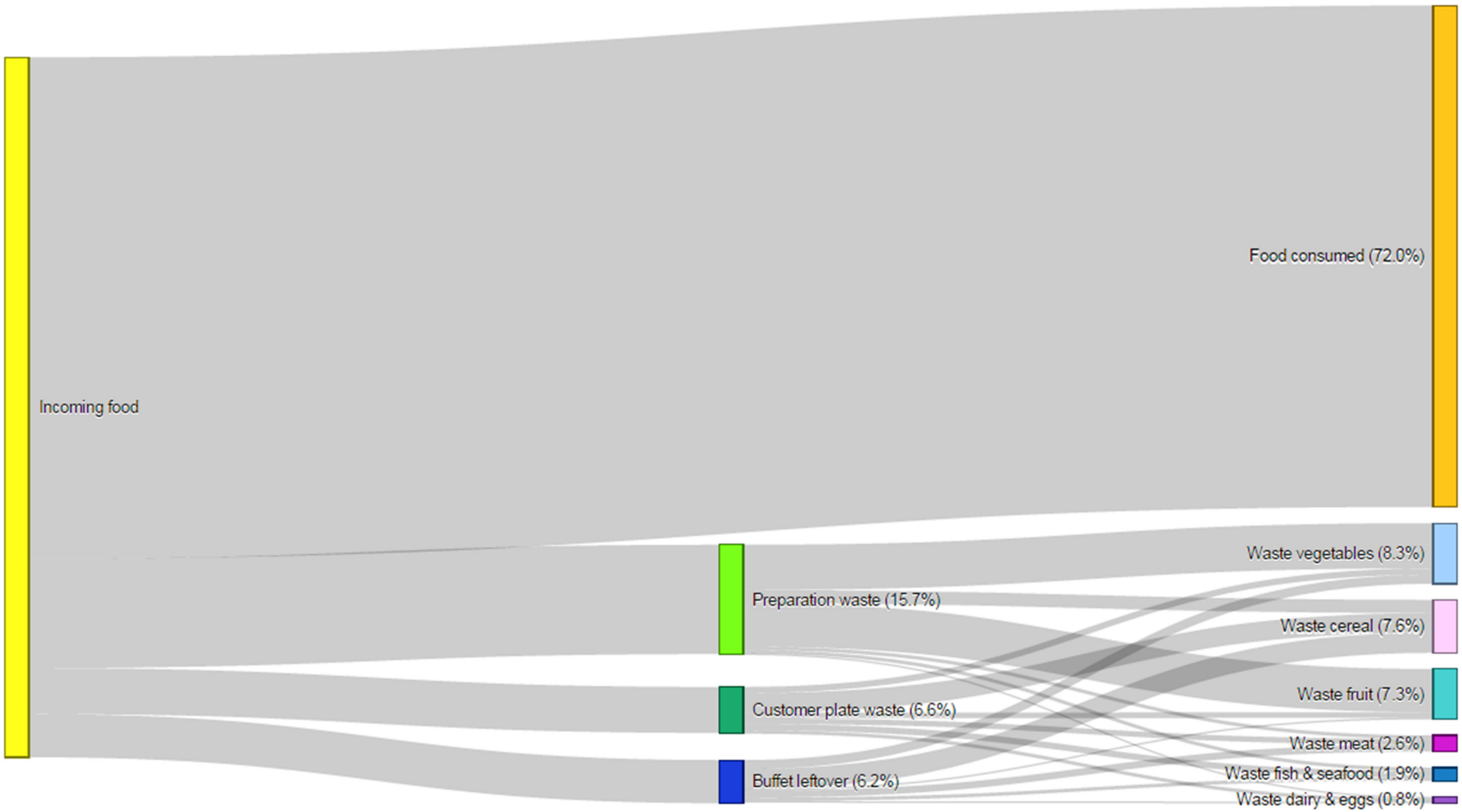


Figure 7. Material Flow Analysis for Operation 4 (Hotel restaurant) [81].

> The customers don't come here for the rice, they come because of our reputation for the meat and fish, and our speciality dishes on the menu. But the habit is always to order rice and most times they order more than they need. But it's cheap so they don't worry about it.

Fruits and vegetables were the main food commodities in the preparation waste of buffets, especially since they were quite heavy (for example watermelon skins) and were used in high quantities as they were cheaper than meat, fish, and seafood.

Food waste represented an economic loss of 16.4% of the value of the food purchased for Operation 1 (banquet facility), 16.8% for Operation 2 (Chinese restaurant) and 31.3% of Operation 4 (hotel restaurant). These results suggested that although Operation 1 was more wasteful in terms of mass, it performed better in economic terms than Operation 2. Operation 1 wasted more fruits and vegetables, that are cheaper compared to fish, seafood, and meat that were wasted in higher quantities in Operation 2. Operation 4 had significant losses both in mass and economic terms.

4.2. Food Waste Prevention Recommendations

The causes of food waste generation were grouped into two categories depending on whether they were related primarily to food production or consumption. In food production, food waste was generated in a systematic manner. The restaurants' operating systems and procedures (e.g. their food procurement, storage and preparation methods, and their reservation system) led to systematic food waste generation. During food consumption, the consumers' social practices were the main causes of food waste generation, however, the restaurants' operating procedures also led to systematic food waste generation. Recommendations for food waste prevention are presented in Tables 3 and 4 tailored specifically for preparation, buffet leftover and customer plate waste. These recommendations are designed to address the causes of food waste generation as observed in this study. They draw on recommendations that emerged in the interviews and from the wider literature.

Table 3. Recommendations for food waste prevention targeting systematic food waste generation.

Causes of Systematic Food Waste Generation	Food Waste Prevention Recommendations	Type of Food Waste Targeted by Recommendation
'All you can eat' buffets [15]	Opt for *a la carte* service	Preparation waste Buffet leftover Customer plate waste
	Opt for a 'pay what you eat' type of buffet	Customer plate waste
	Introduce a charge if food waste is left on customer's plate or offer a reward such as a discount, if no food waste is left on the plate [98]	Customer plate waste
Food surplus generation: policy of preparing 30% more food than what is needed	Prevent food surplus by preparing only what is necessary by improving the demand forecast [86]. This measure can be achieved by improving the reservation system in order to make accurate predictions of customer numbers (see recommendation below). Have staff on stand-by to prepare extra food if necessary. This measure requires the customers to accept that towards the end of the buffet all dishes might not be available. It also requires that the customer pays according to what they eat, or a type of compensation to the late customers that might not receive the full variety of the buffet, for example, a discount for customers arriving half an hour before the buffet closes.	Preparation waste Buffet leftover
Failure of booking system to accurately predict numbers [9]	Improve the booking system by confirming numbers the day before. Request a deposit when reservation is made to limit 'no shows'. Implement an 'only by reservation policy' where only customers that have made a reservation are accepted. A softer approach to this measure is to encourage customers to make a reservation by offering a discount. Customers that have no reservation can still dine, however they miss out on that discount.	Preparation waste Buffet leftover
Food safety policy stipulating that no food should be left on the buffet longer than 4 hours	Instead of having a 'blanket 'policy stipulating a specific number of maximum hours for food to be left on the buffet, develop a strategy that works in stages for assessing food safety. This strategy needs to be in line with the National Food Safety Regulations (Food Regulations 1985) and the Malaysian Food Act 1983. Chefs can assess on a case by case basis which dishes are more likely to become unsafe based on their ingredients, cooking and storage method. This way, dishes of higher risk can be removed from the buffet earlier than food items that can last longer (e.g. whole fruits such as apples, oranges, bananas, or pickled foods, or food items in protective packaging such as crackers). After the closure of the buffet, direct buffet leftover to staff canteen for immediate consumption. Ensure suitable food safety procedures are in place to avoid food poisoning and cross contamination in the staff canteen. Supervise this process closely to avoid staff eagerly removing buffet items earlier than they should in order to enjoy them in the staff canteen. Alternatively, redirect buffet leftover that is safe for human consumption to food charities and soup kitchens for immediate consumption [13]. This measure needs to be accompanied by strict food safety guidelines and a no liabilities agreement between the restaurant and the charity. The agreement needs to remove responsibility for food safety from the restaurant as soon as the food leaves its premises (see successful innovations in this field in [13]). Buffet leftover unfit for human consumption can be diverted to farms to be turned into animal feed. The animal feed needs to comply with food safety laws to prevent infecting animals with viruses such as Foot and Mouth. Diverting the remaining food waste to composting or energy from waste facilities is the next option for treating unavoidable food waste.	Buffet leftover
Lack of coordination between departments in restaurant	Improve communication between departments by regular meetings to resolve any conflicts and plan ahead for the daily schedule. In meetings the latest information should be shared amongst the departments, for example on the items and quantities of food supplies received, the cooking and food preparation schedule and menus, the reservations details including cancellations and last minute changes and feedback from customers and observations by the waiting staff for example which food items are always left on the plate, which buffet dishes need more or less frequent replenishment. Assign food waste prevention champions within each department. Align departmental performance criteria to resolve conflicts between the departments and have common targets [99]. Make food waste reduction one of these targets.	Preparation waste Buffet leftover
Inappropriate menu for eating occasion and sitting layout	In the cases of banquet facilities, train the reservations team to correctly advise the customer on the most appropriate menu for each sitting layout and type of function. Seek feedback from the waiting staff on the menus that work better with certain layouts and functions, based on their observations and customer feedback.	Preparation waste Buffet leftover Customer plate

Table 3. *Cont.*

Causes of Systematic Food Waste Generation	Food Waste Prevention Recommendations	Type of Food Waste Targeted by Recommendation
Aesthetic standards in the buffet and plate presentation	Avoid elaborate buffet and plate decoration designs where possible. Observe which items remain uneaten on the plates and eliminate them from the plate design. For example, garnishes that do not add flavour to the dishes could be eliminated without compromising the integrity of the dish. Reuse the decorative food items in other dishes. For instance, the watermelon cut into the shape of a flower to decorate the buffet, could be made into a smoothie or a juice to include as a special item for the next sitting.	Preparation waste Buffet leftover
Avoidable preparation food waste due to poor cutting skills	Train kitchen staff on cutting techniques. Observe and reward the best 'cutters' each month. Assign food waste prevention champions in the kitchen.	Preparation waste
The perceived value of food is linked to the price, for example, rice is cheap so it can be wasted (this is also relevant to food consumption practices - see Table 4)	Appoint food waste champions in the kitchen to highlight the importance of food waste prevention across all food groups, not only the expensive ones. Provide posters in the kitchen demonstrating good examples of food waste prevention and bad practices [100]. Provide training in cutting skills to reduce avoidable food waste especially of fruits and vegetables [101]. Update cooking equipment and improve cooking techniques to avoid instances whether rice is stuck at the bottom of the pan.	Preparation waste
	Avoid over production of rice, noodles and local fruits (all perceived less valuable due to their comparatively lower price) by reducing how much is prepared per customer in the buffet.	Buffet leftover

Table 4. Recommendations for food waste prevention targeting food consumption practices.

Causes of Food Waste Generation Related to Food Consumption Practices	Food Waste Prevention Recommendations	Type of Food Waste Targeted by Recommendation
Ordering too much food	Train waiting staff to correctly advice customers on the size and richness of the dishes. Offer smaller portions with the option to add more at no extra charge. Offer a range of dish sizes, such as small, regular, big and special sizes for children and side dishes [13,102]. Pack any leftovers and offer them as take away, as a standard practice unless customer instructs otherwise [11,103]. This measure should be accompanied by simple food safety instructions to the customer, such as 'consume within X hours and do not reheat', and a no liabilities clause for the restaurant for food that has left their premises.	Customer plate
Customer does not like a dish they ordered	Train waiting staff to explain the menu and ingredients to the customers, as well as give advice on which dishes complement each other.	Customer plate
Taking too much on plate in 'all you can eat' buffet	Reducing plate size has the potential to reduce food waste without compromising customer satisfaction [70]. Have restaurant staff stationed by the buffet to serve the food onto the customers' plates and explain the dishes and ingredients. Tray fewer systems have been proven to reduce plate waste especially in canteen settings [65].	Customer plate
Trying out all dishes in 'all you can eat' buffet	Offer the option for customers to taste the dishes as they go around the buffet before deciding whether they like it or not.	Customer plate
Customer's perceived value for money: quantity not quality	Altering the customer's perceptions of value is outside the control and remit of the restaurant. However, promoting the quality of the food rather than the quantity of the items on the buffet is one way of shifting the emphasis and attention of the customer. This can be done through the restaurant's marketing material for example by highlighting the culinary skills of the chefs, the uniqueness of the menu and the quality ingredients rather than just the number of the food items on the buffet. Use 'nudging' techniques to promote food waste reduction, such as displaying signs encouraging customers to come back to the buffet and help themselves more than one time, rather than take a lot of food on their plate all at once [70].	Preparation waste Buffet leftover Customer plate
The perceived value of food is linked to the price, for example, rice is cheap so it can be wasted (This is also relevant to the systematic food waste generation – see Table 3)	Display them in smaller serving dishes rather than in big containers. Reduce portion sizes for rice, noodles and local fruits in the *a la carte* service, but offer the option to add more at no extra charge. Place rice, noodles, and fruits at the end of the buffet line.	Buffet leftover Customer plate

5. Conclusions

This research's aim was to determine the patterns and causes of food waste generation in the hospitality and food service sector in Malaysia, in order to identify the most promising measures for food waste prevention. This aim was met by a) quantifying the biophysical and economic flows of food provisioning and waste generation, b) evaluating the social practices associated with food preparation and consumption, and c) linking the two (biophysical and economic flows, with social practices) in order to identify opportunities for food waste prevention.

A significant proportion of all food was wasted (16–28%) in the HaFS case studies presented in this paper, and almost half of it was avoidable (average avoidable food waste across all HaFS operations was 49% of total food waste). Food waste represented a substantial economic loss amounting to approximately 23% of the value of the food purchased. Preparation waste was the largest fraction, followed by buffet leftover and then customer plate waste, challenging the hypothesis that the consumer is to blame for the majority of the food waste. The restaurants' operating procedures and policies led to systematic food waste generation. Social practices related to food consumption were also identified as causes of food waste generation.

This paper provides new empirical evidence to highlight the significant opportunity and scope for food waste reduction in the HaFS sector. By identifying the causes of food waste, strategies for food waste prevention can be developed (for food waste prevention measures refer to Tables 3 and 4). Food waste prevention strategies should be twofold, tackling both the way the HaFS sector operates and organises itself and the customers' social practices related to food consumption. Food waste prevention measures targeting the systematic food waste production due to the restaurants' operations are within the restaurants' control, whereas changing social practices associated with food consumption is a more complex issue and requires a multifaceted approach. The main actor and implementer of these strategies should be the HaFS sector itself, as innovation and leadership in food waste prevention by the operators has the potential for significant cost savings. National policies and regulations can enable and reward food waste prevention. The HaFS associations can also provide support in the form of guidance, tools, and training.

Further research is required to expand on this study's findings in different contexts within the HaFS sector and to test the efficacy of the proposed food waste prevention measures. In this endeavour approaches, methods and tools from a variety of disciplines such as business, management, logistics, economics, environmental and waste management, sociology, phycology, behaviour studies, and sustainable consumption should be employed.

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Review

Transformation of the Food Sector: Security and Resilience during the COVID-19 Pandemic

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Abstract: The ongoing COVID-19 pandemic has resulted in a new era in the efficacy of the food supply chain, while the consequences of this new era on humanity, the economy, and the food sector are still under examination. For example, food security is one vital aspect of food systems which is directly affected. This review summarizes food security during epidemics and pandemics before moving on to panic buying, food shortages, and price spikes observed during the current crisis. The importance of food resilience, together with the need for addressing issues related to food loss and food waste, is underlined in the review towards food security and sustainable development. As a result, the pandemic has shown that our food systems are fragile. Since the global population and urbanization will grow in the coming decades, pandemics will likely occur more often, and climate change will intensify. Consequently, there is a need to ensure that our food systems become more sustainable and resilient. To that end, we have highlighted the need to develop contingency plans and mitigation strategies that would allow a more rapid response to extreme events (e.g., disasters from climate change) and transform the food sector by making it more resilient.

Keywords: food systems; panic buying; food shortage; food waste; food loss; sustainability; food supply chain

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1. Introduction

A sufficient amount of nutritious and safe food is necessary for sustaining life and promoting good health. However, as the world population increases, more efforts and innovations are needed in order to feed the population. Therefore, it is necessary to increase agricultural production sustainably, improve the global supply chain, decrease food waste and loss, and ensure that all people have access to nutritious food [1]. According to the Food and Agriculture Organization (FAO) of the United Nations, "*Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*." This definition points to the different dimensions of food security, including food availability, access, utilization, and stability of food supplies at global, national, and local levels [2]. The concept of stability refers to both the access and availability dimensions of food security, and within this context, the population must have access to enough food at all times. Access to adequate food must be reliable, and therefore, people should not risk losing access to food due to sudden unexpected climate, health, or economic crises. Currently, the world is struggling to fight a health crisis: The COVID-19 pandemic.

The pandemic represented a sudden psychological, economic, and partly physical disruption to markets, societal sub-systems, and citizens. Food security is among the four pillars of the food systems affected in the pandemic era [3], while the latest is additional exacerbating an ongoing nutrition crisis [4]. In 2019, almost 135 million people faced critical levels of acute food insecurity or worse. The number of people in 2019 was the highest in the 4-year existence of the Global Report on Food Crises [5], as shown in Figure 1. According to the United Nations World Food Program, the number people who deal with food insecurity could nearly double to 265 million at the end of 2020 due to the economic fallout of COVID-19 [6,7]. Unfortunately, the pandemic poses a potential threat to the Sustainable Development Goals and especially, the two food-security dependent goals, no poverty and zero hunger, will be hit hard during the lockdown period, particularly in developing countries [7].

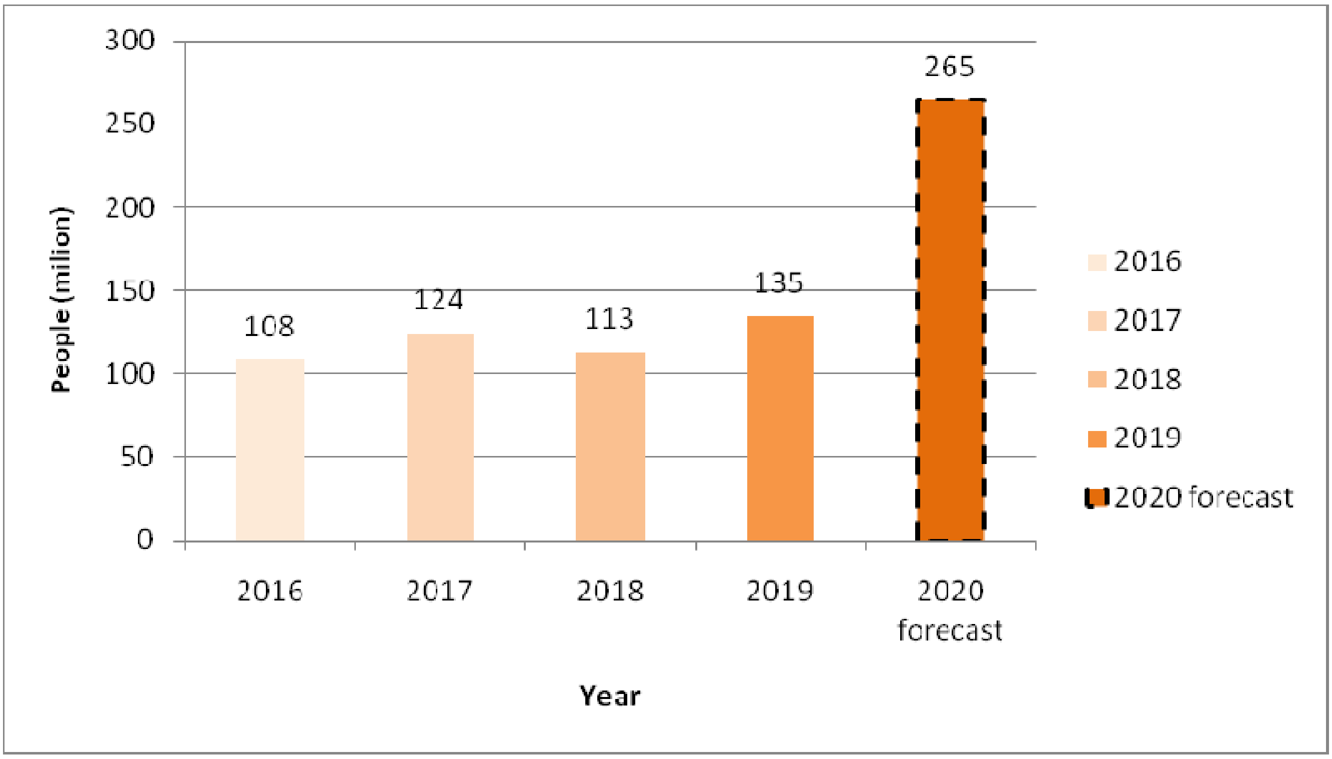

Figure 1. The number of people facing acute food insecurity. Adapted from [5].

The COVID-19 crisis has already changed food systems through its effects on demand, food supply, and capacity to produce and distribute food, the behavior of consumers such as panic buying, shortages in some food groups, and food waste and loss. Therefore, COVID-19 impacts all four elements (availability, stability, access, utilization) of food nutrition and security [8].

In the fall of 2020, the second pandemic wave reached the US, Europe, and other countries worldwide, causing additional lockdowns. Given the present uncertainties in availability, distribution, and acceptance of COVID-19 vaccines, the pandemic might continue well into 2021, and even a third wave cannot be excluded. Such repeated pandemic waves thus bring additional risk to food security. Therefore, the objective of this comprehensive review article is to evaluate the impact of the pandemic on food security. In that context, the article discusses disruptions and future threats to food security in the era of the COVID-19 pandemic and then explores the transformation of the food sector that will be necessary in order to achieve food resilience in the years to come.

2. Food Security during Epidemics and the COVID-19 Pandemic

Epidemics such as HIV/AIDS, Ebola, and Middle East Respiratory Syndrome (MERS) have negatively impacted food security. For example, the Ebola epidemic had a significant effect on the economies of some African countries' agricultural production, marketing, and trade. Vulnerable populations, including children, women, the elderly, and those living in poverty, were most affected [9]. During these crises, farmers could not transport their fresh produce to local and urban markets, and much-needed aid could not be delivered to schools. The distribution chain was also impacted as supply chains were delayed, and the workforce refused to travel to infected countries due to the fear of being infected. As a result, the price of staple foods in Guinea, Liberia, and Sierra Leone increased significantly. For example, the cost of rice and cassava increased by more than 30 and 150%, respectively [10].

During the COVID-19 pandemic, a number of measures were implemented to prevent the spread of the virus and protect public health. As a consequence of lockdowns during the pandemic, households with high dependence on labor income experience a big income shock that would jeopardize the food security of these households [11]. Unfortunately, the current pandemic has precipitated an economic crisis as well as an ongoing food security and nutrition crisis, and it is still not easy to predict how COVID-19 will affect long term food security. However, previous pandemics and global crises have shown that impacts on food security can be rapid and of dramatic proportions [12]. Currently, risks, fragilities, and inequities in global food systems are arising almost daily.

The COVID-19 pandemic has been a wake-up call for food systems, which have already been sitting on a knife-edge for decades [4]. Food systems [13] incorporate all of the various food production stages including preparation, processing, distribution, consumption, and disposal. Moreover, the adequate delivery of food to consumers involves land use, agricultural inputs, infrastructure, shipping, and different actors (e.g., farmers and retailers) [3]. Thus, lockdowns and disruptions triggered by COVID-19 have complicated the interactions among these various food system elements. The whole food system, from the primary supply to the final demand, was disturbed during the COVID-19 pandemic [7]. As reported by the European Commission, the food system itself should be transformed into a more inclusive, diverse, resilient, competitive, responsible, and sustainable form [13]. The current pandemic has already affected the entire food system, presenting an extraordinary challenge with profound social and economic consequences, including compromising food security and nutrition, as outlined in the Joint Statement on COVID-19 Impacts on Food Security and Nutrition [14].

3. Panic Buying, Food Shortages, and Price Spikes

Table 1 presents the impacts of the pandemic on food systems. The instability caused by a shock and the related behavioral modifications can result in occasional price spikes, market and supply disruptions, and food shortages [12]. The COVID-19 pandemic affected the shopping and cooking behavior of consumers who were spending more time at home and started to cook more than ever. In addition, the uncertain consequences of the lockdowns worried consumers with regards to adequate supplies and the distribution of food products. This resulted in panic buying as many people stockpiled large amounts of products. Panic buying behavior typically originates as a result of customers purchasing more than usual not as a result of restricted food availability. Indeed, and ironically, the panic buying trigger seemed to be the moment when people were told *not* to panic. This trend was partly boosted by the media, who frequently showed pictures of empty shelves and consumers who were imitating other people's panic-driven yet irrational and irresponsible behaviors.

Table 1. Impact of the COVID-19 pandemic on the food systems.

Sector	Impact
Production	• Decreased availability of food • Price spikes • Shortage of inputs and labor • Demand collapsed due to lockdowns • Disposal of perishable foods and increased food waste amounts
Processing	• Price spikes • Innovations gap due to lack of investments • Demand collapsed due to lockdowns • Income reduction and unemployment of workers • Disposal of perishable foods and increased food waste amounts
Retailing	• Food shortage due to panic buying • The rapid development of e-commerce and direct connection of farmers with consumers • Reduced local availability • Disruption of transportation flows and wholesale markets
Consumption	• Demand collapsed due to lockdowns • The rapid development of home delivery • Food insecurity for vulnerable individuals • Income reduction and unemployment of workers in the catering sector • Change in eating behaviors

Subsequently, a surge in demand for organic and staple foods was observed similarly to what had occurred with other crises. These events included the Bovine Spongiform Encephalopathy (BSE) outbreak (2000), Severe Acute Respiratory Syndrome (SARS, 2004), and the melamine scandal (2008) that bolstered demand for organic baby food in China [15]. Indeed, food shortages and rising prices occurred in different countries (e.g., Ghana, Italy, Malaysia, and New Zealand) due to the high demand [10,16–19]. In Italy, France, Spain, Germany, Denmark, the United Kingdom, and the United States, consumers stocked up on dry yeast, which became a hard-to-find commodity [20]. In Russia, panic buying was observed the week before the self-isolation announcement, with people stocking up on buckwheat, garlic, and non-perishable foods, which were among the top-selling categories during the coronavirus panic shopping [21,22]. Subsequently, prices for staple food (e.g., sugar, tomatoes, garlic, lemon, buckwheat, and bread) prices increased by 16, 15, 9, 8, 6, and 7%, respectively) [23]. The government had advised consumers to use food delivery services, but most of them collapsed logistically as placing orders became increasingly impossible since there were no free time slots [10]. In Malaysia, the prices of cabbage and cucumbers increased by 62.5 and 300%, respectively [24]. Another consequence of the food shortage by COVID-19 panic buying could be the spread of unsafe practices, such as methanol in alcoholic beverages [25].

Food shortages and price spikes could also be related to the difficulties observed in supply chains due to border closings and quarantine measures, as well as fewer workers available for harvesting, production, logistics, and decreased production. Over the long term, labor shortages will affect the production and processing of food, particularly labor-intensive crops. For example, high-value commodities such as fruits, vegetables, and fisheries require a large amount of labor for their products, and thus, have been greatly impacted by the current situation [26]. In Germany, Britain, and Italy, rising prices were expected for certain vegetables such as asparagus and strawberries since these products are all hand-harvested by experienced workers from Eastern Europe that cannot reach the field to work [27].

According to FAO, the COVID-19 pandemic has also disrupted the food supply chain due to trade and logistics issues [12]. These disruptions reflect interruptions in the production or distribution of the products [28]. For example, due to the fact that the production of staple commodities such as wheat, maize, corn, soybeans, and oilseeds is capital intensive, the labor shortage issue will have a greater negative impact on the distribution logistics of these products and less impact on their production [26]. In Thailand, at the beginning of the COVID-19 outbreak, supermarkets were able to stay well-stocked up despite the observed panic buying. Still, a few days later, many items (especially fruit and vegetables) were missing from store shelves [10]. Commodity prices have edged up by 17.34% of the average export price (from US 481.50/tn to 565/tn) due to the higher global demand [24]. However, in this case, the main obstacle for Thai food exports was logistics, as most countries had taken lockdown measures in the aviation sector [29].

Moreover, although there is no indication that Thailand will restrict its own exports, the authorities there should consider the possibility of other countries restricting their exports. For example, the Vietnamese government announced banning new rice-export contracts at the end of March [24]. With such new export policies in place, governments of other countries may realize that they are now too dependent on foreign food supplies, and thus, should consider globalization impacts on their own food systems. Whether or not this tendency prevails will depend on the economic situation and social aspects following the post-lockdown period and the disequilibrium precipitated by the pandemic [30].

Food shortages and price increases caused by an excessive demand for particular food products have affected food availability and are disturbing for consumers. Moreover, these conditions could potentially worsen if the COVID-19 pandemic lasts for a long time. The FAO declared that panic buying and consumer stockpiling of foods reduced the donations made to food banks from supermarkets. Thus, it is essential for consumers to avoid panic buying and stockpiling in order to minimize the resultant food bank stress to food-insecure populations [31]. There is also a need to continually remind consumers that adequate food supplies are available and that the stockpiling of food is not only unnecessary but unwittingly contributes to food insecurity for many vulnerable individuals. The OECD reported that for the current pandemic situation, there is no basis for the development of a global food crisis since staple crop supplies and cereal stocks are sufficiently large. Moreover, compared to other sectors, the food sector has been less affected by business closures and movement restrictions during the pandemic. However, the pandemic poses a severe threat to food security in the poorest countries where agricultural production systems are more labor-intensive [32].

4. Other Impacts of the COVID-19 Pandemic

4.1. Impacts of the Pandemic on Agriculture

The full effect of the COVID-19 pandemic on the food chain includes not only empty shelves due to panic-buying, but also other aspects that are hard to predict in either scale or nature and yet to be seen. These impacts concern both small and commercial farming, especially in developing countries where lockdowns have led to slower food distribution systems due to border delays and the reduced ability of workers to migrate for agricultural labor and food harvesting. Unfortunately, the pre-existing food crises will continue to worsen and negatively impact the impoverished and vulnerable populations. According to the FAO, critical negative impacts on producers, transporters, processors, and consumers have been observed and will continue [12].

The problems are more intense in developing countries where many smaller farmers must transport produce and inputs by bus [33]. In particular, as the COVID-19 pandemic sweeps through the developing countries, more than 30 of them are facing a widespread famine of historical proportions, whereas, in 10 of those countries, more than a million people are on the verge of starvation [34].

The COVID-19 pandemic caused the food and agricultural sector to experience a negative downturn with an immense labor loss [35]. Labor loss prevented agricultural activities and affected supply chains. On the other hand, it caused the loss of income of the people with agricultural economies and millions of households are faced with poverty.

Unfortunately, many farmers and farm laborers suicides were reported as a loss of income during the pandemic in India [36].

4.2. Impacts of the Pandemic on Food Supply Chains

Other impacts of the pandemic on the food chain include the following: Reduced incomes, reduced access to essential services, (e.g., veterinarians, seeds, and fertilizers) and buyers, modifications in food distribution and increased delivery needs due to closed restaurants, children losing free school meals, absenteeism due to illness across the food chain industries, increased food waste from farm to fork, as well as potential spikes in food prices due to the increased demand and slower food supply chains [19,37–39]. Fresh produce can accumulate without being sold which leads to food losses, loss of income, and higher food prices. Similarly, the shelf life of fresh food for the foodservice sector is very limited which leads to additional food waste [10]. Auditing, inspections, and monitoring regulations could be temporarily reduced or modified in order to expedite the movement of products. For example, in the United States, the Food and Drug Administration has issued interim guidelines that provide flexibility for various parameters such as product labeling in order to help support the food supply chain and meet consumer demand during the crisis [40]. Such administrative and regulatory changes could be supportive for some food businesses attempting to cope with lower margins and fractured supply lines, thereby addressing food quality, safety, and authenticity concerns.

These impacts highlight the need to proactively ensure contingency planning and the implementation of effective mitigation strategies and control measures, which help ensure that the health or economic crisis will not turn into a food crisis. Therefore, the recent COVID–19 health crisis could become a food crisis if adequate contingency plans are not implemented [31,41]. Indeed, an integral approach from governmental and research bodies, as well as the industry and consumers is essential in order to provide a safety net for the most vulnerable populations and to ensure that the food supply chain operates efficiently. This approach includes health and safety measures [42] and social distancing [43], as well as government interventions, investments, and reduced tax policies in the agricultural sector [26]. Other relevant measures include purchasing agricultural products from small farmers and shorter supply chains [44], development of e-commerce platforms, and mobilization of non-governmental food banks whose staff have the technical knowledge and experience to deliver food efficiently [26]. However, those actions will not be sufficient unless implemented in a timely and coordinated manner. For instance, local food crop production can only fulfill less than one-third of the world's population [45]. Despite the pandemic, the food supply chain must keep working, and, at the same time, adequate measures must be in place to ensure the highest standards in order to prevent further spreading of the virus. Unfortunately, the supply chain is sometimes weak, and many products have been lost since the demand is not adequate enough to purchase the products at their regular price [26].

Moreover, the food chain is complex and involves many factors from farm-to-table. This complexity can create gaps among the producer, consumer, and the product itself. Consumers' food choices are influenced by the following factors: Price, nutrition, health benefits, quality, origin, seasonality, emotions, habit, labeling, access, sensory characteristics, culture, personal preference, environmental footprint, and previous positive experience and information. Other factors include a preference for organic products, choosing local products, animal welfare, sourcing ingredients for planned meals, advertisements, minimal processing, and shelf-life [46–49].

4.3. Impacts of the Pandemic on Packaging

The COVID-19 pandemic has also affected the packaging industry in different sides such as increasing the consumer awareness on the hygiene and safety of packaging materials, increasing the digital printing, packaging for e-commerce shipments, as well as rethinking the materials and design requirements of sustainable packaging [50,51]. For achieving sustainable goals, many packaging companies had developed reusable innovative packaging technologies. However, the pandemic caused by a coronavirus affected consumer behaviors due to the concerns on hygiene. In addition, the safety of reusable packaging temporarily halted the packaging industry's improvements on a sustainable supply chain [50]. For example, Starbucks temporarily suspended the use of personal cups rather than single use paper cups at its stores around the world in response to the COVID-19 pandemic [52,53], since concerns on hygiene have a greater priority than environmental concerns. In that context, packaging companies should transform packaging design taking into consideration the main requirements including sustainability, heightened hygiene and safety concerns of the consumers as well as, design for e-commerce, ship-ready design, and direct-to-consumer models [51].

5. Food Loss and Waste

The COVID-19 pandemic may also affect the lost and wasted food on a short and long term basis [32]. Consumer waste has arisen mainly from the over-buying trend and improper storage of high quantities of foods. On the other hand, food supply chains were disrupted due to road closures which caused an accumulation of products, resulting in the increased levels of food loss and waste [26]. In order to reduce food waste, the EU Platform on Food Losses and Food Waste shared the food loss and waste prevention actions taken by EU Member States of the EU in the context of this unprecedented crisis [54]. Likewise, many governments warned citizens that no widespread food shortages had been observed and informed them regarding how to plan shopping and food storage in order to modify their consumption habits [32,54]. The mobilization of private charities and community-based groups to distribute food during the lockdown could solve several problems concomitantly by helping to reduce food waste while supporting people in need [3]. A similar practice was implemented by several cooperatives and municipalities that collected surplus food from school cafeterias and restaurants and redistributed it to the low-income and other vulnerable groups [54]. Such alternative supply channels for handling potential surpluses or potential food loss and waste that have resulted from the closure of restaurants, schools, hotels, and catering businesses have been significant and appreciated resources during the pandemic [32].

In general, modern food supply chains have focused on reducing food loss and waste (basically to minimize cost), and subsequently, environmental impacts. However, the unpredicted spike in food demand as a result of COVID-19 control measures has led to empty shelves. This massive shock to well-organized food supply chains highlighted the need for increased consumer education. Many modern technologies proposed helping to monitor food production and consumption (aiming at reducing food loss and waste), which can be used to ensure a reliable, uninterrupted food supply during these challenging times.

6. Food Resilience

Any organized system aims to reach an optimal operational state and remain stable. However, this approach is ideal and often not possible in our fast-changing world where systems stability depends on the outbreak frequency of extreme events rather than typical conditions. The greater the attempt to optimize the elements of a complex system, the more diminished the resilience. An external change during the optimal state could result in disturbances and, subsequently, a more vulnerable system [55]. The current food systems could be disrupted due to many factors, including urbanization, population aging, and occasional shocks such as economic crises, natural disasters due to climate change, and unpredicted responses to extreme events [56]. Therefore, food systems should be more resilient in order to adapt to extreme situations such as the one we are living in today [13], and system weaknesses, choke points, vulnerabilities, and critical services should be well-refined [32].

Resilient food systems could contribute to food security and, ultimately, to sustainable food systems [57], as those are complementary concepts [58]. In particular, sustainability concerns the capacity to achieve today's goals without compromising the future ability to achieve them, and resilience is the dynamic capacity to continue achieving goals despite shocks and disturbances [59,60]. Thus, the food systems could be sustainable when their elements are flexible enough to absorb shocks and mitigate damages as a result of changes in their natural conditions [58,61,62].

In complex systems, sudden shifts could surprise us, but working at the crossroads of these emerging fields offers new approaches to anticipate critical transitions [63]. In the case of the COVID-19 pandemic, food security is affected [6], showing that our food systems are not resilient enough to adapt to severe changes such as economic crises [3] and climate change [64]. Although different, the pandemic and climate risk share common characteristics as both of them represent physical shocks, systemic, non-stationary, and regressive changes. Therefore, the current pandemic provides us with a preview of future challenges to supply and demand, disruption of food supply chains, and amplification mechanisms due to climate change. Moreover, the measures taken for each could result in an enhanced understanding of the other one. For instance, climate-resilient infrastructures could increase economic and environmental resiliency [65].

This pandemic and the occurring disruptions offer a unique opportunity to learn more about the fragility and critical points of the system in order to increase preparedness for future disruptions [66]. Likewise, it has created opportunities for innovations [67], e.g., the need for social distancing, remote work, and improved delivery systems leading to the development of mobile applications and internet and communication technologies that can also be implemented with regard to food loss and waste [3]. The conversion of farms to carbon and organic farming could contribute to a more resilient urban food system [68]. However, this will not completely solve food insecurity and diet-related problems. Likewise, there is a need for increased policy intervention with regard to dietary patterns, e.g., more regulation of the ingredients in junk food and actions to make fresh food more accessible and affordable [69]. Within the global food syndemic, there are opportunities to develop healthy eating patterns for consumers' wellness based on products that address food insecurity, malnutrition, and obesity.

Huff et al. [70] predicted the pandemic's effect on the US-food system, showing that a severe event resulting in a higher than 25% reduction in labor availability could lead to significant food shortages [70]. Therefore, it is essential to limit the disruption of critical infrastructures during a pandemic or a climate crisis in order to maintain an adequate movement of food and water supplies which are critical for the survival and health of society. Progress can be achieved by accelerating investments in data systems in order to enhance consumer confidence in supplies during disruptions [32]. The preparation of food systems against potential hazards is also essential [4]. Mitigation measures such as enhanced biosecurity arrangements to manage sanitary and phytosanitary risks should be considered [32]. In addition, system changes should result in a shift from an optimized shorter-term performance model to an approach that ensures equally longer-term resiliency [65,71].

The COVID-19 pandemic has showed the importance of resilient agri-food system. The agricultural and food systems cannot be resilient if they are not sustainable. Therefore, it is very important to transform food systems using new technologies and scientific discoveries, combined with an increasing public awareness and demand for sustainable food [72].

7. Transformation of the Food Sector

Food security depends not only on food availability but also on food access and utilization. Subsequently, significant improvements in the global food system and forest/land governance are required [69]. The 47th Session of the UN Committee on World Food Security recommended joint action towards a comprehensive transformation of global agri-food systems, to make them more inclusive, resilient, and sustainable [73]. The cornerstones of the transformation are innovation [74] and productivity [75], together with the way in which the biomass for food and feed is produced, processed, and consumed [3]. During the transformation, it is essential to adopt an integrated approach that includes food waste reduction and valorization [3,76] and a shift to the climate-neutral economy [77]. This approach would provide new perspectives for farmers and rural areas, reducing greenhouse gas (GHG) emissions, as well as improving carbon, nitrogen, and phosphorous circularity and overall land-use efficiency [69].

Among the urgent challenges for the food industry in the post-COVID era is the development of competitive, sustainable, and affordable products that promote and enhance health. Researchers are not only seeking food bioactive compounds [78], but also recovering these compounds from food processing by-products in order to replace synthetic additives with natural ingredients that possess health benefits [79–84]. Additional energy-efficient and sustainable processing technologies are needed to support these efforts [85–92]. Phenotyping and gene editing have also resulted in new opportunities. Advances in precision fermentation, synthetic biology, and microbiology will soon result in food produced in laboratories, e.g., lab-grown meat and novel alternative protein sources [69]. Consumers, governments, and companies will also play a vital role in the transformation by helping in changing dietary behaviors to include healthier choices such as plant-based foods and less meat. The latest would eliminate food overconsumption, end malnutrition, and finally improve health [93,94]. Moreover, there is a need to develop bioanalytical tools to ensure food and environmental safety during this transformation [95].

The transformative food sector requires different policies that reconsider the elements of our food systems and facilitate the relations between them. Taking the EU as an example, the Biodiversity Strategy [96] and the EU Farm to Fork [97] strategies have highlighted the transformation of the food system by reducing the use of fertilizers and pesticides and promoting carbon neutrality, as well as the increase in organic farming and protected agricultural areas. In addition, many shifts must take place simultaneously at the societal level. For instance, spending more on local food should become a priority to shrink the urban-rural gap considering potential energy savings from the transportation expenditure [69]. Moreover, consumer confidence in the safety of the agro-food system should be taken into consideration by enhancing government communication strategies [32].

The agricultural self-sufficiency of people, cities, and countries should also increase, whereas agriculture and aquaculture should be resilient against market failure and climate change. In such a system, healthy societies will grow, and this system could be achieved by human-centered and nature-based design [67]. Emergency cash flow and economic measures for the food supply chain are necessary in order to support the needs of farmers, fishers, and agri-food businesses [98]. For example, governments should consider crowdfunding for local bioeconomic investments as part of their regional development funds and recovery plans. Finally, the implementation of technology disruptions is necessary in order to transform the food sector in the new era. Industry 4.0 applications, blockchain in the food supply chain, and Internet and Communication Technologies are the innovations with the highest potential in the new era. There is also an equally pressing need to exploit social marketing to understand consumers' attitudes in order to adapt to new norms forged by the COVID-19 pandemic, where there is a significant gap in knowledge for decision making [99].

8. Conclusions

The COVID-19 pandemic ushered in a new era in the food supply chain as we are still trying to figure out the consequences on humanity, the economy, food safety, and food security [3]. From panic buying, food shortages, and price spikes, to other social and economic impacts, as well as food loss and waste issues, this crisis has shown that our food systems are fragile and need to be redesigned in order to increase food security. Improving food systems to make them more sustainable and resilient should be more than ever an urgent priority. Over the next decades, both the global population and urbanization will grow, pandemics will occur more often, and climate change will intensify. As a result, our societies' transitions towards sustainable development and a climate-neutral economy must be based on resilient food systems. Such systems should include contingency plans and mitigation strategies based on innovations, productivity issues, and consumption patterns that would allow rapid response and adaptation to extreme events, as well as ensuring that inevitable crises will minimally affect the food chain and our most vulnerable populations.

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ARTICLES FOR FACULTY MEMBERS

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Trophic state index (TSI) and carrying capacity estimation of aquaculture development; the application of total phosphorus budget

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Abstract

The aquaculture industry is crucial for sustainability and food security. Nevertheless, it is also one of the significant causes of water quality degradation, reducing water bodies' carrying capacity. One of the degradation factors is the improper discharge of phosphorus. This study aimed to evaluate the trophic state index (TSI) and carrying capacity for tilapia aquaculture development at the Temengor Reservoir, Malaysia, based on the Dillon–Rigler phosphorus budget model. The data permit the evaluation of the limit for fish production capacities that could retain acceptable water quality conditions. This study was carried out monthly from April 2014 to March 2015, focusing on cage sites within the Aquaculture Industrial Zone (AIZ). A total of 15 sampling points were established within a 5 km radius of the fish cages at 1 km horizontal intervals. The TSI values based on three indicators, total phosphorous, Secchi depth and chlorophyll-a, showed a significant difference ($p<0.05$) among sampling points. Areas in the vicinity of the fish cages (<3 km) were at a eutrophic state. However, the current aquaculture production at 9.13×10^3 tonnes per year, which comprises three fish cage modules, has not yet reached the optimum capacity of 325.23×10^3 tonnes per year. Although the lake could accommodate another 105 fish cages, the eutrophic state near the cages signalled water quality deterioration. As there is a plan to increase the number of cages, it is hoped that these findings will be taken into serious consideration in the implementation of any aquaculture expansion in this man-made lake. [Correction added on 13 September 2022, after first online publication: study date range has been updated.]

KEYWORDS
carrying capacity, man-made lake, phosphorus budget, tilapia aquaculture, trophic state index

1 | INTRODUCTION

As traditional capture fisheries supplies have declined worldwide, aquaculture is now recognized as an essential source for enhancing household food security (Ahmed & Lorica, 2002; Aura et al., 2021; Béné et al., 2016). Furthermore, the expansion of aquaculture provides an answer in overcoming the unsustainable and limited supply of capture fisheries, as many fish stocks have either reached maximum yields or have been over-exploited (Cretu et al., 2016). The demand and importance of this sector as a significant protein source will continue to accelerate with the increase in human population (Bouwmeester et al., 2021; Degefu et al., 2011). For this reason, aquaculture has become an attractive business venture for both government and private sectors (Aura et al., 2021; Miod et al., 2009) in Malaysia as it contributes to the nation's economic growth.

The Malaysian government has significantly supported the rapid growth of the aquaculture industry via physical and financial

[Correction added on 29 August 2022, after first online publication: For clarity, the spacing has been updated for equations 2, 3 and 4, Table 2 and under the Results section, 3.2, sections 4 and 6.]

allocations in various aquaculture development plans primarily through the Aquaculture Industrial Zone (AIZ) projects (Hamdan et al., 2015). Thus, lakes and reservoirs in several states have been identified to run commercial-scale aquaculture projects within the AIZ (Yusoff, 2015). Temengor Reservoir, Perak was selected to run the venture out of several lakes in Malaysia due to its favourable environmental conditions (including water quality), covering a water body of 100 ha (Hashim, 2015; Jumatli & Ismail, 2021). The reservoir has a great potential for aquaculture development and is internationally acknowledged (Jamtøy et al., 2011). Moreover, the reservoir is part of the mega diversity area of the Royal Belum State Park, which is a highly invaluable biodiversity hotspot, yet significantly supports the local economic activities such as hydroelectricity generation, fisheries, domestic water supply and eco-tourism (Abdullah et al., 2011; Omar, 2015).

The aquaculture project at Temengor Reservoir has been in operation since late 2008, focusing on the new strain of Genetically Improved Farmed Tilapia (GIFT,) a strain derived from the several generations of the selective breeding of the Nile tilapia *Oreochromis niloticus* (Jamtøy et al., 2011; Jumatli & Ismail, 2021). The fish are reared in 20-m diameter floating cages. Each cage has a cone-shaped entrapment below the cage for waste collection. The production capacity of aquaculture production at Temengor Reservoir is 25 metric tonnes (MT) per day. The aquaculture project is operated by Trapia Malaysia Sdn. Bhd. in alliance with GenoMar AS from Norway and a local partner, Dalefin Holding Sdn. Bhd (Perak State Agriculture Development Corporation). Department of Fisheries (DOF), Malaysia fully administers the project. The aquaculture company has made a lease agreement with the Perak state government (federal) for 30 years (Hashim, 2015).

Although the positive economic impact of aquaculture is well acknowledged, it has not been without its problems and criticisms. The related issues on the present and future negative environmental impacts of aquaculture have been widely reported in the scientific literature (Beveridge, 1984; Bouwmeester et al., 2021; Ling et al., 2016; Naylor et al., 2009; Pauly et al., 2002; Primavera, 2006; Weber, 2003). Effects resulting from the establishment and operations of aquaculture farms include various associated effluents such as feed wastes, faeces, pesticides and antibiotics that could reduce water quality (Cretu et al., 2016; Freeman et al., 2012; Khairy et al., 2020; Lewandowski et al., 2018; Miod et al., 2009; Sawestri et al., 2021).

The deterioration of water quality, notably due to excessive nutrient loading, has become an environmental concern in an aquaculture system (Lee et al., 2019; Mhlanga et al., 2013). The status of lake water is strongly related to the quantity and quality of waste discharge from the animal culture systems, such as phosphorus, nitrogen and other biological nutrients (Barak & Rijin, 2000; Buyukcapar & Alp, 2006; Neto et al., 2015; Sawestri et al., 2021). However, among these elements, phosphorus function is more significant than nitrogen in controlling eutrophication and productivity of the lake as this nutrient is usually a limiting factor for plant (algae and macrophyte) growth, as highlighted by Mhlanga et al. (2013), Schindler et al. (2016), Bueno et al. (2017), Simanjuntak and Muhammad (2018), Lee et al. (2019), Sá et al. (2021) and Sheng et al. (2021).

Phosphorus is excreted either in soluble or insoluble forms (Canale et al., 2016). Soluble conditions such as orthophosphate (PO_4^{3-}) can affect water quality directly, while insoluble forms tend to settle at the bottom or accumulate in the sediment of a water body. While nitrogen is bonded in the form of a sedimentary organic material that must be decomposed first, phosphorus is bound in an inorganic form and accumulates (Simanjuntak & Muhammad, 2018; Søndergaard, 2007). According to Beveridge (2008), <20% of phosphorus supplemented fish feed is taken up by the farmed fish; the remaining phosphorus is lost to the surrounding environment, in the waters and sediment. Furthermore, the excess phosphorus loading emanating from fish feed that is washed into water bodies could alter the trophic status of a lake, resulting in eutrophication and a negative influence on aquaculture operations (Beveridge, 2008; Lee et al., 2019; Lewandowski et al., 2018; Schindler et al., 2016). Therefore, reducing phosphorus is more critical than reducing nitrogen to mitigate eutrophication (Cunha et al., 2013; Lewandowski et al., 2018; Vrede et al., 2009). Thus, the determination of water quality status based on trophic status must include the impact of phosphorus to ascertain the sustainability of environmental conditions and fisheries in lakes (Dillon & Rigler, 1975; Guo & Li, 2003; Lee et al., 2019; Sheng et al., 2021).

According to Cunha et al. (2013) and Saluja and Garg (2017), the determination of trophic state based on trophic state index (TSI) has been widely used by researchers and government institutions to determine the level of tolerated eutrophication in lentic systems. The tool assesses the development of algal biomass in limnological systems as a function of nutrient concentrations, light availability and other factors influencing primary production (Aura et al., 2021). This information is crucial in environmental impact assessment initiatives regarding environmental capacity (Lewandowski et al., 2018; Mhlanga et al., 2013; Sawestri et al., 2021). Environmental capacity is defined as a property of the environment, a measurement of its ability to accommodate a particular activity or rate of an activity, such as the discharge of contaminants, organic matter or nutrient loading, without violating the water quality standard for a healthy water body (World Health Organization WHO, 1986).

As Sharma et al. (2010) highlighted, an increasing trend in TSI over several years could signal the degradation of the lake's health. Therefore, as the trophic state of a water body could be determined, any management and conservation approach should be formulated for the long-term utilization of water bodies. An example is to predict the acceptable fish culture capacity in lakes and reservoirs (Lewandowski et al., 2018; Neto & Ostrensky, 2015). It is essential to consider the carrying capacity of a water body to ensure the sustainability of the aquaculture sector and its environment, and to reduce the ecological effects and any possible risks to the aquatic biota (Guo & Li, 2003; Lee et al., 2019; Pulatsu, 2003).

Several models and methods have been developed for estimating the carrying capacity of inland waters where intensive fish farming is performed (Mhlanga et al., 2013; Pulatsu, 2003), including Dynamic Models (Jones & Lee, 1982) and Statistical Models (Beveridge, 1984). However, in this study, the Dillon and Rigler model (Dillon & Rigler, 1975) was used as this model has the best predictive abilities (Mhlanga et al., 2013) and is widely used by limnologists (Lee et al., 2019; Pulatsu, 2003). Furthermore, the Dillon-Rigler model is applicable both in shallow and deep lakes and in the reservoirs of both warm and tropical areas (Beveridge, 1984; Buyukcapar & Alp, 2006).

Considering the need for a continual supply of clean water and freshwater resources, best aquaculture management practices that comply with environmental aspects are a must in safeguarding the pristine ecosystem of Temengor Reservoir and, in general, other water bodies utilized for this activity. Therefore, it is essential to estimate a lake's carrying capacity to retain acceptable water quality conditions and status in the lake ecosystem for sustainable aquaculture development. Importantly, clean, healthy water is also critical for aquaculture to thrive.

To date, there is no documentation on the trophic state index (TSI) and carrying capacity of aquaculture activity at Temengor Reservoir. Therefore, this study aims to evaluate these practical tools based on the phosphorus budget in the lake.

2 | MATERIALS AND METHOD

2.1 | Study area

Temengor Reservoir (15, 200 ha) is the second-largest reservoir in Peninsular Malaysia after Kenyir Reservoir (36, 900 ha). It is located in the uppermost part of the Sungai Perak basin. With a length of 427 km, Sungai Perak is the second-longest river in Peninsular Malaysia and has four dams along its course (Figure 1). Four forest reserves surround Temengor Reservoir; Belum Forest Reserve (117, 500 ha), Gerik Forest Reserve (35, 000 ha), Aman Jaya Forest Reserve (18, 866 ha) and Temengor Forest Reserve (148, 800 ha) (Malik, 2016). The reservoir receives water from its surrounding water catchment and headwaters (Hashim et al., 2012). Consequently, the water flows into a series of hydroelectric reservoirs, namely Bersia, Kenering and Chenderoh Reservoirs (Ambak & Jalal, 2006; Dahlen, 1993).

2.2 | Sampling design

Monthly spatial and temporal sampling was conducted from April 2014 until March 2015 at Temengor Reservoir in the vicinity of tilapia cages within the Aquaculture Industrial Zone (AIZ). A total of 15 sampling points were established; 5B, 4B, 3B, 2B, 1B, 0, 1A, 2A, 3A, 4A, 5A, Rokan, Telang, Teluk 1A and Teluk 2B (Figure 2). These sampling points were selected along the designated line across three modules of fish cages at a horizontal interval of 1 km; in the vicinity of the fish cage culture area towards open waters (without any fish cages), following Demir

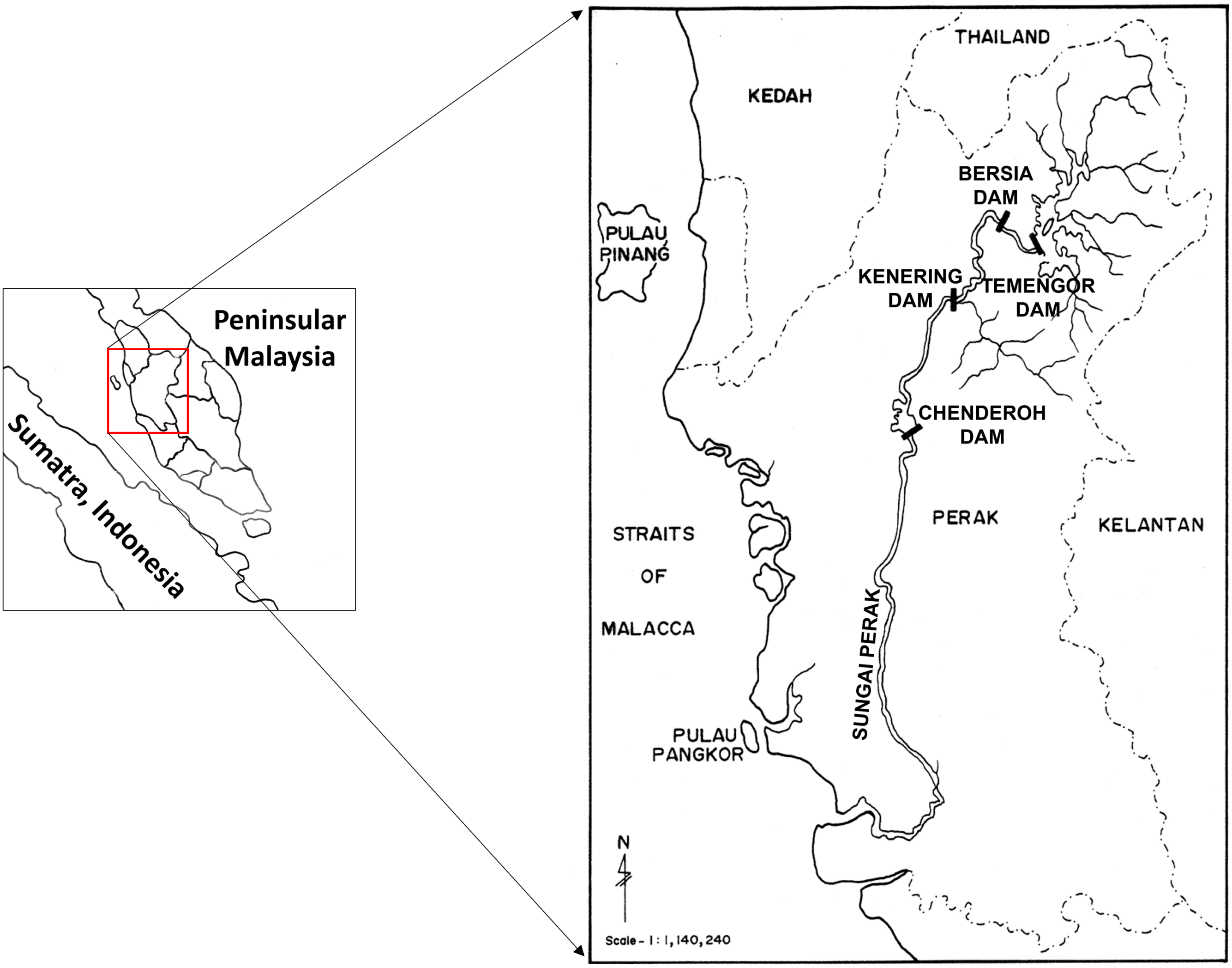


FIGURE 1 The location of four hydroelectric dams across the Sungai Perak basin, namely the Temengor, Bersia, Kenering and Chenderoh Dams.

et al. (2001) and Kashindye et al. (2015) (Figure 3). Using the Global Positioning System (GPS), each sampling point was coded and saved into the system according to its respective position (i.e. sampling points 'A' refer to those 'After' the sampling origin 0), i.e. the fish cage (towards the Temengor Dam). In contrast, sampling points 'B' are in the opposite direction, referring to those 'Before' the sampling origin 0. All sampling points were numbered according to the distance from sampling point 0 (i.e. 1A refers to 1 km distance after the origin point 0, whereas 5B refers to 5 km distance before the origin point 0). The 1 km interval was determined using an odometer from the starting point to the last at 5 km away. In addition to the samples along the mainline of the reservoir, four additional samples were included; Teluk 1A and Teluk 2B are coves near the fish cage areas, whereas Rokan and Telang are two tributaries nearby (Figure 3). Data was collected at these coves and tributaries at a sampling point located 1 km upstream from the samples in the mainline. This method was applied to assess the impact of tributaries and coves without the direct influence of the reservoir (Hashim, 2013).

2.3 | Water parameter assessment for the trophic state index (TSI) determination

Three water parameters for the determination of trophic state index (TSI): water transparency, total phosphorous (TP) and chlorophyll-a concentrations were collected in two replicates at each sampling point. The transparency level of the water column was determined based on Secchi depth (Hunter III, 2011; Luhtala & Tolvanen, 2013). The Secchi disk device was lowered into the water column until it disappeared from view from the lake surface. This distance (m) was measured and recorded. The measurement of Secchi depth indicates the maximum depth at which photosynthesis takes place. The aphotic zone was estimated to be 2.7 times the average of Secchi depth. To determine the total phosphorus and chlorophyll-a concentrations, water samples were collected using a Van Dorn water sampler and transferred into 500 ml polyethylene bottles. The bottles were immediately stored in an icebox and transported to the Universiti Sains Malaysia Ecology Laboratory, Pulau Pinang, Malaysia, for further analyses. Collected samples were then stored in a refrigerator at <4°C to reduce the activities and metabolism of organisms in the water (Adams, 1990). The total phosphorus and chlorophyll-a concentrations were quantified using a spectrophotometer with a 1-cm cell at different wavelengths (Adams, 1990; APHA, 2005).

The levels of eutrophication were then categorized according to the TSI values as presented in Table 1. Equations and symbols to calculate and represent each trophic state category are presented below;

$$TSI = \frac{2 \times (TSI_P + TSI_{Chl}) + TSI_{WT}}{5} \quad (1)$$

$$TSI_P = 10 \times \left\{6 - \left[\frac{1.77 - (0.42 \times \ln P)}{\ln 2}\right]\right\} \quad (2)$$

$$TSI_{Chl} = 10 \times \left\{6 - \left[\frac{0.92 - (0.34 \times \ln Chl)}{\ln 2}\right]\right\} \quad (3)$$

$$TSI_{WT} = 10 \times \left[6 - \left(\frac{\ln WT}{\ln 2}\right)\right] \quad (4)$$

where

- TSI is the trophic state index of a water body
- TSI_P is the TSI relative to the total phosphorus concentration
- P is the water total phosphorus concentration (mg m^{-3})
- TSI_{Chl} is the TSI relative to the chlorophyll-a concentration
- Chl is the water chlorophyll-a concentration (mg m^{-3})
- TSI_{WT} is the TSI relative to water transparency
- WT is the water transparency measured using a Secchi disk (m)

All TSI values data were $\log_{10}(x+1)$ transformed and subjected to the Shapiro–Wilk test to meet the statistical assumption of normally distributed data (Oztuna et al., 2006). Based on a significance cut-off value of >0.05, one-way ANOVA was conducted to analyse the variation of the three water parameters (transparency, total phosphorus and chlorophyll-a) and TSI values among the 15 sampling points (along a distance gradient from the fish cage). In addition, cluster analysis was performed to group the sampling points into clusters based on their similarities in TSI values. The similarity analysis was carried out by using Unweighted Pair Group Method (UPGMA) incorporated in Multi-Variate Statistical Package (MVSP) software Version 3.1 (Krebs, 1999). In this study, the constructed dendrogram from the similarity distance demonstrated the relationship among 15 sampling points based on TSI values.

2.4 | Estimated carrying capacity of tilapia cage culture within the Aquaculture Industrial Zone (AIZ) of Temengor Reservoir

For the estimation of aquaculture carrying capacity, data on total phosphorus (TP) concentration, lake characteristics of Temengor Reservoir (Table 2) and phosphorus budget of the aquaculture farm (Table 3) were used.

The relevant morphometric and hydrological parameters of Temengor Reservoir, such as surface area, volume, mean depth, total outflow, flushing rate and water replenishment time, were calculated based on Dahlen (1993). In addition, the surface area and depth of the Aquaculture Industrial Zone (AIZ) were based on DOF (2015) and Omar (2015), respectively (Table 2).

The technical data on the aquaculture farms, such as feed conversion ratio (FCR), the phosphorus content of the feed and current aquaculture production, were obtained from the aquaculture company, Trapia Malaysia Sdn. Bhd, whereas the phosphorus content in tilapia was based on WWF (2009) and Mhlanga et al. (2013) (Table 3).

The aquaculture carrying capacity of Temengor Reservoir was estimated based on Dillon and Rigler (1975) by examining the phosphorus budget before the fish cage establishment. The steady-state total phosphorus (TP) concentration and the capacity of the water

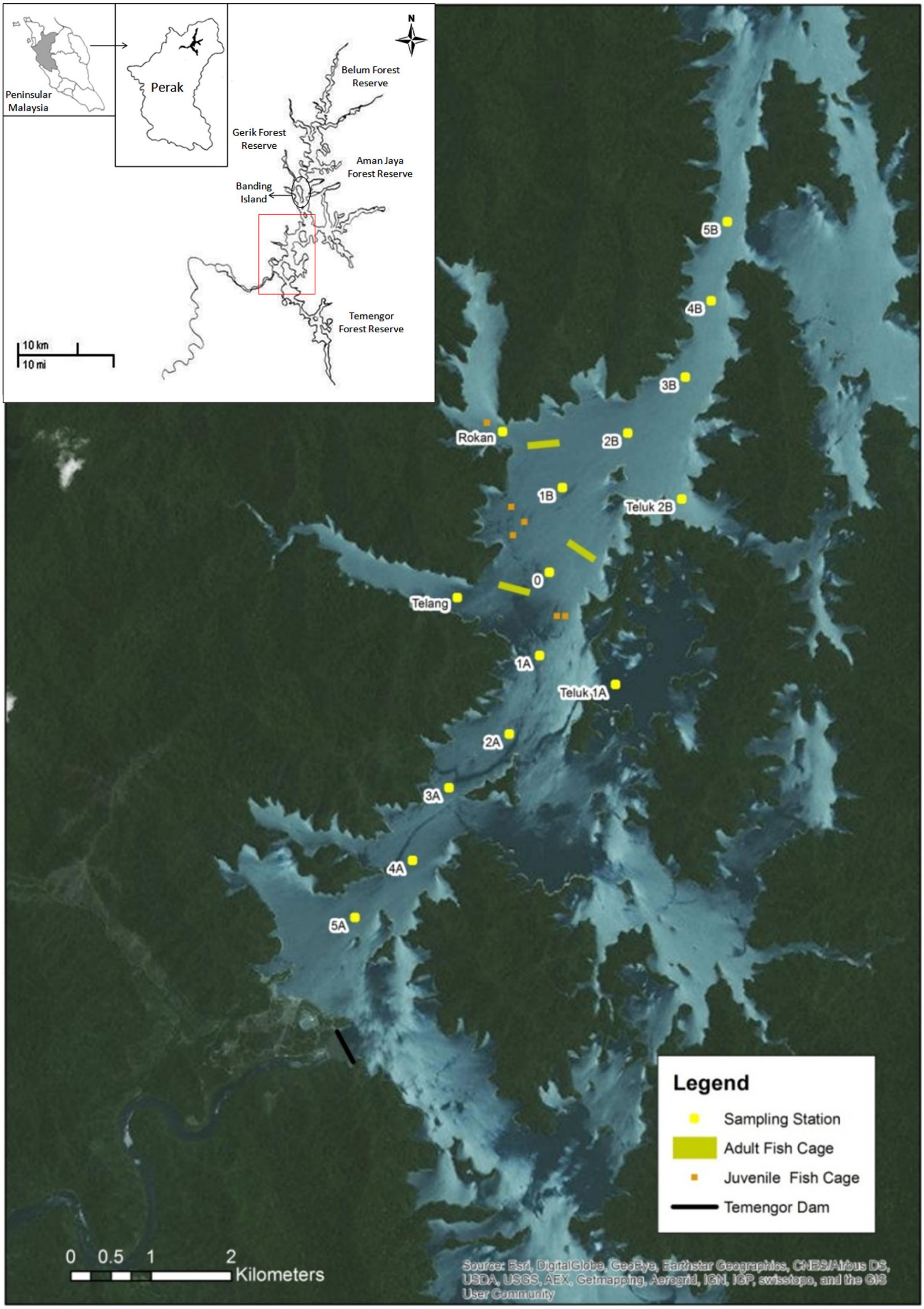


FIGURE 2 Location of 15 sampling points at the Temengor Reservoir (inset: Map of Peninsular Malaysia, Perak state and Temengor Reservoir).

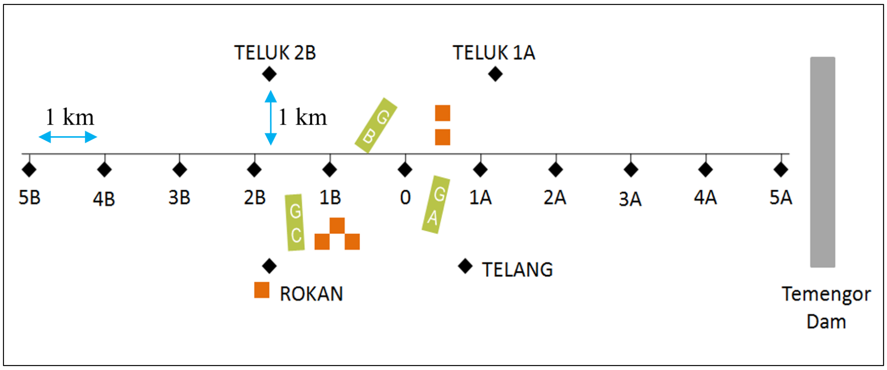


FIGURE 3 Schematic diagram of 15 sampling points at the Temengor Reservoir, Perak. Sampling points 5B to 5A were established along the designated line across three modules of the fish cage at a horizontal interval of 1 km. The sampling points Rokan, Telang, Teluk 1A and Teluk 2B were located 1 km upstream from the mainline across the fish cage area. (◆) = sampling points, (▬) = three adult fish cage modules; GA, GB, GC, (■) = juvenile fish cages.

TABLE 1 Trophic state categories based on the trophic state index (TSI) values with the characteristic of water bodies (adapted from Cunha et al., 2013; Neto et al., 2015)

Trophic states	TSI values	Water body characteristics
Ultra-oligotrophic	<47	Very clean water; negligible nutrient concentrations; adequate water quality for different uses
Oligotrophic	$47 \le TSI < 52$	Clean water; low nutrient concentration; no undesirable effects on water quality
Mesotrophic	$52 \le TSI < 59$	Water with intermediate nutrient concentrations; possible effects on water quality with acceptable levels
Eutrophic	$59 \le TSI < 63$	Water with decreased transparency; high nutrient concentrations; undesirable changes to water quality; increased algal blooms
Supereutrophic	$63 \le TSI < 67$	Water with low transparency; high nutrient concentration; undesirable changes to water quality; frequent algal blooms
Hyper-eutrophic	≥67	Water with high turbidity; high organic matter and nutrient concentrations; a pronounced decrease in water quality; intense algal blooming; fish mortality

body for intensive fish cage culture were measured based on a series of steps;

$$\Delta[P] = [P]_f - [P]_i \quad (5)$$

where

- $\Delta[P]$ = the capacity of the water body for intensive caged fish culture to be able to accept total phosphorus intake (mg m^{-3})
- $[P]_f$ = maximum acceptable TP concentration once the fish culture is established (mg m^{-3})
- $[P]_i$ = average TP concentration before the aquaculture exploitation (mg m^{-3})

The maximum acceptable total phosphorus $[P]_f$ in tropical water bodies used for the tilapia culture is 250 mg m^{-3} based on Beveridge (1984) and Mhlanga et al. (2013). However, in this study, a TP level of 200 mg m^{-3} was used based on the recommendation by Malaysia's quality standard of phosphorus for freshwater (Mahmudi et al., 2019; Philminaq, 2006).

For $[P]_i$, as there were no previous data on the average TP concentrations at surface water before the fish cage establishment, therefore, the average TP at the most distant sampling point from the fish cages (without fish cages, i.e. 5 km distant) with the lowest concentration was used to represent the $[P]_i$.

$$\Delta[P] = L_{fish}(1 - R_{fish}) / \bar{z}\rho; L_{fish} = \Delta[P]\bar{z}\rho / (1 - R_{fish}) \quad (6)$$

$$R_{fish} = x + [(1 - x)\ R] \quad (7)$$

$$R = 1 / (1 + 0.75\rho^{0.507}) \quad (8)$$

where

- L_{fish} = TP loadings from the fish cages (mg m^{-2} year^{-1})
- $\bar{z}$ = mean depth (m)
- ρ = flushing rate (year^{-1})
- x = the net proportion of TP lost permanently to the sediments as a result of solid deposition (0.90)

TABLE 2 Morphometric and hydrological parameters of Temengor Reservoir, Perak

Parameters	Description
Surface area, A (m^2) of Temengor Reservoir	$=1.52\times10^8\,m^2$
Surface area of AIZ (DOF, 2015)	$=1.0\times10^6\,m^2$
Volume, V (m^3)	$=6.05\times10^9\,m^3$
Mean depth, $\bar{z}$ (m) of Temengor Reservoir	$=V/A$ $=6.05\times10^9/1.52\times10^8$ $=39.80\,m$
Depth of AIZ (Omar, 2015)	$=80.00\,m$
Total outflow, Q ($m^3\,year^{-1}$)	$=2830\,m^3\,S^{-1}$ $=89.25\times10^9\,m^3\,year^{-1}$
Flushing rate, ρ ($year^{-1}$)	$=Q/V$ $=89.25\times10^9/6.05\times10^9$ $=14.75\,year^{-1}$
Water replenishment time, t_w (year)	$=1/\rho$ $=1/14.75$ $=0.07$ year

TABLE 3 Technical data on the aquaculture farms of Trapia Malaysia Sdn. Bhd

Technical data	Details
Feed Conversion Ratio (FCR) (Carvalho et al., 2012; Lee et al., 2019)	=1.50
Phosphorus content of the feed	=1.00%
Phosphorus content of tilapia (Mhlanga et al., 2013; WWF, 2009)	=0.75% wet weight of fish
Current aquaculture production at Temengor Reservoir	$=25$ tonnes day^{-1} $=9.13\times10^3$ tonnes $year^{-1}$

- R_{fish} = the proportion of TP loadings from the fish cages that dissolves into the sediment
- R = phosphorus retention coefficient

Carrying capacity (CC) or intensive cage fish production (tonnes per year) is given by;

$$CC = L_a / P_{env} \tag{9}$$

$$L_a = A.\,L_{fish} \tag{10}$$

$$P_{env} = P_{food} - P_{fish} \tag{11}$$

where

- CC = carrying capacity or intensive caged fish production ($t\ year^{-1}$), i.e. the optimum number of a particular species that can safely grow in a particular water body without negatively affecting their growth rates
- L_a = acceptable TP loading ($g\ year^{-1}$)
- A = lake surface area (m^2)
- P_{env} = phosphorus release to the environment because of aquaculture activity
- P_{food} = phosphorus content in fish food (determined by the amount of phosphorus content in the fish food multiplied by Feed Conversion Ratio, FCR)
- P_{fish} = phosphorus content in the fish body (determined based on cultured fish species)
- FCR = the amount of feed it takes to grow a kilogram of fish

Based on the results, the ratio of current aquaculture production to the estimated aquaculture carrying capacity at 100 ha AIZ was calculated:

$$\text{Ratio} = \frac{\text{current aquaculture production (Table 3)}}{\text{estimated aquaculture carrying capacity (CC)}}$$

2.5 | Research ethics

This study did not involve live fish or other organisms as part of the experiments and data collection, thus ethical approval is unnecessary.

3 | RESULTS

3.1 | The variation of water parameters and trophic state index (TSI) values along a distance gradient from the tilapia aquaculture

All sampling points showed slight mean variations of the three parameters, namely water transparency, total phosphorus and chlorophyll-a, across the 15 sampling points (Figure 4). The mean transparency ranged from $1.79\pm0.35\,m$ (Rokan) to $2.28\pm0.49\,m$ (4B). The sampling points in the vicinity of fish cages recorded lower transparency than points further away from fish cages. The lowest concentration of total phosphorus was recorded at 5B with $67.37\pm7.53\,mg\,m^{-3}$, and the highest was at 1A with $108.54\pm16.90\,mg\,m^{-3}$. The mean chlorophyll-a concentration ranged from $5.53\pm0.51\,mg\,m^{-3}$ (5B) to $8.94\pm1.11\,mg\,m^{-3}$ (Telang). The total phosphorus and chlorophyll-a concentrations increased towards the fish cages and decreased away from the fish cages. Although only total phosphorus ($p < 0.05$) showed a significant difference, the values of these parameters were observed to depend on the distance from the fish cages; the trend of water parameters deteriorated upon approaching the fish cages (Figure 5).

The TSI values at 15 sampling points ranged from 57.77 ± 0.84 (5B) to 60.49 ± 0.84 (1A). Based on the TSI values, sampling points in the immediate vicinity of fish cages (within 3 km; except Teluk 1A and Teluk 2B) recorded values >59 (59.16 ± 0.79 to 60.49 ± 0.84); indicating a eutrophic state while sampling points distant away from the fish cages showed values <59 (57.77 ± 0.84 to 58.79 ± 1.25); indicating a mesotrophic state. The TSI values among the 15 sampling points were significantly different ($p < 0.05$).

The constructed dendrogram demonstrated the relationships among 15 sampling points along the tilapia cage culture area of Temengor Reservoir based on TSI values (Figure 6). Sampling points that are relatively near to fish cages (≤1 km distance) were grouped in one cluster (Node A) at 0.64, showing 64% similarity of the TSI values between these points (1A, 0, 1B). However, sampling points that are distant away (≤3 km distance) were grouped under one cluster (Node B) at 0.51, showing 51% similarity of the TSI values between these points (Telang, Rokan, 2A and 3A, 2B, 3B). Node C groups two clusters (Node A and Node B) at 0.49 similarity distance, showing 49% similarity of the TSI values between these sampling points, corresponding to the eutrophic state. Node D groups the sampling point Teluk 2B and Node C with 25% similarity. Subsequently, the sampling points that were located even further away from the cage (>3 km distance; except Teluk 1A) were grouped under another cluster (Node E) at 0.33; showing 33% similarity of the TSI values between these points (Teluk 1A, 5A, 4A, and 4B, 5B). This result indicates that TSI values at points near fish cages differed from those recorded distant from the fish cages. This analysis supported that the fish cages influenced the trophic status of Temengor Reservoir.

3.2 | Estimated carrying capacity of tilapia cage culture within the Aquaculture Industrial Zone (AIZ) of Temengor Reservoir

Estimation of the aquaculture carrying capacity of Temengor Reservoir;

1) Maximum acceptable TP concentration in tropical water body used for the tilapia culture, $[P]_f$
$= 200.00\,mg\,m^{-3}$

2) Average TP concentration of water sample at surface water, $[P]_i$
= Average TP concentration at the most distant sampling point from the fish cages with the lowest value
$= 55.30\,mg\,m^{-3}$

3) The capacity of Temengor Reservoir for intensive fish cage culture, $\Delta[P]$

$\Delta[P] = [P]_f - [P]_i$
$= 200.00\,mg\,m^{-3} - 55.30\,mg\,m^{-3}$
$= 144.70\,mg\,m^{-3}$

4) Phosphorus loadings from the fish cages, L_{fish}

$R_{fish} = x + [(1 - x) R]$

where x	where R
= 0.90	$= 1/(1 + 0.75\,\rho^{0.507})$
(Kunz et al., 2011;	$= 1/(1+0.75\times 14.75^{0.507})$
Mhlanga et al., 2013)	= 0.25

$= 0.9 + [(1-0.9)\,0.25]$
$= 0.9 + 0.025$
$= 0.93$

$L_{fish} = \Delta[P]\,\bar{z}\rho/(1 - R_{fish})$
$= 144.70\,mg\,m^{-3} \times 39.80\,m \times 14.75/(1-0.93)$
$= 1213516.21\,mg\,m^{-2}\,year^{-1}$
$= 1213.52\,g\,m^{-2}\,year^{-1}$

5) Acceptable total phosphorus loading, L_a for the whole Temengor Reservoir

$L_a = L_{fish} \times A$
$= 1213.52\,g\,m^{-2}\,year^{-1} \times 1.52 \times 10^8\,m^2$
$= 1.84 \times 10^{11}\,g\,year^{-1}$
$= 1.84 \times 10^8\,kg\,year^{-1}$

6) Carrying capacity or intensive caged fish production for the whole Temengor Reservoir before the fish cages establishment

Feed/food pellet		Tilapia	
P_{food}	=1.00%	P_{fish}	=0.75% wet weight of fish
	=(1/100)× 1000		=(0.75/100)× 1000
1-tonne feed	=10.00 kg P		=7.50 kg/tonne fish
FCR (1.5)	=15.00 kg/ tonne feed		

P_{env} =P release to the environment because of aquaculture activity
=difference between (kg P/tonne feed) and (kg P/tonne tilapia)
=15.00 kg–7.50 kg
=7.50 kg/tonne fish produced

CC $= L_a$/average TP wastes per tonne of fish production
$= L_a$/P losses
$= 1.84 \times 10^8\,kg\,year^{-1}/7.5$ kg tonne fish produced^{-1}
$= 24533333.33\,t\,year^{-1}$
$= 24533.33 \times 10^3\,t\,year^{-1}$ .... (1)
=Estimated carrying capacity for the whole Temengor Reservoir

From the above calculations, the aquaculture carrying capacity based on the phosphorus budget model for the whole area of Temengor Reservoir ($1.52 \times 10^8\,m^2$) was estimated at 24533.33×10^3 tonnes per year. This is 2600 times higher than the present fish production level, 9.13×10^3 tonnes per year.

Since the carrying capacity should be calculated based on the area utilized, the calculation was based on the extent of the allocated zone to remove any bias if the whole lake ecosystem was taken into account. Based on the specific area of AIZ, which is 100 ha ($1.0 \times 10^6\,m^2$), the carrying capacity was estimated with the same calculations by using different values of surface area and depth for AIZ, which are $1.0 \times 10^6\,m^2$ and 80.00 m (Table 2) respectively.

L_{fish}	$=\Delta[P]\,\bar{z}\rho/(1-R_{fish})$ $=144.70\,mg\,m^{-3} \times 80.00\,m \times 14.75/(1-0.93)$ $=2439228.57\,mg\,m^{-2}\,year^{-1}$ $=2439.23\,g\,m^{-2}\,year^{-1}$
L_a	$=L_{fish} \times A$ $=2439.23\,g\,m^{-2}\,year^{-1} \times 1.0 \times 10^6\,m^2$ $=2,439,230,000\,g\,year^{-1}$ $=2439230.00\,kg\,year^{-1}$
CC	$=L_a$/average TP wastes per tonne of fish production $=L_a$/P losses $=2439230.00\,kg\,year^{-1}/7.5$ kg tonnes of fish produced^{-1} $=325230.67\,t\,year^{-1}$ $=325.23 \times 10^3\,t\,year^{-1}$ .... (2) =Estimated carrying capacity for the allocated 100 ha AIZ before the fish cage establishment

The ratio of current aquaculture production to the estimated aquaculture carrying capacity at 100 ha AIZ is as follows:

Estimated carrying capacity for the whole Temengor Reservoir (1)	$=24533.33 \times 10^3\,t\,year^{-1}$
Estimated carrying capacity for the allocated 100 ha AIZ (2)	$=325.23 \times 10^3\,t\,year^{-1}$
The current aquaculture production at Temengor Reservoir (Table 3)	$=9.13 \times 10^3\,t\,year^{-1}$
Ratio of current aquaculture production to estimated aquaculture carrying capacity at 100 ha AIZ	$=9.13 \times 10^3\,t\,year^{-1}$: $325.23 \times 10^3\,t\,year^{-1}$ =1: 36

The results showed that the current aquaculture production at Temengor Reservoir was 36 times lower than the estimated carrying capacity based on the phosphorus budget model before the fish cages establishment. As the current production, which comprises three fish cage modules, was 36 times lower, the optimum number of allowable fish cage modules was 108. This shows that, within the 100 ha allocated AIZ, another 105 modules of fish cage could be erected at Temengor Reservoir.

4 | DISCUSSION

4.1 | Trophic state index (TSI) along a distance gradient from the tilapia aquaculture

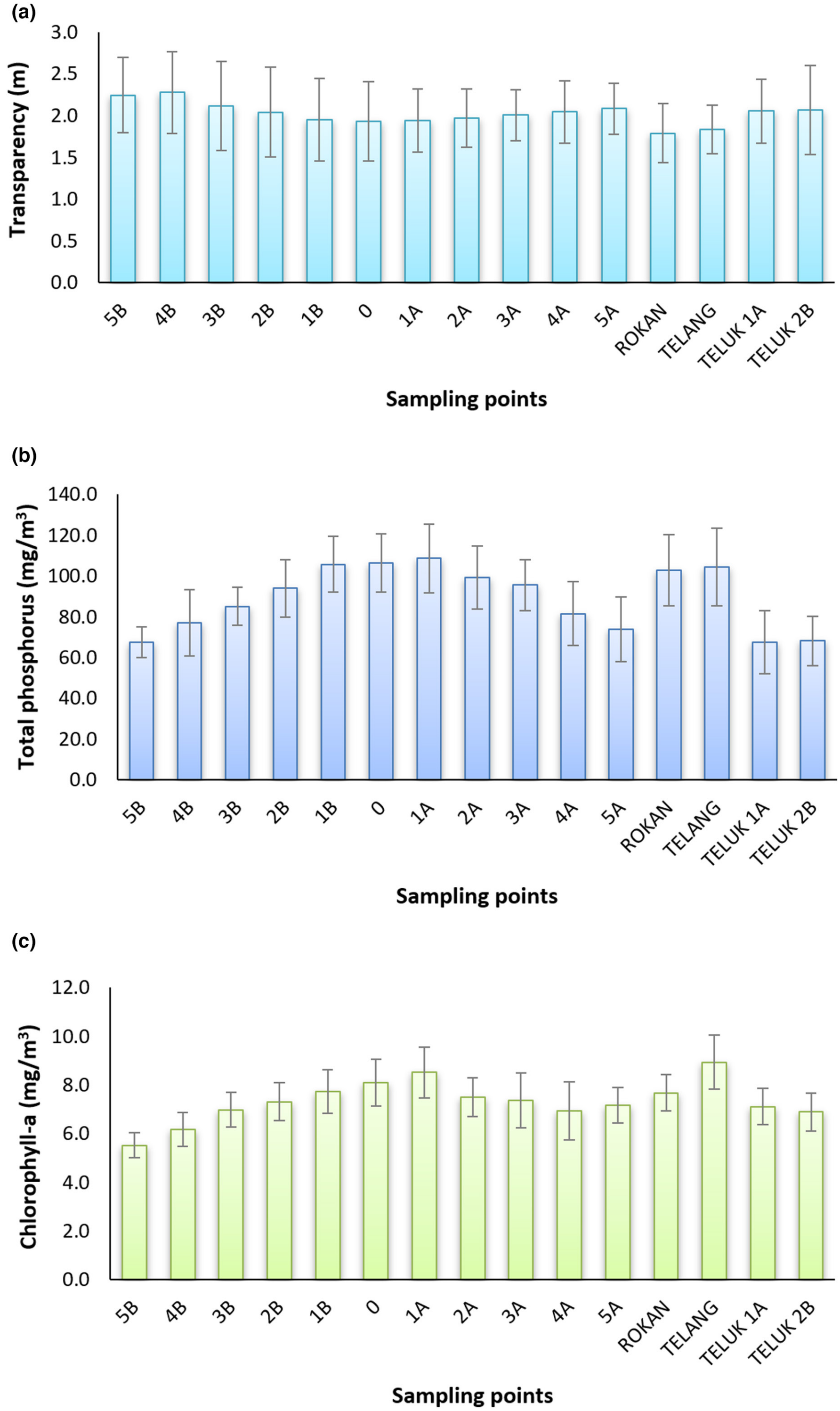
The water in the vicinity of fish cages had higher total phosphorus and chlorophyll-a concentrations and lower transparency compared with points that were more distant from the fish cage. This translated to a significant trend towards eutrophication with higher TSI values ($p < 0.05$), at near cage sites. Although the differences in TSI values among all sampling points (57.77–60.49) were relatively small, the values indicated different trophic states of the sampling points based on the distance to fish cage sites. According to Brandão et al. (2012), fish excretions and leftover fish food have different effects on the aquatic ecosystem, depending on the time and amount released, dilution and dispersion capacity in the water column. The nutrient levels near the cages were relatively higher due to the influx of fish wastes and excess feed. Since running water can self-purify, the more distant points would have a lower concentration (Mirrasooli et al., 2012; Nyanti et al., 2012).

TSI values showed that the sampling points within 3 km from the fish cage were eutrophic (3B, 2B, 1B, 0, 1A, 2A, 3A, Rokan, Telang). This indicated that the areas surrounding the fish cages at Temengor Reservoir are at a high risk of excessive phytoplankton growth, also known as algal blooms (Sá et al., 2021). Thus, these areas had a relatively higher level of productivity. According to Sharma et al. (2010) and Lewandowski et al. (2018), the light availability and intensity, and concentrations of total phosphorus and chlorophyll-a influence the development of algae biomass both directly and indirectly, thus providing insight into the abundance of biological productivity in the water body. Although sampling points located at distances >3 km from the fish cage were mesotrophic, there was a trend towards becoming a eutrophic state. According to the previous studies conducted by Abu Bakar (2004) and Omar (2015), the water at sampling point 2B was then mesotrophic. It appears now to exhibit a decrease in water quality in the same area over the last decade; eutrophic in this study and mesotrophic in both previous studies, showing that the water quality has now deteriorated. Likewise, Nur et al. (2021) noted the changes in trophic status from oligotrophic (2009) to mesotrophic (2019) in Riam Kanan Reservoir, Indonesia due to the input of organic matters into the reservoir from the floating fish cage culture. Hence, uncontrolled production and lack of management would be detrimental to the water quality at Temengor Reservoir.

Overall, the three water parameters that determine the trophic state index (TSI), namely water transparency, total phosphorus and chlorophyll-a concentrations, are interconnected in the generation of algal blooms (Carlson, 1977). The increase of phytoplankton biomass, indicated by chlorophyll-a concentration, is triggered by high phosphate concentration (Neto et al., 2015; Saluja & Garg, 2017). Total phosphorus has a reciprocal relationship with transparency because phosphate is the limiting factor for algal growth. A doubling of algal biomass results in a halving of transparency (Mahmudi et al., 2019). Furthermore, dissolved material reduces the water clarity, preventing sunlight penetration and affecting other water processes (Sawestri et al., 2021).

As Sá et al. (2021) highlighted, TSI is the best tool to reflect the phytoplankton blooming phenomenon, therefore this monitoring tool could also be used for temporal analysis. Early alarms on the occurrence of algal blooms and rapid countermeasures are crucial in safeguarding the Temengor Reservoir. The trophic states are already showing trends of deterioration at near cage sites. Thus, the Temengor Reservoir should be regularly monitored to maintain an acceptable healthy level to prevent algal bloom and eutrophication, which would cause economic hardship to the community depending on it.

FIGURE 4 The mean readings (mean ± s.d.) of (a) transparency, (b) total phosphorus and (c) chlorophyll-a at all sampling points along the tilapia cage culture at Temengor Reservoir analysed from April 2014 to March 2015.



4.2 | Estimated carrying capacity of tilapia aquaculture within the Aquaculture Industrial Zone (AIZ) of Temengor Reservoir

The findings of this study revealed the estimated carrying capacity as represented by the optimum number of allowable units of the fish cage within the Aquaculture Industrial Zone (AIZ) to prevent the detrimental effect of nutrient enrichments at Temengor Reservoir. This number is a critical consideration for local authorities in evaluating the impacts of any proposed aquaculture development in the lakes.

Kelly (1992) and Buyukcapar and Alp (2006) highlighted that phosphorus loading produced by fish farms depends primarily on the lake's annual fish production area, depth and water replenishment time. Therefore, the carrying capacity estimated in this study would also depend on the lake depth. A deeper lake would have a higher carrying capacity. Although the mean depth for the whole

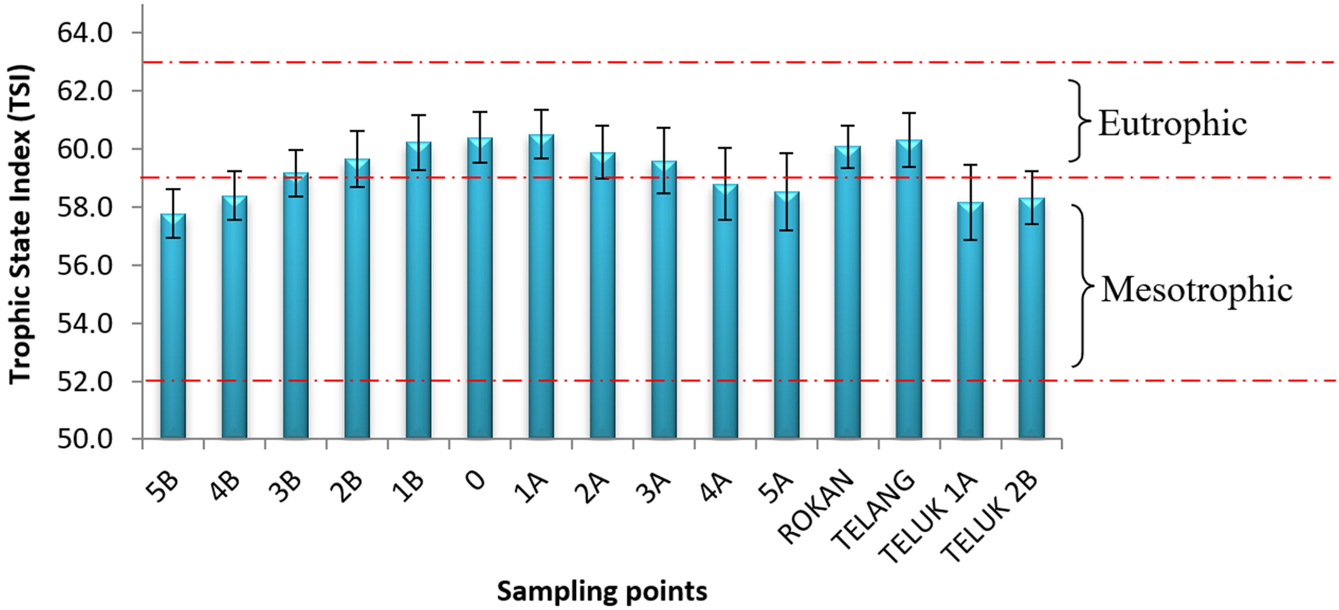


FIGURE 5 Trophic state index (TSI) values at 15 sampling points along the tilapia cage culture at Temengor Reservoir analysed from April 2014 to March 2015.

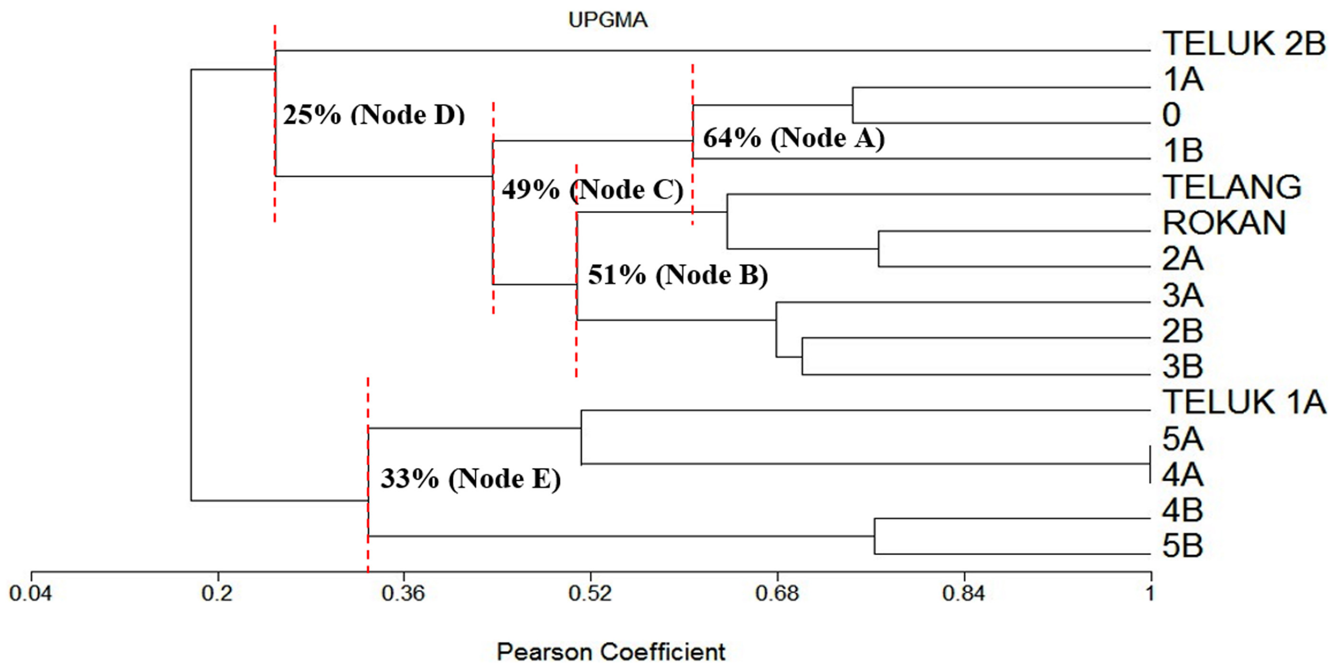


FIGURE 6 The UPGMA dendrogram of TSI values at 15 sampling points along with the tilapia cage culture at Temengor Reservoir. The vertical cuts (red dashed lines) represent points of reference where the cluster is formed based on the similarity distance.

Temengor Reservoir was 39.8 m (Table 2), the allocated zone for the current fish cages is deeper at 80.0 m (Omar, 2015). This allows for a slight increase in the carrying capacity at the allocated zone. Thus, identifying the most appropriate zones for aquaculture development is imperative.

The carrying capacity for a 100 ha area of Temengor Reservoir based on the phosphorus budget model before the fish cage establishment was estimated at 325.23×10^3 tonnes per year. The calculated value can be referred to as a baseline that can indicate a possible ecologically sustainable aquaculture production level (Mhlanga et al., 2013) at Temengor Reservoir. This means that the current fish production of 9.13×10^3 tonnes per year has not yet reached the estimated carrying capacity. However, there is already a marked indication that the available number of the fish cage have deteriorated the ambient water quality based on the current eutrophic state in the vicinity of the tilapia aquaculture site (within 3 km from the fish cage). This indicated that the water capacity in the 100 ha has limitations to accommodate more cages based on the phosphorus budget. If the fish production increases in the next 20 years without an efficient management plan, the whole Temengor Reservoir might become a eutrophic lake. In the short term, fish production appears lucrative, but the deteriorating health of the lake would lead to the rapid depletion of fish populations.

For example, the activity of floating fish cage cultures in Maninjau Lake, Indonesia started in 1990, leading to excessive eutrophication in 2000. Unfortunately, the fish cages continued to be added, surpassing the carrying capacity limit (Sulastri et al., 2015). At least 23,566 units of floating net fish cages have been erected in the lake, whereas the carrying capacity of the Maninjau Lake could only accommodate about 6000 units of the fish cage (Yodfiatfinda, 2017). Thus, the present number of fish cages at Maninjau Lake is four times higher than the carrying capacity. Consequently, this lake faced a eutrophication problem with the severe occurrence of the harmful blue-green algae *Microcystis aeruginosa* in 2000 and a high chlorophyll-a concentration (63 $mg\,m^{-3}$). Similarly, Legovic et al. (2008) reported that aquaculture production in Taal Lake, Philippines was greater than the sustainable carrying capacity and was at risk of algal blooms. In a study at Bacanga River Estuary (BRE), Brazil, the hypereutrophic of TSI showed a significant relationship with several specific phytoplankton blooms, namely *Skeletonema costatum*, *Protoperidinium* sp., *Euglena gracilis*, *Chlamydomonas* sp. and *Leptocylindrus danicus*, critical indicator species of the trophic status (Sá et al., 2021).

Based on the estimated aquaculture carrying capacity in this study, the planned proposal of Trapia Malaysia Sdn. Bhd to increase the fish production to 1.5×10^4 tonnes per year (personal communication with the farm manager) may still be within the acceptable ecological limits within the 100 ha AIZ. However, this may still pose a challenging environmental situation at Temengor Reservoir as production is conducted within a small area. In addition, it should be reminded that the trophic status along 10 km of the fish cage area is already in a meso-eutrophic state. Mhlanga et al. (2013), in their study on the estimation of aquaculture carrying capacity at Lake Kariba, Zimbabwe noted that a precautionary approach would ensure that a particular water body would not instantly tip over from mesotrophic-eutrophic to hypertrophic. Therefore, to ensure that the lake does not become hypereutrophic, the development of aquaculture should be carried out with proper management planning and mitigation measures (if necessary). This can also be done through the regular removal of waste materials that remain floating near the cages, as the wastes are sources for nutrient enrichment in the water. Furthermore, any increase in fish production level should be done in a step-wise manner accompanied by strict monitoring of nutrient loading. Otherwise, this lake could be irreversibly damaged due to high productivity that could trigger an algal bloom, mainly the noxious blue-green algae.

On the upside, water flow into the Temengor Dam may effectively reduce some of the adverse effects caused by high nutrients from the tilapia cages. As one of the hydropower generators of Perak, Temengor Reservoir is subjected to periodic fluctuations in water levels, from both the rainfall and the operations of Temengor Dam monitored by TNB Hydro Sdn. Bhd. (Najid et al., 2016). Hashim et al. (2016) reported that the water level at Temengor Reservoir is controlled by two major factors: dam discharge through hydropower generation and stream discharges through rainfall. When the amount of rainfall increases and exceeds the maximum reservoir level, the dam gate will be opened, and excess water will be released to maintain the optimal reservoir level of the Temengor Reservoir (Zakeyuddin, 2016) and vice versa; the gate is closed when the water level is low. Therefore, contamination water from the fish cage area is diluted, negating the harmful effects of aquaculture activity at Temengor Reservoir. As highlighted by Rangel et al. (2012) and Lewandowski et al. (2018), water flow is vital in negating the excess nutrients and phytoplankton populations from the cages and ensuring constant water exchange. Nevertheless, this cannot be maintained with increased and relentless exposure to potential environmental risks in the future. Although reservoirs have the capacity to neutralize and balance the impacts of nutrient input, aquaculture wastes must be within the environmental capacity to avoid eutrophication (Degefu et al., 2011; Lewandowski et al., 2018; Venturoti et al., 2015), which in turn affect the sustenance of the aquaculture development itself.

The data obtained from this study are crucial in assisting and guiding the relevant parties to make an environmentally appropriate decision on any future related projects with serious consideration of the environment and the people who depend on it. In addition, due to the economic values and ecosystem services of this lake, its environmental health must be consistently examined and assessed to understand and subsequently address any negative environmental impact due to aquaculture activity at Temengor Reservoir. If the ecosystem is not adequately conserved, environmental degradation could worsen until it could reach the point of no return.

5 | CONCLUSION

The trophic state index (TSI) revealed that sampling points in the immediate vicinity of tilapia cages had a relatively higher productivity level than distant sites. The carrying capacity for the 100 ha allocated aquaculture zone before the establishment of fish cages was estimated at 325.23×10^3 tonnes per year. The current aquaculture production is 9.13×10^3 tonnes per year, which translates into a 36X lower production than the optimum carrying capacity, suggesting more room for expansion. However, the current meso-eutrophic state along the 10 km aquaculture sites highlights the areas with a greater tendency towards eutrophication. This situation signals an alarming scenario if fish production continues to increase in the next 20 years without any strategic management efforts at the lake. Thus, the outcomes of this study may be able to address some of the issues as a guideline in planning additional fish cages at Temengor Reservoir. This carrying capacity model can be applied to any other lakes worldwide.

AUTHOR CONTRIBUTIONS

Muzzalifah Abd Hamid involved in writing—original draft, methodology, conceptualization, validation and formal analysis. **Amir Shah Ruddin Md Sah involved in** supervision, writing—review and editing. **Izwandy Idris involved in** supervision, writing—review and editing. **Siti Azizah Mohd Nor involved in** supervision, and writing—review and editing. **Mashhor Mansor involved in** supervision, writing—review and editing, funding acquisition.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial or personal interests that could have influenced the work presented in this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Who Brings in the Fish? The Relative Contribution of Small-Scale and Industrial Fisheries to Food Security in Southeast Asia

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Amidst overexploited fisheries and further climate related declines projected in tropical fisheries, marine dependent small-scale fishers in Southeast Asia face an uncertain future. Yet, small-scale fishers are seldom explicitly considered in regional fisheries management and their contribution to national fish supply tends to be greatly under-estimated compared to industrial fisheries. Lack of knowledge about the small-scale sector jeopardizes informed decision-making for sustainable ecosystem based fisheries planning and social development. We fill this knowledge gap by applying reconstructed marine fish catch statistics from Cambodia, Malaysia, Thailand, and Vietnam—countries of the Gulf of Thailand—from 1950 to 2013 to assess the relative contribution of small-scale and industrial fisheries to national food security. Reconstructed catches quantify reported and unreported fish catch from industrial, small-scale, and recreational fishing. We then conduct a comparative analysis of the degree to which the industrial and small-scale sectors support food security, by converting total catch to the portion that is kept for human consumption and that which is diverted to fishmeal for animal feed or other purposes. Total reconstructed marine fish catch from the four Southeast Asian countries totalled 282 million t from 1950 to 2013, with small-scale sector catches being underestimated by an average of around two times. When the amount of fish that is diverted to fishmeal is omitted, small-scale fishers contribute more food fish for humans than do industrial fisheries for much of the period until 2000. These results encourage regional fisheries management to be cognisant of small-scale fisheries as a pillar of socio-economic well-being for coastal communities.

Keywords: fishmeal, small-scale fisheries, food fish, food security, Southeast Asia

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INTRODUCTION

Small-scale inshore fisheries are the backbone of socio-economic well-being in coastal communities throughout the world (Béné, 2006; Harvey, 2006; Teh and Sumaila, 2013), particularly in the tropics where the majority of countries with heavily fish dependent populations are situated (Golden et al., 2016). In these locations, fish is crucial for food security and health, providing not only daily protein requirements, but also a range of essential micronutrients that fend off diseases of malnutrition. The importance of fish to society is more so given that it is relied upon by some of society's most vulnerable groups, including the poor and stateless migrants, who might otherwise have no other means of livelihood (Béné et al., 2007, 2010). Fisheries in the tropics are predicted to fall by as much as 30% by 2050 as a result of global ocean warming and changes in net primary production (Cheung et al., 2016). Despite this abject negative outlook, national governments are not well-prepared to deal with its potential socio-ecological outfalls, not least due to glaring gaps in knowledge about the magnitude and nature of small-scale fisheries (Pauly, 1997, 2006; van Zwieten et al., 2002). There is thus a very real and urgent need to assess the role of small-scale fisheries, and to translate this knowledge to timely and relevant policies on sustainable fisheries and marine management for food security (Teh et al., 2007; Barnes-Mauthe et al., 2013).

The definition and terminology for small-scale fishers varies from country to country (**Table 1**). In Malaysia, small-scale fisheries are most consistent with traditional fisheries which include those fishers who use traditional gears such as hook-and-line, bagnets, traps, lift nets, seine nets, barrier nets, and scoop nets. In Vietnam, fisheries are commonly classified as near-shore and offshore rather than as small and large scale (Pomeroy et al., 2009), while in Cambodia the term coastal fisheries is used, and involves family-scale fishing units operating from the coast to a depth of 20 m (FAO, 2011b). Thailand's Department of Fisheries' definition is based on boat gross tonnage, whereby small-scale is defined as inboard powered boats of less than 10 GT, and that generally operate inshore. For the purpose of this study, we define small-scale fisheries as those that exhibit some or all of the following characteristics: (i) primarily geared toward household consumption, sale at the local level, or export in the case of high value species; (ii) usually at low level (primary and secondary) of economic activity; (iii) for fulfilling cultural or ceremonial purposes; (iv) non-mechanized, or involve low technology and low capital investment; (v) undertaken by the fisher and/or family members only; (vi) conducted within inshore areas; and (vii) minimally managed (Teh and Sumaila, 2013). We consider industrial fisheries to be large-scale, commercial fishing operations that involve substantial capital investment and take place in coastal or offshore fishing grounds, in which fishing is typically carried out by a crew and lasts from days to months at a time.

Small-scale fisheries in Southeast Asia (SEA) tend to be overshadowed by the large-scale commercial (industrial) sector, which, due to a larger fishing capacity, has historically been favored by governments as the more efficient method of marine resource exploitation. Starting with the introduction of trawling in the mid-20th century, first in Thailand then Malaysia, governments rapidly expanded the fishing power of their industrial fleets in the "race for fish" toward national social and economic development objectives (Morgan and Staples, 2006). These fisheries generated national income, supplied food to feed the country, and provided local jobs that were ironically supposed to benefit poor fishing households, i.e., small-scale fishers. Yet, the concerns of small-scale fishers were considered secondary or even completely overlooked at the national level (van Zwieten et al., 2002; Pauly, 2006). Tellingly, small-scale fishers and their catch are largely unaccounted for in the fisheries statistics of many countries, including Vietnam and Cambodia (van Zwieten et al., 2002; Pomeroy et al., 2009; Teh et al., 2016b,c), or greatly under-represented in others such as Thailand and Malaysia (Teh and Teh, 2016; Teh et al., 2016a) (**Table 1**).

The biased investment in industrial fisheries has resulted in overfishing throughout Southeast Asia—in the Gulf of Thailand, demersal fish stocks in the 1990s had fallen to just one tenth of their levels in the mid-1960s when trawling began (FAO, 1997). The depletion of inshore fish stocks has often come at the socio-economic expense of small-scale fishers (Panayotou, 1980; Salayo et al., 2006), many of whom have limited control over marine resource access issues (but see Kurien, 2004). Up to now, the disparity between industrial and small-scale sector catches has not been easily quantified due to inconsistent or lack of accounting of small-scale catches. Small-scale fisheries are notoriously hard to quantify. Often, they take place in rural areas that may be remote and difficult to monitor, but even in urban areas small-scale fisheries can be poorly monitored due to low prioritization and budgetary constraints (Pauly, 1997; Béné et al., 2010). Ignorance also plays a role, as activities such as gleaning by women and children have until recently not been recognized for their important role in securing household food and nutritional requirements (Harper et al., 2013).

The objective of this paper is to assess the relative contribution of the industrial and small-scale fishing sectors to national food security. We do this by analyzing previously reconstructed marine fisheries catch data from four countries that border the Gulf of Thailand—Vietnam, Cambodia, Thailand, and Malaysia—for the period 1950 to 2013, and estimating the proportion of fish catch from each sector that is available directly for humans' consumption.

METHODS

The historical reconstruction of fisheries catch statistics for Cambodia (Teh et al., 2014a), Malaysia (Teh and Teh, 2014), Thailand (Teh et al., 2015), and Vietnam (Teh et al., 2014b) estimated total fish catch from each country's EEZ in the period 1950 to 2010 that were caught by their domestic fishing fleet, by adding unreported catch to officially reported fish landings. Reported fish landings were typically extracted from the FAO's fisheries statistics database while unreported catches from small-scale (artisanal and subsistence), industrial, and recreational fishing were estimated by synthesizing data from a variety of literature. As each of the four countries' detailed catch reconstruction methods are explained elsewhere (Teh and Teh, 2014; Teh et al., 2014a,b, 2015), we have not reproduced them in this paper. Rather, we briefly describe how unreported fish catches were estimated in each country's fishing sectors (**Table 2**).

Industrial Sector

Unreported industrial catch was estimated by raising reported landings by a multiplier which reflects the level of illegal, unregulated, or unmonitored fishing. In Thailand, 20% was added to catches of demersal fisheries to account for unreported industrial catch (Teh et al., 2015), while in Vietnam, total landings were raised by an unreported catch ratio of 1.9 (Teh et al., 2014b). In Cambodia, "A significant amount of the marine catch

TABLE 1 | Description of fisheries that are considered industrial and small-scale in each of the four studied countries, and their coverage in national fisheries statistics.

	Industrial	Small-scale	Sectors covered in national statistics
Cambodia	Boats > 30 m	Family-scale fishing units, fishing up to depth of 20 m	Boats > 30 m that pay tax
Malaysia	Deep-sea fishing vessels > 70 GRT that operate beyond 30 nautical miles from shore, and fishing with commercial gears (trawl, purse seine, driftnet, and gill net)	Fishing with traditional gears (hook-and-line, bag net, trammel net, lift net, and traps)	Licensed industrial and traditional gears
Thailand	Inboard powered boats > 5 GRT	Boats < 5 GT that operate near shore, with inboard or outboard engines, or are non-powered	Landed industrial and small-scale catches
Vietnam	"Offshore" boats with engines > 90 hp	Near shore fisheries	Not specified

TABLE 2 | Methods for estimating unreported industrial and small-scale catch for each country.

	Cambodia	Malaysia	Thailand	Vietnam
Industrial	Unreported catch multiplier	Fishing effort	Unreported catch multiplier	Unreported catch multiplier
Small-scale	Fish consumption & fishing effort	Fishing effort	Fishing effort	Unreported catch multiplier

is transferred to foreign vessels at sea and is not landed in Cambodia" FAO (2017), with suggestions that up to 80% of marine fish catch is sold at sea and not reported (Chansothea et al., 2007; FAO, 2011a). Reported landings were thus raised by a factor of 4 during years when fisheries management was minimal (1960–1990), after which the percentage of catch sold at sea was linearly decreased to 25% in 2000 and then held constant to the end of the catch reconstruction period (Teh et al., 2014a). Unreported industrial fish catch in Malaysia was based on the fishing effort of unlicensed trawlers. The catch by unlicensed (unreported) trawlers was derived by applying an unlicensed to licensed ratio to the number of licensed trawlers. There were an estimated 452 unlicensed, as opposed to 138 licensed trawlers operating in Peninsular Malaysia in 1966 (Anon, 1968). This generates an unlicensed to licensed ratio of 3.28, which was used as the starting anchor point in 1964, the year that industrial sector catches were first accounted for in the catch reconstruction. Thereafter, anchor points were 5.06 and 1.46 in 1967 and 1998 respectively. Intervening years between anchor points were linearly interpolated, and the 1998 anchor point was carried forward to 2010 due to reports of ongoing unlicensed fishing by trawlers along the East Coast in the mid-2000s (Anon, 2008).

Small-Scale Sector

Two methods were used generally, one based on fish consumption and the other on fishing effort. The fish consumption method estimated catch by assuming that small-scale fishing was supplying at least enough fish to feed the coastal population. Thus, fish catch was estimated by multiplying coastal population by a fish consumption rate. This approach was typically used in the earlier reconstruction periods when local fisheries were less commercialized. For example, in Malaysia the fish consumption method was used from 1950 to 1965. Thereafter, fishers were assumed to have become more market oriented and increased production levels, and the small-scale catch estimation was accordingly adjusted to the fishing effort method. Similarly, small-scale fishing in Cambodia was assumed to be mostly subsistence based from 1950–1980, during which the fish consumption method was used. The fishing effort method estimated total catch by multiplying the number of fishers or boats with a catch rate to derive a time series of catch. Appendix 1 in Supplementary Materials provides more information on the methods used to estimate unreported small-scale sector catch.

Discards

Fish discarded at sea are treated as part of industrial catch, and were generally estimated by applying a discard rate to total industrial (reported and unreported) catch. Fish discards tend to be low value fish which have no commercial value or are too small to be eaten. Fish discarding in Southeast Asia is generally low because of existing markets for fertilizer and fishmeal, which use low value fish as inputs. Discard rates were primarily extracted from a study on fish discarding practices in marine fisheries around the world (Kelleher, 2005). In Cambodia, a discard rate of 1% (Kelleher, 2005) of industrial catch was used starting in the mid-1990s. In Thailand, the discard rate was linearly decreased from 22% (Kungsawan, 1996) of total catch in the 1960s when industrial trawling began to 1% (Kelleher, 2005) by 2000. In Vietnam, only large trawlers that operate offshore for several days discard low value fish (Long, 2003), which made up about 50–60% of their total catch (Long, 2003). We treated these as the amount of fish discarded at sea. In Peninsular Malaysia, fish discards was estimated based on the proportion of low value fish in landed catch, which averaged 30% from 1976 to 2010.

Recreational Catch

Recreational catch – recreational catch, which is defined as fish caught for leisure, was estimated for Thailand and Malaysia. This method will not be described here as it is not considered in this paper.

Reconstructed Fish Catch Statistics Extension to 2013

We updated reconstructed marine fish catch statistics from their ending year of 2010 to 2013. To calculate total reconstructed catch in 2011 and subsequent years, we adjusted the preceding year's catch by the percentage change in annual reported landings as reported by FAO in FishStatJ[1].

In this study we use previously reconstructed catch data from 1950 to 2010, and extended catch data from 2010 to 2013, to estimate the quantity of industrial and small-scale fish catch that is used directly for human consumption.

Fishmeal Production

We used the quantity of catch that is channeled to fishmeal production as the proxy for the amount of fish used for non-human consumption. Trawl nets are the dominant gears that catch low value fish (LVF) that are processed into fishmeal (Pomeroy et al., 2007). Thus, we only used the quantity of catch from industrial trawlers in deriving the amount of fish for fishmeal. This was calculated as follows:

$$C_{fishmeal} = C_{ind}{}^{*}\%\ \text{trawl}^{*}\%\ \text{LVF}_{trawl}{}^{*}\%\ \text{LVF}_{fishmeal}$$

Where $C_{fishmeal}$ is the amount of fish for non-human consumption, C_{ind} is industrial sector catch, % trawl is the % of catch caught by trawl nets, % LVF_{trawl} is the % of trawl catch that is LVF, and % $LVF_{fishmeal}$ is the % of LVF used for fishmeal. The exception was Cambodia, for which, due to lack of data on % trawl and % LVF_{trawl}, we estimated $C_{fishmeal}$ based on the reported percentage of trash fish in total marine catch.

The percentage of catch caught by trawl nets was estimated from national fisheries statistics that provided landings by gear type (Malaysia, Thailand), or from published literature (Vietnam). Data on the species composition of trawl catches were also obtained from national statistics and literature, and were used to derive the proportion of low value fish in trawl catches. The proportion of low value fish that is channeled toward fishmeal ranged from a high of 100% in Cambodia to 50% in Vietnam, where there are competing uses of low value fish for fishmeal and fish sauce production (Edwards et al., 2004). Anchor points of the parameters used to calculate fishmeal production are detailed in Appendix 2.

Data Uncertainty

The uncertainty associated with each catch reconstructions is addressed using a "pedigree" procedure (Pauly and Zeller, 2016). In this approach, the authors of each catch reconstruction evaluate the quality of the time series data in each fisheries sector over three time periods (1950–1969), 1970–1989, and 1990–2010) by assigning a score from a scale of 1 (very low) to 4 (very high). Each score has a percentage uncertainty range associated with it, as shown on **Table 3**. This same procedure was used by the Intergovernmental Panel on Climate Change to quantify uncertainty in its assessments (Mastrandrea et al., 2010). We then calculate the average of the uncertainty percentages across all sectors, time periods, and countries to generate the upper and lower bounds for uncertainty.

[1]Food and Agriculture Organization of the United Nations, Fisheries and Aquaculture Department. Software available at URL: http://www.fao.org/fishery/statistics/software/fishstatj/en.

TABLE 3 | "Score" for evaluating the quality of time series of reconstructed catches, with their confidence intervals (IPCC criteria from Figure 1 of Mastrandrea et al., 2010)†.

Score		−%	+%	Corresponding IPCC criteria*
4	Very high	10	20	High agreement & robust evidence
3	High	20	30	High agreement & medium evidence **or** medium agreement & robust evidence
2	Low	30	50	High agreement & limited evidence **or** medium agreement & medium evidence **or** medium agreement & robust evidence
1	Very low	50	90	Less than high agreement & less than robust evidence

†This table is from Zeller et al. (2015).
**Mastrandrea et al. (2010) note that "confidence increase" (and hence confidence intervals are reduced) "when there are multiple, consistent independent lines of high-quality evidence."*

RESULTS

Reconstructed marine fish catches from the industrial and small-scale (artisanal and subsistence) sectors, as well as recreational fishing, in Cambodia, Malaysia, Thailand, and Vietnam totalled about 282 million t from 1950 to 2013, averaging 972,000 t in the 1950s and increasing to 7.3 million t in the last decade (**Figure 1**, Appendix 3 in Supplementary Materials). Total reconstructed catch was about 1.7 times higher than the catch amount reported to the FAO on behalf of the four countries for the same time period, which we show with the average percentage uncertainty associated with the reconstructed catch (**Figure 2**). The highest contribution to total catch was made by Thailand with 37%, while at 2% Cambodia contributed the least (**Figure 3**). Highest under-reporting occurred in the 1950s when reconstructed catches were 2.3 times that of reported catch, then decreased to a level of 1.8 in the last decade. Small-scale catches were similarly under-reported by about two times across the catch reconstruction period (**Figure 4**). The proportion of small-scale sector catch fell from comprising almost all of total reconstructed catch in the 1950s to about 35% in 2013, with the largest drop observed in the 1960-1970 decade (**Figure 5**). Overall, industrial sector catch comprised 70% of total catches in Cambodia; 76% in Malaysia; 53% in Thailand; and 32% in Vietnam.

Small-scale fisheries, from being the main source of fish in the 1950s, were overtaken in the mid-1970s by industrial sector catches (with the exception of Vietnam, where the industrial sector did not take off until the late 1980s). Although much higher than small-scale catches, the contribution of industrial catch to local food security is not as great as initially appears to be when assessed by the proportion of industrial catch that is channeled toward human and non-human consumption, the latter as measured by catch amount used for fishmeal production. Across all four countries, the proportion of industrial catch used for fishmeal averaged 30%. When fishmeal is omitted, catch from the small-scale sector exceeds the portion of industrial catch that is consumed by people from 1950 until around 2000 (**Figure 6**).

Depending on the fisheries sector and time period, the original reconstructed catch data were estimated with uncertainty ranges

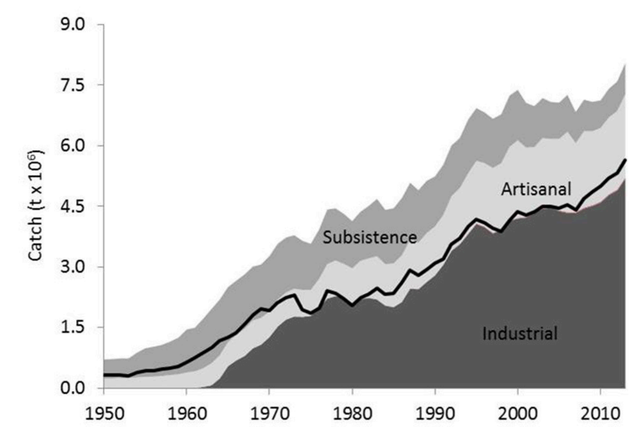

FIGURE 1 | Total reconstructed catch of Cambodia, Malaysia, Thailand, and Malaysia showing the contribution of different sectors. The solid line indicates reported catch. Recreational catches are too small to appear on this graph.

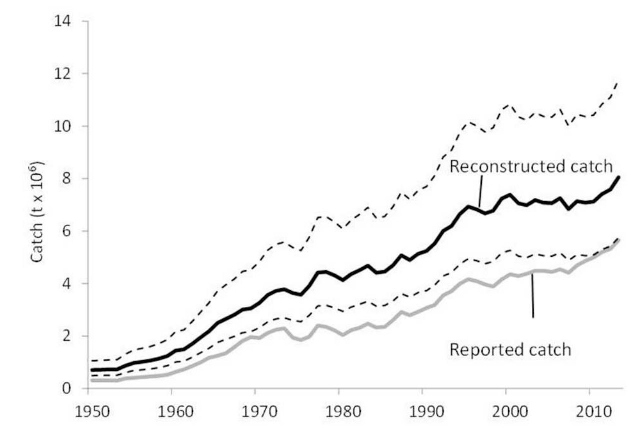

FIGURE 2 | The mean weighted uncertainty (dashed lines) of total reconstructed catch. Uncertainty is based on data quality scores assigned to each country.

of between 20–50%, associated with high to low confidence in data quality.

DISCUSSION

Throughout Southeast Asia small-scale fishing is vital for the well-being of coastal communities, where it provides food, informal employment, and income for some of the poorest and most marginalized segments of society (Béné, 2006; Pomeroy, 2012). Despite this, the contribution of small-scale fisheries is inherently overlooked by national governments. The reconstructed marine fisheries catch of Cambodia, Malaysia, Thailand, and Vietnam show clearly the significant contribution of this sector. For the first time, we quantified the amount of fish caught by small-scale fishers and find that they were the main providers of fish nationally until the rise of industrial fishing. Even when overtaken in terms of catch amount by the industrial

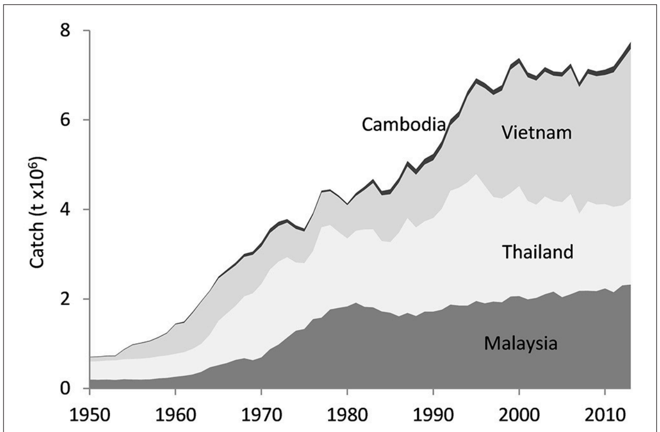

FIGURE 3 | Total reconstructed catches from four Southeast Asian countries.

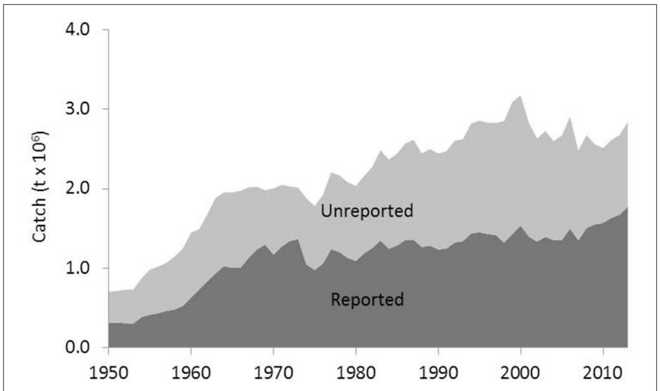

FIGURE 4 | Unreported and reported small-scale sector catches from four Southeast Asian countries.

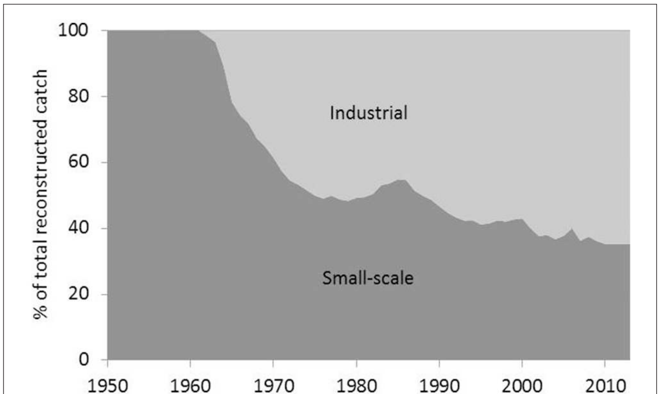

FIGURE 5 | Percentage change in small-scale and industrial sector catch contribution from 1950 to 2013.

sector, small-scale fisheries remain important at the community level where they act as social safety nets (Béné et al., 2007, 2010). Coastal dwellers in Southeast Asia, whose fish consumption rates are high (Needham and Funge-Smith, 2014), and especially those

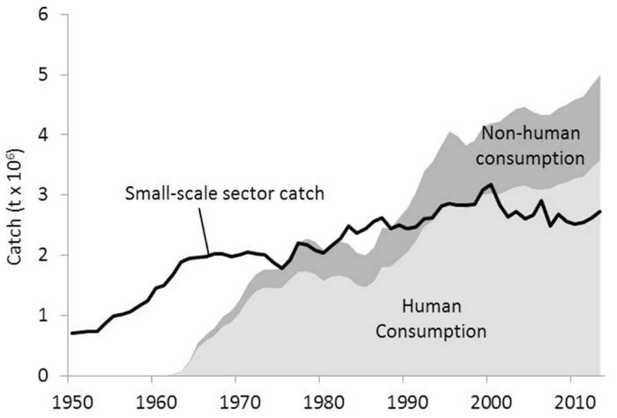

FIGURE 6 | The proportion of industrial sector catch (aggregated across all four countries) that is used for human and non-human consumption (fishmeal). The solid line shows small-scale sector catch.

in rural or remote locations, rely on the catch brought in by small-scale fishers for meeting daily protein and micronutrient needs (Needham and Funge-Smith, 2014).

In each of the four countries, accelerated industrial sector catch coincided with national fisheries expansion plans after World War II which looked to fishing as a way to achieve food security and economic development. In Thailand the otter trawl was introduced as part of the government's National Economic and Social Development Plan in 1961 (Butcher, 2004). This paved the way for subsequent depletion of Thailand's inshore marine resources, and intensification of the "race for fish" in the Gulf of Thailand (Butcher, 2004). Fisheries expansion in Vietnam during the late 1950s to mid-1960s was supported by investments from the U.S. government (Butcher, 2004), while economic liberalization policies introduced in 1986 spurred rapid growth of the country's industrial fisheries (Pomeroy et al., 2009). In Malaysia, government investment in commercial fisheries through a series of National Economic Plans led to rapid growth in the number of trawlers and surge in industrial fish landings in the mid-1960s to 1970s (Butcher, 2004).

The rise of industrial fishing has come at the expense of small-scale fisheries, as small-scale catches from the four countries have declined from comprising 80% of total reconstructed catch in the mid-1960s to 35% in 2013. Reports of decreased catches in small-scale fisheries are common throughout Southeast Asia (Butcher, 2004; Morgan and Staples, 2006; Teh et al., 2007), a trend that is supported by this study. The overall decline in small-scale catches shown in this study concurs with fishers' perceptions of reduced catches regionally. In Thailand, small-scale fishers apparently were able to catch up to eight times as much fish in the 1980s compared to 2000s (Lunn and Dearden, 2006). In Vietnam, small-scale fishers perceived that fish catch had decreased by slightly over 40% over the span of the 2000s (Sinh and Long, 2011). Similarly, small-scale fishers in Cambodia experienced a marked reduction in catches in the 2000s (Doma, 2011). Not surprisingly, the unequal distribution of marine resources has been the root cause of on-going conflict between small-scale fishers and large commercial fishing operators across Southeast Asia (Salayo et al., 2006). When trawling started to expand in the 1960s, trawlers and traditional fishers got into violent confrontations over valuable shrimp stocks in in the Straits of Malacca (Butcher, 2004). Then, as now, indiscriminate trawling not only damaged small-scale gears but also crowded small-scale fishers out of their traditional fishing grounds (Pomeroy et al., 2007).

The higher catches obtained by industrial vessels do not translate to increased fish supply for human consumption. The conversion of low value fish to livestock feed and the negative implications of this practice for societal food security and fisheries sustainability is widely acknowledged (Pauly, 1996; Funge-Smith et al., 2005). However, it has been difficult to make policies to manage this issue due to insufficient monitoring and data on the catch of low value fish. Our results indicate that across all four countries, the amount of catch diverted to fishmeal accounts for 14% of total reconstructed fish catch (excluding recreational fishing) from 1950 to 2013 (**Figure 6**). This is lower than existing estimates, where 25% of landed fish is thought to be used for livestock/fish feed purposes (Funge-Smith et al., 2005). Despite being on the low end, the loss of fish to fishmeal as estimated in this study is still substantial to the extent that it diminishes the contribution of industrial fishing to human food security relative to the small-scale sector.

In other words, our analysis highlights the importance of small-scale fishing in supplying fish to feed local populations. When the quantity of fish not intended for human consumption is taken out of industrial catch, small-scale sector catch is higher than that of the industrial sector from 1950 until 2001, with the exception of minor deficits in 1995 and 1996, whereas this threshold would have occurred earlier in the 1980s if all industrial catch was destined for human consumption. If the proportion of total marine fisheries catch used for fishmeal was 25% as estimated elsewhere, the small-scale sector would be the main supplier of food fish until 2009 when it gets outpaced by the industrial sector, assuming small-scale catches are entirely consumed by humans. This reinforces the important role of small-scale fisheries in supporting food security at household and national levels (FAO, 2005; Sowman and Cardoso, 2010). This should not imply that industrial fishing completely erodes food security, as labor income earned by fishing crew and national revenue from fisheries exports indirectly support people's ability to purchase fish or other food.

In this study we have attributed all fishmeal catch to the industrial sector. This does not suggest that the small-scale sector does not catch low value fish, which it in fact does. Rather, since "trash fish that could be used for human consumption are produced by fishermen on short fishing trips." (Goh and Tan-Low, 2008), we have made the assumption that low value fish caught by small-scale fishers are still entirely consumed by humans, either fresh or processed into fish sauce or other edible products, for example *nam pla* in Thailand and *nuoc mam* in Vietnam (Pauly, 1996). The results should also not be interpreted to mean that industrial landings are entirely wasteful, as portions of low value trawl catches do get channeled for direct human consumption (Sowman and Cardoso, 2010). Moreover, as a primary input for aquaculture, fishmeal can be indirectly linked to food security and livelihoods. In the past 20 years, aquaculture production has increased quickly and is predicted to exceed capture fisheries production in the near future (World Bank, 2013). Increasing human demand for fish is expected to be met by aquaculture, which, aside from direct consumption, also supports food security through the provision of income and employment (Belton and Thilsted, 2014).

The fishmeal catch estimates we have provided here tend to be conservative, so are more likely to be on the lower side of actual fish tonnage used to produce fishmeal. We accounted only for low value fish from trawlers, as this is the gear responsible for the vast majority of "trash fish" catch. In Thailand, about 95% of low value fish are reportedly from trawl fisheries (Funge-Smith et al., 2005).Other industrial gears such as purse seine also bring in some low value fish, but the contribution is comparatively minor at around 3% of total low value fish catch (Funge-Smith et al., 2005). The production of fishmeal often makes use of low value fish that are categorized as "trash fish" but also other food fishes of commercial value that are either damaged, too small, or not fresh enough. The proportion of catch we attributed to low value fish did not take into account other food fish (except for Thailand, where "food fish" was identified specifically as a component of "trash fish"), thus actual amounts of low value fish in total catch are likely to be higher than that estimated here.

The reconstructed catch data were estimated with uncertainty ranges of −29–48% when averaged across countries, fisheries sectors, and time periods. This level of uncertainty carries over to the current study, which is based on the original country reconstructions. Specifically, the results are driven by the amount of fisheries catch that is used for fishmeal production, an estimate that is based on reconstructed industrial catch and thus subject to this uncertainty range. Much of the uncertainty is due to extremely limited fisheries data, especially in the early time period of 1950-1969 and within the small-scale fishing sector. To help readers manage uncertainty, we have provided data sources and stated study assumptions in the main text and supporting information, so that readers can identify where potential data discrepancies may have entered the computations. To this extent, we acknowledge the dynamic nature of this research and invite suggestions on data sources we may have overlooked, and/or to improve underlying assumptions. The uncertainty levels we have presented should be interpreted with caution—in the later period from 1990 to 2010, Thailand and Malaysia received "high" data quality scores in their industrial sectors, suggesting improved data quality through time. We also emphasize that the uncertainty levels we have presented are concerned with the statistical accuracy of data, which is different from conventional uncertainty measures such as confidence intervals and error bars which deal with the statistical precision of sampled data (Pauly and Zeller, 2016). Lastly, we point out that marine capture statistics collected by national governments and reported by the FAO are also based on estimates. They are not qualified by any indicators of uncertainty, yet are accepted as "official" and used by the academic community and policy makers (Pauly and Zeller, 2016).

There has been a tendency for governments to focus excessively on large-scale fisheries for national socio-economic growth (Butcher, 2004; Sinh and Long, 2011). Investment in trawl gear, which was seen as the most efficient method of catching large amounts of fish, has instead degraded marine ecosystems (SeaWeb, 2008). The competition for space between large trawlers and traditional fishers has not been adequately managed, nor has the inequitable distribution of resources between the two sectors been addressed (Salayo et al., 2006). The anticipated negative impacts of future climate change on tropical fisheries (Cheung et al., 2016) will hit vulnerable groups such as marginalized and poor fishers especially hard (Béné, 2006; Davis and Ruddle, 2012). The extent to which this will further erode local food security, the cornerstone of societal stability, will likely be greater than what is expected if planning is based on current incomplete knowledge of small-scale fisheries. We emphasize the urgency for governments to focus on sustaining small-scale fisheries for future long-term ecosystem and socio-economic well-being. Acknowledged for many years, the undervaluation of small-scale fisheries is finally gaining traction in the international policy arena. The recent and timely release of the FAO's Guidelines for Securing Sustainable Small-Scale Fisheries (FAO, 2015) provides a basic starting point for governments to start addressing small-scale fisheries in their countries.

AUTHOR CONTRIBUTIONS

DP and LT: Conceptualized the study; LT: Analyzed and interpreted the data, and wrote the manuscript; DP: Revised the manuscript.

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SUPPLEMENTARY MATERIAL

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