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Channels of distribution in Malaysian organic durian: Case study approach / Safari, S., Razali, N. A., Manickam, T., Mansor, H., & Yusof, R.

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Volume 3 Issue 2 (2023) Pages 347-352
https://www.multiresearchjournal.com/admin/uploads/archives/archive-1679125076.pdf
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Durian disease classification using vision transformer for cutting-edge disease control / Mat Daud, M., Abualqumssan, A., Nor Rashid, A., Hanif Md Saad, M., Mimi Diyana Wan Zaki, W., Safie Mohd Satar, N., & Malaysia, K.

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Volume 14 Issue 12 (2023) Pages 446-452
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**Durio Zibethinus L plantation intelligent web-based irrigation system using fuzzy logic (DuWIMS) based on IoT / Ahmad, Z. A., Chow, T. S., Jack, S. P., Abdullah, A. H., Ahmad, M. I., & Daud, S.**

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**Evaluation of morinda citrifolia leaf extract against phytophthora palmivora in controlling stem canker on durian (durio zibethinus) / Nor Danial, N. D., Asib, N., Sadi, T., & Ismail, S. I.**

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| *Journal of Information and Communication Technology*<br>Volume 23 Issue 4 (2024) Pages 667–707<br>https://doi.org/10.32890/jict2024.23.4.4<br>(Database: UUM Press) |

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# COMMERCIALISED DURIAN PLANTATION: DEVELOPMENT AND DESIGN OF WEB AND MOBILE APPLICATION

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## ABSTRACT

Durian farmers face many challenges in managing their plantations efficiently and effectively. These challenges include unpredictable weather patterns, labour shortages, pest and disease outbreaks, market fluctuations, and the complexity of managing farm operations. The commercialisation of durian plantations represents a significant shift in the agricultural landscape, driven by increasing demand for this prized tropical fruit. This project focuses on developing and designing a comprehensive web and mobile application explicitly tailored for commercialised durian plantations in Malaysia. Employing the Rapid Application Development (RAD) approach, the project encompasses four main phases: analysis, rapid design, prototyping, testing, and deployment. By leveraging digital technology, the application aims to address these challenges by streamlining various aspects of durian plantation management, including crop monitoring, inventory management, pest and disease tracking, and yield forecasting. Through user-friendly interfaces and intuitive functionalities, the application seeks to empower durian growers with actionable insights and decision-making tools to navigate these challenges and enhance their operations' productivity, efficiency, and sustainability. An evaluation component was conducted to assess the usability and effectiveness of the application in real-world plantation settings. Overall, the response to the evaluation indicated that both applications are valuable and easy to use, justifying their integration into durian plantation management practices. The significance of this project lies in its potential to revolutionise durian plantation management practices, contributing to the broader goals of sustainable agriculture and economic development in the durian industry. Findings from the project evaluation will inform future directions for refinement and expansion of the application, ensuring its continued relevance and impact in supporting the growth and competitiveness of commercialised durian plantations.

**Keywords:** Durian cultivation, Commercialisation, Agricultural technology plantation management, durian information system

## INTRODUCTION

Durian, native to Southeast Asia, holds the moniker "King of Fruits." Scientifically named Durio zibethinus, it thrives primarily in Malaysia, Thailand, Indonesia, and the Philippines. Recognisable for its intense aroma, large size, and tough, thorn-covered shell, durian is a staple in the region. Southeast Asian countries like Malaysia provide ideal conditions for durian cultivation, with temperatures ranging from 27°C to 35°C and annual rainfall between 1800 mm to 4000 mm, favouring its growth in tropical climates (Rasad, 2020). Cultivating durians is a meticulous endeavour, requiring careful consideration of numerous factors to produce marketable fruit suitable for commercialisation. However, farmers often face challenges in managing durian plantations, as manual cultivation management lacks efficiency. Additionally, the absence of a systematic information system among farmers can result in poorly maintained plantations and unmarketable durian fruits. Moreover, a lack of knowledge in disease and pest control, soil preparation, and drainage systems further complicates cultivation efforts.

The commercialisation of durian plantations in Malaysia represents a significant shift in the durian industry landscape. Historically, durian cultivation in Malaysia was largely subsistence-based, with small-scale farmers growing durian primarily for local consumption (Baharum et al., 2019). However, increasing demand, coupled with advancements in agricultural technology and infrastructure, has led to the establishment of large-scale durian plantations aimed at meeting both domestic and international markets (Abdullah et al., 2020). The growing popularity of durian has prompted a surge in research exploring market trends and consumer preferences. Studies have identified factors influencing durian purchasing decisions, including fruit quality, variety, price, and convenience (Lim & Yacob, 2018). Additionally, according to Roslan et al. (2021), consumer preferences vary across different demographic segments, highlighting the importance of targeted marketing strategies and product differentiation in the commercialised durian industry.

However, technology is crucial in modern durian plantation management, facilitating efficiency, productivity, and sustainability. Web and mobile applications have emerged as valuable tools for durian growers, offering real-time monitoring of plantation conditions, inventory management, pest and disease tracking, and yield forecasting (Mohd Radzuan et al., 2022). These applications empower farmers with data-driven insights and decision-making capabilities, ultimately enhancing farm management practices. This project tackles these obstacles by customising web-based and mobile applications to meet durian farmers' requirements. These applications provide pertinent information and support for durian cultivation, facilitating streamlined plantation management and increased productivity. Through this initiative, the project seeks to alleviate the challenges encountered by durian farmers and foster the sustainable development of the durian industry. The envisioned web-based and mobile applications are poised to benefit durian farmers significantly by facilitating the growth and maintenance of durian trees through systematic plantation management. Particularly advantageous for farmers with sizable staff, this system synchronises data across multiple devices, ensuring seamless access to vital plantation information. Tasks, tree condition reports, and production details can be effortlessly accessed on various devices, mitigating challenges such as disorganised task scheduling and inaccurate production data. By leveraging these benefits, the system holds the potential to address critical challenges faced by farmers, thereby enhancing efficiency and productivity in durian cultivation.

To tackle the challenges, the project endeavours to aid durian farmers across Malaysia by establishing a mobile and web-based application as the central network. To achieve this, the project has been structured into three main objectives: (1). Identify the requirements for the Commercialised Durian Plantation Information System, (2). Develop the prototype of the Commercialised Durian Plantation Information System and (3). Evaluate the usability of the Commercialised Durian Plantation Information System. By pursuing these objectives, the project aims to offer comprehensive support to durian farmers, thereby improving their cultivation practices and ultimately advancing the durian industry in Malaysia. Despite the promising prospects of commercialised durian plantations, several other challenges persist. Climate change, land scarcity, labour shortages, and pest infestations threaten durian cultivation (Environment Asia, 2020). Moreover, ensuring sustainable practices and maintaining product quality remains paramount for durian growers. However, these challenges also present opportunities for innovation and collaboration within the industry, driving the development of novel technologies and practices to address emerging issues.

## BACKGROUND AND RELATED STUDIES

Plantation or orchard management is a process of management that includes all the stages involved in transforming a piece of land into a productive and profitable crop (Upson, 2021). Figure 1 shows the stages involved in orchard management. The process begins before the trees are planted. The plantation farmer needs to determine certain aspects, such as goals, work plans and priorities related to the plantation, before planting a seed on the land. These aspects are crucial for the growth of any trees to produce marketable fruits, nevertheless durian fruits. After identifying the factors above, the tree saplings are planted according to the work plan.

The second stage takes place during tree growth and is tree care. This includes fertilising and applying pesticides to the crop. It also includes determining the necessary action or steps to deal with a diseased tree and having a disaster plan, such as fires, droughts, or floods. It is crucial to address the possible issues as soon as the problem is identified, as it has a higher chance of saving and repairing the tree. The last stage in plantation management is harvesting. When the trees can bear mature fruit, harvesting and selling the production occur at this stage. The harvesting process includes hiring a group of workers, keeping account of the amount of fruit collected, and finally finding markets for the product. During this stage, necessary data such as the fruit size and weight, age of the tree, and type of fruit are recorded, as the data can provide an overview of what to improve for the future harvest.

**Figure 1**

*Plantation Management Phases*

An information system is a collection of interconnected components for collecting, storing, and processing data, as well as supplying information, knowledge, and digital products (Zwass, 2020) Information systems are used by businesses and other organisations to conduct and administer their business operations. The same is true for durian plantations. Information systems play a massive role in each stage of plantation management, mainly in the harvesting stage. Therefore, a systematic information system is essential for durian cultivation as the yield condition depends on the steps taken for each stage. With the advancement of technologies, the commercialisation of durian plantations has emerged as a critical trend in the Malaysian agricultural sector, reflecting the growing recognition of durian as a lucrative cash crop. Large-scale durian plantations have proliferated nationwide, particularly in regions with favourable climatic conditions and soil quality for durian cultivation. This shift towards commercialisation has been facilitated by various factors, including advancements in agricultural technology, improved infrastructure, and strategic marketing initiatives aimed at capitalising on the global appeal of durian (Abdullah et al., 2021). With the rise of commercialised durian plantations, there has been a growing emphasis on leveraging digital technologies to enhance farm management practices, streamline operations, and optimise yields. Web and mobile applications have emerged as valuable tools for durian growers, offering functionalities such as real-time monitoring of plantation conditions, inventory management, pest and disease control, and direct consumer engagement.

**Related Studies**

A few Studies were conducted on the existing system for durian plantation management. Five studies related to durian digital technologies are compared, as written in Table 1.

**Table 1**

*Previous Studies Related to Durian and Digital Technologies*

| Related Study | Result | Suggestion | Authors |
|---|---|---|---|
| Factors Influencing the Adoption of Digital Technologies in Durian Plantations: A Case Study in Malaysia | Explores factors driving the adoption of digital technologies, including web and mobile applications, in durian plantations in Malaysia. | Investigates perceived benefits, challenges, and adoption barriers faced by durian growers in integrating digital tools into farm management practices. | Abdullah, et al., (2021) |

| | | | |
|---|---|---|---|
| Consumer Preferences and Purchasing Behavior in the Malaysian Durian Market: Implications for Web and Mobile Application Design | Examines consumer preferences and purchasing behaviour in the Malaysian durian market. | This paper discusses implications for the design of web and mobile applications aimed at enhancing the durian shopping experience based on consumer preferences and behaviour. | Lim and Yacob (2019) |
| Technological Innovations in Durian Plantation Management: Opportunities and Challenges for Sustainable Agriculture | Provides a comprehensive review of technological innovations in durian plantation management. | Evaluate the potential benefits of technologies for enhancing productivity, sustainability, and profitability in durian cultivation while addressing challenges growers face. | Mohd Radzuan et al., (2020) |
| Transformation of Traditional Durian Orchard into Commercial Durian Orchard in Pahang, Malaysia | Explores the process and challenges of transforming traditional durian orchards into commercial ventures in Pahang, Malaysia. | Identifies key factors influencing successful transition and offers insights for farmers considering commercialising durian cultivation. | Baharum et al. (2019) |
| Marketing Strategies of Fresh Durians among Tourists in Penang, Malaysia | Investigates marketing strategies employed by durian sellers targeting tourists in Penang, Malaysia. | Provides insights into effective marketing tactics, product presentation, and customer engagement strategies for durian sellers in tourist destinations. | Roslan et al., (2018) |

Instead, this study found that two (2) commercial information systems developed for the durian industries, Durian Plantation Management (PMMP) and E-Soft Durian Plantation System, are software solutions designed to assist in managing durian plantations. However, they differ in several aspects: PMMP is a comprehensive system for managing various aspects of durian plantation operations. It offers crop monitoring, inventory management, financial tracking, and labour management functionalities. PMMP is designed to cater to the needs of durian plantations of various sizes, from small-scale operations to more significant commercial ventures. On the other hand, the E-Soft Durian Plantation System is a specialised software solution tailored explicitly for durian plantation management. It focuses on specific tasks related to durian cultivation, such as crop monitoring, inventory management, and possibly labour tracking. This system may offer fewer features than PMMP but provides a more focused and specialised approach to durian plantation management.

Both systems may integrate with IoT devices and sensors to collect real-time data on environmental conditions, soil moisture levels, and plant health. They may also offer mobile accessibility through companion mobile applications, allowing users to access essential features and data anywhere. While PMMP may provide a broader range of functionalities and scalability options, the E-Soft Durian Plantation System offers a more specialised and potentially streamlined approach explicitly tailored for durian cultivation. The choice between the two systems would depend on factors such as the size and specific requirements of the durian plantation, as well as the preferences of the users.

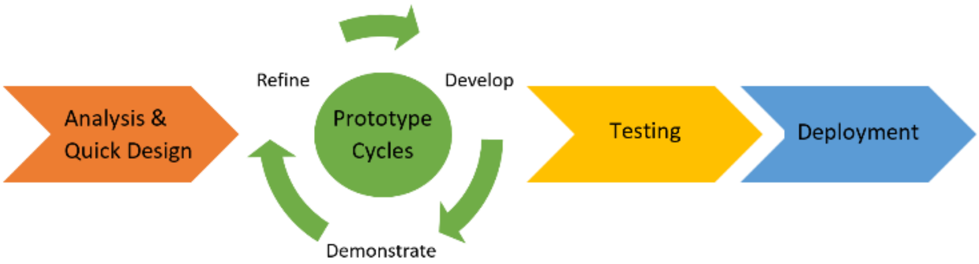
Regarding limitations, both PMMP and E-Soft Durian Plantation System may have limitations in terms of customisation options. Users may find it challenging to tailor the software to their needs or integrate custom features essential for their durian plantation management processes. While PMMP and E-Soft Durian Plantation System offer valuable tools for durian plantation management, they may have limitations regarding customisation, scalability, compatibility, data analysis, user interface, cost, and mobile accessibility. Durian growers should carefully evaluate these limitations and consider their specific requirements before selecting a software solution for their plantation management needs.

We aim to develop a user-friendly application tailored specifically for small and medium durian orchard farmers. Recognising farmers' diverse needs and constraints in managing their orchards, we aim to create an intuitive and accessible platform that simplifies essential tasks and streamlines operations. By prioritising ease of use and accessibility, we aim to empower durian farmers of all skill levels to effectively utilise digital tools for managing their orchards, optimising resource allocation, and enhancing productivity. Through close collaboration with farmers and continuous feedback gathering, we are committed to developing a solution that meets the unique needs of small and medium durian orchard farmers, ultimately contributing to the sustainability and success of their operations.

## METHODOLOGY OF STUDY

Rapid Application Development (RAD) was adopted as the project management process in completing this project. A form of the agile methodology development process, RAD emphasises rapid prototyping and iterations. It allows developers to quickly make several iterations and updates to a program without starting from the beginning of the development schedule for each update . This method was chosen as the project management process because the project was completed within a short period, which was 28 weeks.

**Figure 2**
*Rapid Analysis Design (RAD) Phases*




In the first phase, analysis and quick design were done by gathering the necessary information to obtain an overview of the programme needed to solve the problems. The information-gathering process consisted of reviewing articles and researching the durian domain. Necessary information on the process of durian cultivation, which includes preparation of soil, drainage system, fertilisation system and harvesting, was collected for a better understanding of the domain. In addition, this project was constructed to compare the existing applications during this phase. When there is sufficient information, analysis defines the objectives, scope, timelines, and expectations.

The second phase is the prototype cycle, where this project carries out three steps: to develop, demonstrate, and refine the prototypes. During this phase, this project developed prototypes of the applications based on the requirements obtained from the clients and the research conducted on similar applications. The requirements were obtained through questionnaires that collect data on the current system used by the clients and the situation or problem faced by the clients in durian cultivation. Then, the prototypes were shown to the clients to determine the suitability of the application in durian cultivation. When the project was in line with the client's requirements, the project proceeded with the refinement process. Updates and changes on the prototype issued by the clients were considered and used to improve the product. This project converted the prototypes about the updates to a working product during this phase. To develop the working product, this project used HTML, PHP, CSS, and SQL languages for the web-based application and Java language for the mobile-based application.

This project tested the application using pilot and field testing in the testing phase. Testing was conducted to ensure every function worked smoothly and met the client's requirements. Five people were handpicked for pilot testing, including three males and two females, who were selected to test both applications. The participants were selected from a group of conveniently available people, including friends and family. On the other hand, durian farmers or fruit farmers were contacted to conduct field testing. During this phase, the participants were allowed to propose new ideas, alterations, or updates to the working application. Subsequently, both tests were implemented, and the updates presented during the process were used to make necessary changes to the application.

In the last phase, this project deployed the finalised application to the client using a web host selected, 000WebHost, and FileZilla to upload the related files on a remote server for the web-based application. The coding files for the mobile-based application were transformed into an APK file shared through the Google Drive folder link. This phase consisted of constructing documentation on the user manual, including screenshots and descriptions for functions featured in the application, which was aimed to assist the user in navigating the application. Final changes were also made while checking the system for bugs during this phase.

## DESIGN DEVELOPMENT

The system developed is divided into two systems: web-based applications and mobile-based applications. Both applications are interrelated with each other and share the same database. Each plantation system can only be accessed by the farmers of the plantation, both the owner and the workers. People outside of the plantation, including other durian farmers, cannot access the plantation system except for their plantation system if they have registered with the system developer. The system also requires a primary internet connection as both applications will be connected to the web server. Storage is also required for mobile-based applications as it takes up a relatively small amount of device storage when installed. This system assumes that the user is familiar with a web-based application and mobile-based application interface and with handling and interacting with computer and mobile device hardware such as keyboard, mouse, and touch screen. Since the web-based application requires a web browser to be accessed, it is assumed that the user has an internet browser installed on the computer.

### The Requirements of the Commercialised Durian Plantation Information System (CDPIS)

The CDPIS requirements were obtained using three methods: (1) interviewing selected durian farmers and (2) analysing the documents and existing durian management plantation system. The interview was informal on a durian farmer using the Phone Interview method. The durian farmer mentioned was contacted through an acquaintance. Open-ended questions were asked during the interview, mainly about the difficulties faced in managing durian plantations and the functions expected for the system. The farmer's responses were recorded and analysed to obtain the requirements. Besides, the documents and existing systems related to this project were analysed. The documents or articles were found by searching related keywords, such as "durian farming system", "farming app", and "farming management system" on the Google search engine. The documents were examined to determine the system application requirements that could aid the farmer in durian plantation management.

The functional requirements for the CDPIS web-based application consist of six significant requirements, namely "login account", "manage plantation", "schedule task", "manage report", "view production", and "generate QR", as rendered in Table 2. In comparison, the CDPIS mobile app consists of three significant requirements, namely "login account", "list task", and "scan QR", as rendered in Table 3. As for the non-functional requirements, the CDPIS web-based application consists of three significant requirements, namely "secure system", "performance system", and "design website", as rendered in Table 4, while the CDPIS mobile app consists of two significant requirements namely "secure system" and "design app" as rendered in Table 5. M indicates the priority of the requirements for both applications – mandatory requirements (something the system must do), D – desirable requirements (something the system preferably should do) and O – optional requirements (something the system may do).

**Table 2**

*Functional Requirements for Web-based Application*

| No. | Requirements ID | Requirements Description | Priority |
|---|---|---|---|
| **1** | **CDPIS01** | **Login Account** | |
| | CDPIS01_01 | Existing users can log in to their account with the | M |

| | | | |
|---|---|---|---|
| | | correct username and password | |
| | CDPIS01_02 | New users can register by contacting the developer via email | M |
| | CDPIS01_03 | The system will display an error message if users enter the wrong username and password. | O |
| **2** | **CDPIS02** | **Manage Plantation** | |
| | CDPIS02_01 | The system should display the records of the tree background | M |
| | CDPIS02_02 | The system should display records of fruit background | M |
| | CDPIS02_03 | The system should allow users to add records of tree background | D |
| | CDPIS02_04 | The system should allow users to remove records of tree background | D |
| | CDPIS02_05 | The system should allow users to add records of fruit background | D |
| | CDPIS02_06 | The system should allow users to remove records of fruit background | D |
| | CDPIS02_07 | The system should allow users to edit records of tree background | O |
| | CDPIS02_08 | The system should allow users to edit records of fruit background | O |
| | CDPIS02_09 | The system should display an error message if there is an empty field when the user saves the records. | O |
| | CDPIS02_10 | The system should display an error message if the ID entered to add a record exist in the database. | O |
| **3** | **CDPIS03** | **Schedule Task** | |
| | CDPIS03_01 | The system should display the task list | M |

| | | | |
|---|---|---|---|
| | CDPIS03_02 | The system should sync the system task list with the app task list | M |
| | CDPIS03_03 | The system should allow users to add tasks to the task list | D |
| | CDPIS03_04 | The system should allow users to remove tasks from the task list | D |
| | CDPIS03_05 | The system should allow users to edit tasks in the task list | O |
| | CDPIS03_06 | The system should display an error message if there is an empty field when the user saves the task. | O |
| **4** | **CDPIS04** | **Manage Report** | |
| | CDPIS04_01 | The system should display all reports made through the app | M |
| | CDPIS04_02 | The system should allow users to remove reports | D |
| | CDPIS04_03 | The system should allow users to edit reports | O |
| | CDPIS04_04 | The system should display an error message if there is an empty field when the user saves the report. | O |
| **6** | **CDPIS05** | **View Production** | |
| | CDPIS05_01 | The system should display all records of good fruits from the app | M |
| | CDPIS05_02 | The system should display all records of rotten fruits from the app | M |
| **7** | **CDPIS06** | **Generate QR** | |
| | CDPIS06_01 | The system should generate unique QR codes for trees | M |
| | CDPIS06_02 | The system should generate unique QR codes for fruits | M |

| | | | |
|---|---|---|---|
| | CDPIS06_03 | The system should allow the user to display the existing QR code. | D |
| | CDPIS06_04 | The system should display an error message if the ID entered to generate QR does not exist in the database. | O |

**Table 3**

*Functional Requirements for Mobile-based Application*

| No. | Requirement ID | Requirements Description | Priority |
|---|---|---|---|
| **1** | **CDPIS07** | **Login Account** | |
| | CDPIS07_01 | Users can log in to their account with the correct username and password | M |
| | CDPIS07_02 | The app will display an error message if users enter the wrong username and password. | O |
| **2** | **CDPIS08** | **List Task** | |
| | CDPIS08_01 | The app should display the list of tasks from the scheduling system | M |
| | CDPIS08_02 | The app should allow the user to checkboxes in the list of tasks | D |
| | CDPIS08_03 | The app should allow the user to uncheck boxes in the list of tasks | D |
| **3** | **CDPIS09** | **Scan QR** | |
| | CDPIS09_01 | The app should allow users to scan the QR codes from trees and fruits | M |
| | CDPIS09_02 | The app should display the tree details after scanning the tree's QR code | D |
| | CDPIS09_03 | The app should display an option to add a report for tree inspection after scanning the tree QR code. | D |
| | CDPIS09_04 | The app should display the fruit detail function after scanning the fruit QR code. | D |
| | CDPIS09_05 | The app should display an option to select the fruit's condition after scanning the QR code. | D |
| | CDPIS09_06 | The app should allow users to key in reports after selecting Add Report. | O |
| | CDPIS09_07 | The app should allow users to select the option good for fruit condition after selecting harvest fruit. | O |

| | | | |
|---|---|---|---|
| | CDPIS09_08 | The app should allow users to select the option bad for fruit condition after selecting harvest fruit. | O |
| | CDPIS09_09 | The system should display an error message if there is an empty field when the user saves the report. | O |

**Table 4**

*Non-Functional Requirements for Web-based Application*

| No. | Requirement ID | Requirements Description | Priority |
|---|---|---|---|
| **1** | **CDPIS10** | **Secure System** | |
| | CDPIS10_01 | Only the owner and workers of the plantation can access the system | M |
| | CDPIS10_02 | Password must be the length of more than eight digits | M |
| | CDPIS10_03 | Password must contain characters and numbers | M |
| | CDPIS10_04 | The owner is creating a user ID | M |
| | CDPIS10_05 | The account for workers is created under the owner ID | M |
| **2** | **CDPIS11** | **Performance System** | |
| | CDPIS11_01 | If the system breaks, it will return to the last position before it crashes. | D |
| **3** | **CDPIS12** | **Design Website** | |
| | CDPIS12_01 | The system theme is minimalist | D |
| | CDPIS12_02 | The system font must be easy to read | D |

**Table 5**

*Non-Functional Requirements for Mobile-based Application*

| No. | Requirement ID | Requirements Description | Priority |
|---|---|---|---|
| **1** | **CDPIS13** | **Secure System** | |
| | CDPIS13_01 | Only the owner and workers of the plantation can access the app | M |
| | CDPIS13_02 | Password must have a length of more than eight digits | M |
| | CDPIS13_03 | Password must contain characters and numbers | M |
| **2** | **CDPIS14** | **Design App** | |
| | CDPIS14_01 | The app theme is minimalist | D |
| | CDPIS14_02 | The app font must be easy to read | D |

The requirements in Tables 3,4 and 5 were visualised and modelled using the proper modelling methods and tools. The requirements were visualised and modelled using this project's Unified Modelling Language (UML). Two behavioural diagrams, namely use case and activity diagrams, as well as a class diagram that illustrates the app's structural components, were employed in this study. StarUML was used to create the mentioned diagrams. Figures 3 and 4 represent the use case diagram of the system, which describes the interactions between the use cases and the actor of the application. The use cases are the primary functional requirements for each application. The use case of “Manage Plantation” for web-based applications enables the user to conduct sub-functions such as “Manage Tree” and “Manage Fruit”. The use case diagram is elaborated to highlight the app's dynamic behaviour. As a result, the interactions involved when using the system are depicted in an activity diagram. The class diagram, as shown in Figure 5, depicts the structural components of the system in durian plantation information management.

**Figure 3**

*Web-based Application Use Case Diagram*

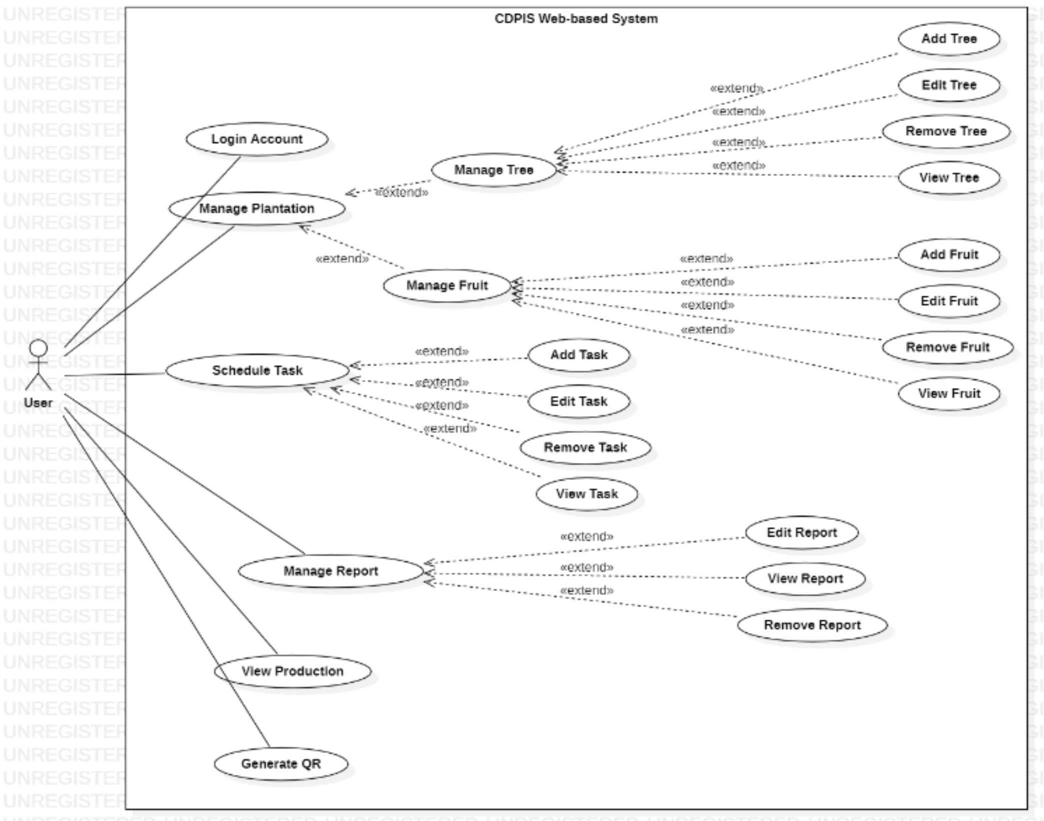


**Figure 4**

*Mobile-based Application Use Case Diagram*

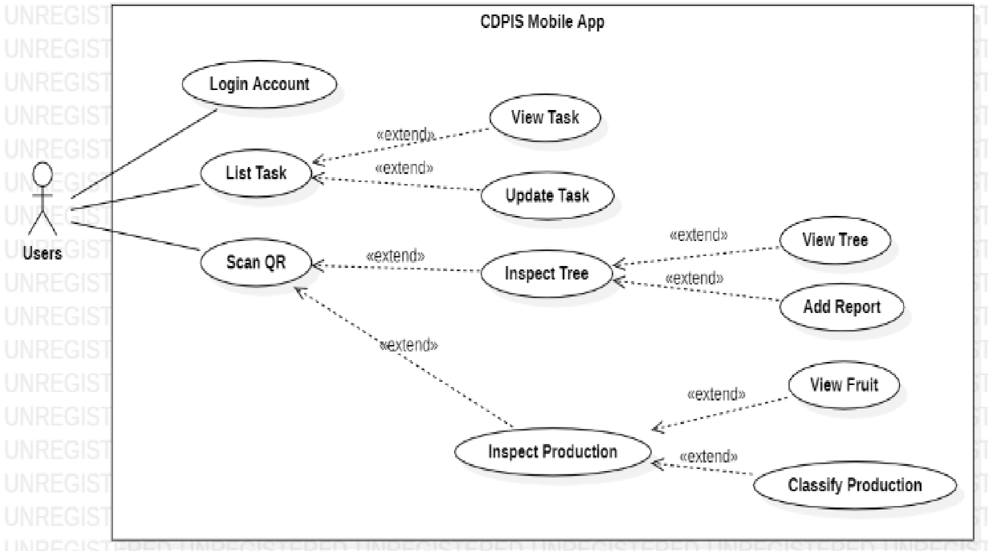
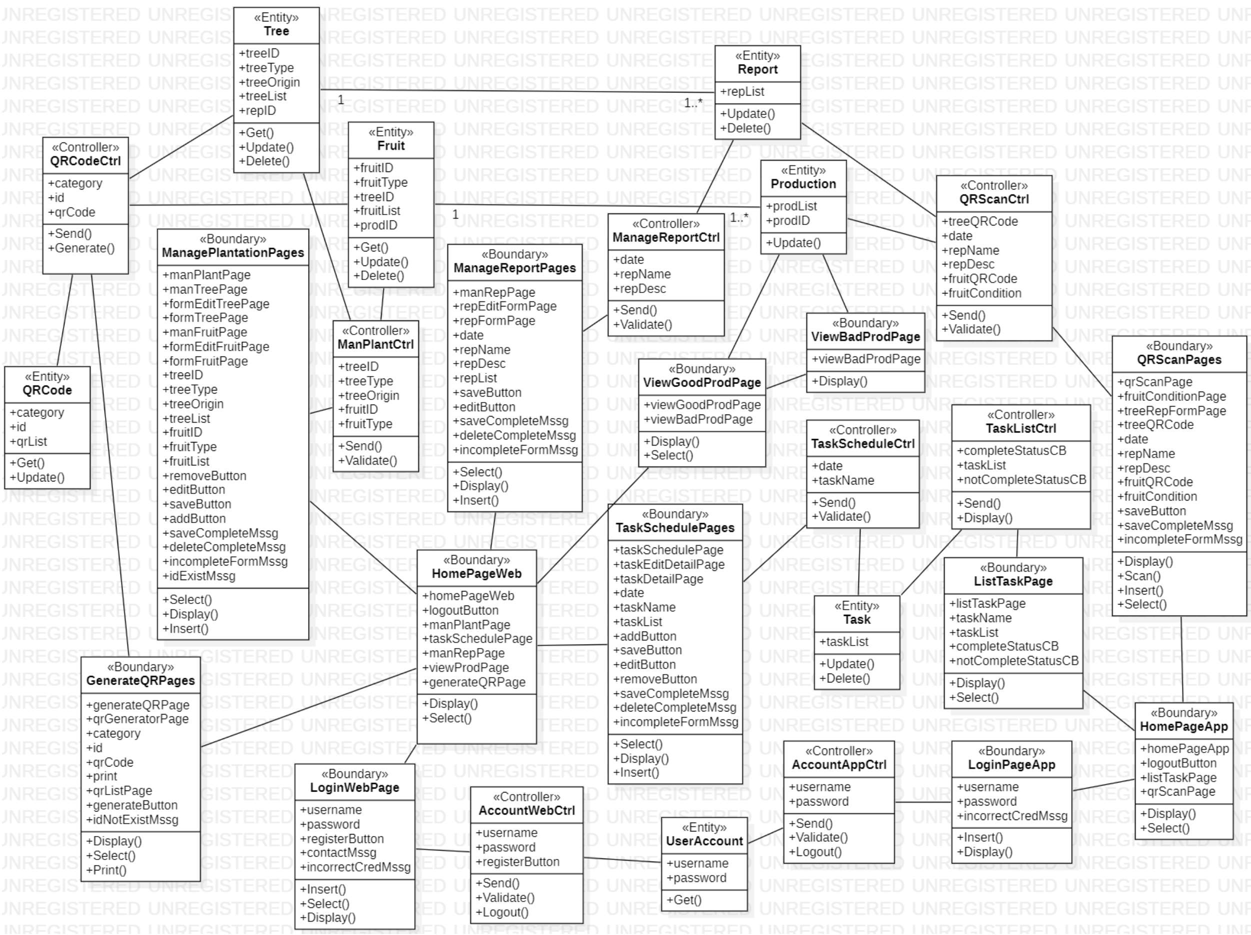



**Figure 5**

*Class Diagram of CDPIS*



## THE PROTOTYPE DEVELOPMENT OF CDPIS

CDPIS, an integrated system for durian plantation management that consists of web-based and mobile-based applications, was developed as a prototype. It encapsulates the requirements outlined in the preceding section. Software prototyping is a standard method of displaying software requirements so that users can provide additional feedback and suggestions based on their interactions with the prototype. Visual Code Studio was the tool used to develop the web-based prototype, which is the CDPIS website, while Android Studio was used to develop the mobile-based prototype, the CDPIS mobile app. Both applications are interconnected with a database server developed using PHPMyAdmin. The development of the website prototype was also made possible using the XAMPP Control Panel. Figures 6 and 7 show the screenshots of the selected interfaces for the CDPIS website, while Figure 8 shows the screenshots for the CDPIS mobile app.

**Figure 6**

*Login Account Page (Web-based Application)*

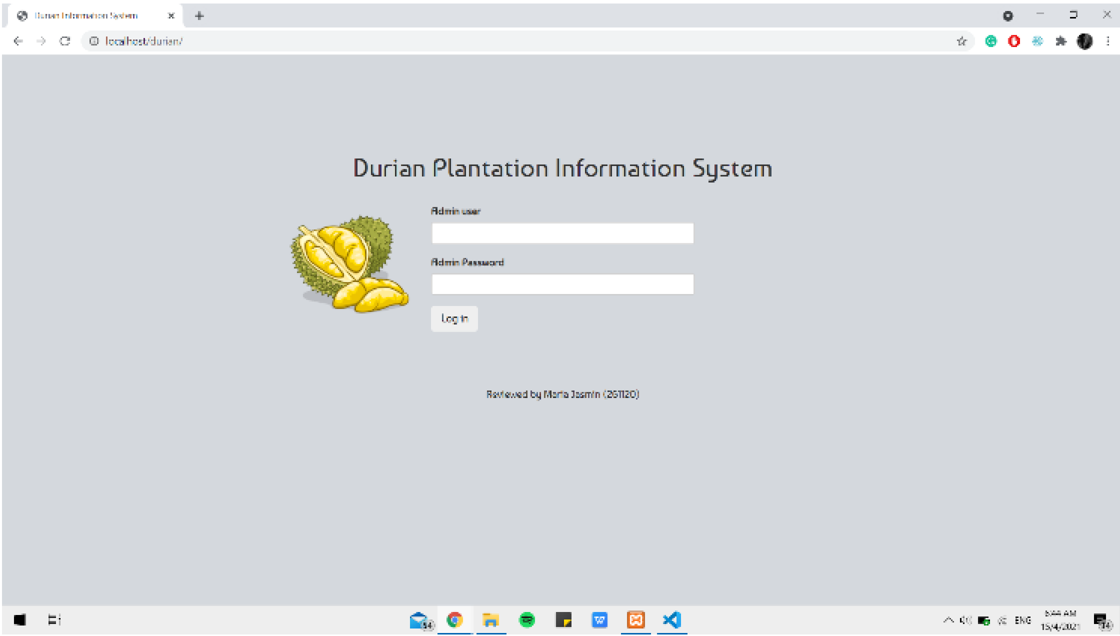


**Figure 7**

*Manage Plantation and View Production Page (Web-based Application)*

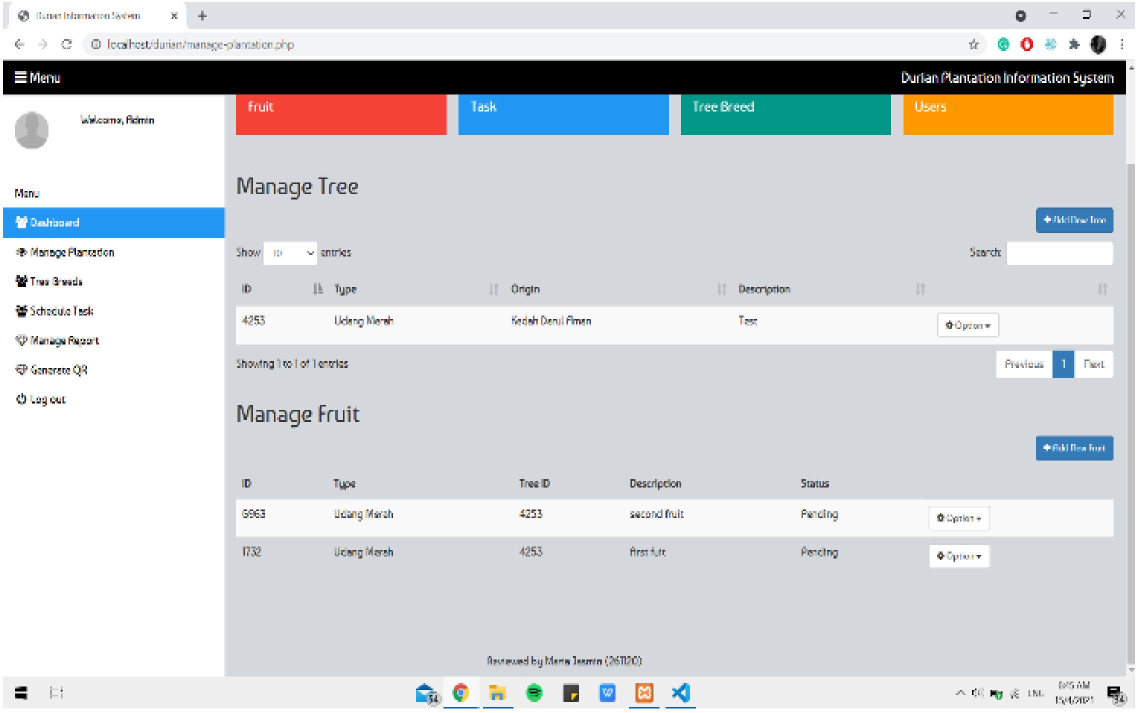
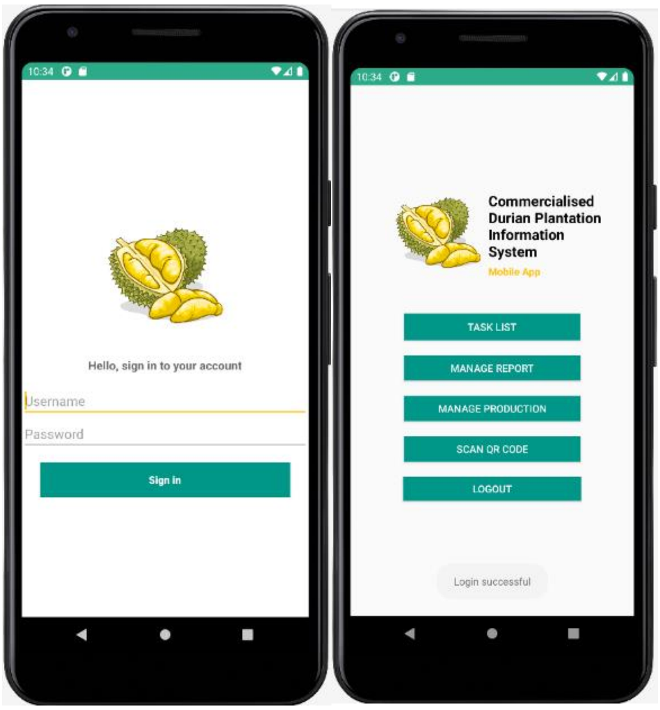



**Figure 8**

*Login Account and Main Page (Mobile-based Application)*



## EVALUATION AND RESULT

### The Evaluation Settings

Due to the current situation and the pandemic, the testing was conducted unmoderated and remotely. A usability evaluation was conducted to determine the ease of use of the applications' design and development among the representative users who participated in the field testing. Usability testing is one type of evaluation, which includes developing a test plan, gathering participants, and analysing the result in the field-testing report.

The target population for this project is durian farmers and people interested in durian cultivation. To evaluate the system, a sampling technique was used to select the participants. The technique adopted was a combination of quota and convenience techniques from the non-probability sampling category. Quota is a sampling technique in which the participants were chosen according to traits. The traits mentioned are gender, age, and knowledge of computers and technologies. The convenience method was also used, in which the participants were chosen from a group of people who were the easiest to contact or to reach. For field testing, a handful of durian farmers were personally contacted. However, only two durian farmers were willing to conduct the evaluation anonymously. To obtain more participants, the convenience method was applied by reaching out to the participants through social media platforms such as WhatsApp and Facebook. The total number of participants for the whole system is unclear, as the field testing was taken anonymously. Some participants may partake in the evaluation for both applications if not one. Therefore, the number of participants was counted according to the number of records in the post-task questionnaires for each category, which is the type of application.
The instrument used for this evaluation is a Word document. The document contains the instructions on how to conduct the system testing and evaluation, the credentials to log into the system, the link to the Google Form for the post-task questionnaires, and the link to the system, which includes the website link and Google Drive link to download the Android application package (APK). The post-task questionnaire consisted of 21 questions in 4 sections. Section A asked for the participants' demographic information; Section B asked about the type of application reviewed by the participants; Section C asked for the participants' opinions and experiences on the applications; and Section D asked for the participants' thoughts on the application in terms of suggestions for improvements or the general thought. Section C comprises 13 questions on a five-point Likert scale where one represents strongly disagree, and five represents strongly agree. The participants performed the following step-by-step procedure for the evaluation: (1) read the instructions, (2) access the system for each application, (3) conduct the task on the applications as stated in the experiment procedure, and (3) answer the post-task questionnaire.

### The Participants' Demographic Information

#### *Web-based Application*

Based on the analysis conducted on the participants' demographic information for web-based application testing, it was found that most participants, 64.7% of 17 participants, were male. Only 17.6% of the participants were male and aged 30 years and below, while the rest were male and aged 31 to 50. The rest were female, with the number evenly distributed for 30 years and below and 31-50 years old. Most participants, which was 47.1%, do farming or Durian farming as a part-time job, with most of the participants venturing into Durian farming for 2 to 4 years as a part-time job. 35.3% of the participants do this job full-time, and most have done it for over six years as a full-time job. 5.9%

of the participants intend to do Durian farming full-time. 17.6% of them have not or may not want to venture into Durian cultivation. As for the type of durian, most participants have cultivated or want to cultivate Musang King as it has the highest frequency, which was 13 records, followed by D24, with 11 frequencies, and D101, with eight frequencies. The least cultivated type of Durian was XO, as only 2 of the participants have cultivated or intended to cultivate this Durian type.

**Mobile-based Application**

Based on the analysis conducted on the participants' demographic information for mobile-based application testing, it was found that 80% of 16 participants are male, with 40% being male and at the age of 30 years and below. A small number of participants are female, only 20% of the total. Only 2 participants are male and at the age of 51 years and above. Most of the participants, which was 46.7% of them, does farming or Durian farming as a full-time job with most of the participants have been venturing in Durian farming for 2 to 4 years or over six years as a full-time job. 40% of the participants do this job part-time, and most have done it for 2 to 4 years or 4 to 6 years as a part-time job. 6.7% of them have not or may not want to venture into Durian cultivation, while 6.7% have cultivated other fruits or vegetables for less than two years. As for the type of durian, most participants have cultivated or want to cultivate D101, Durian Kampung and Musang King as they have the highest frequency, eight records, followed by Black Thorn and D24, with six as frequency. The least cultivated type of Durian was Red Prawn XO, as only 2 participants have cultivated or intended to cultivate this Durian type.

**The Usability of Commercialized Durian Plantation Information System**

The questions in Section C of the post-task questionnaire were used to measure the system's task performance, usefulness, ease of use, and satisfaction based on the participants' experience during the testing. Figures 9, 11, and 13 illustrate the percentage of the responses for the web-based application testing, while Figures 10, 12, and 14 illustrate the response for the mobile-based application.

**Figure 9**

*The Usefulness of CDPIS Web-based Application Responses*

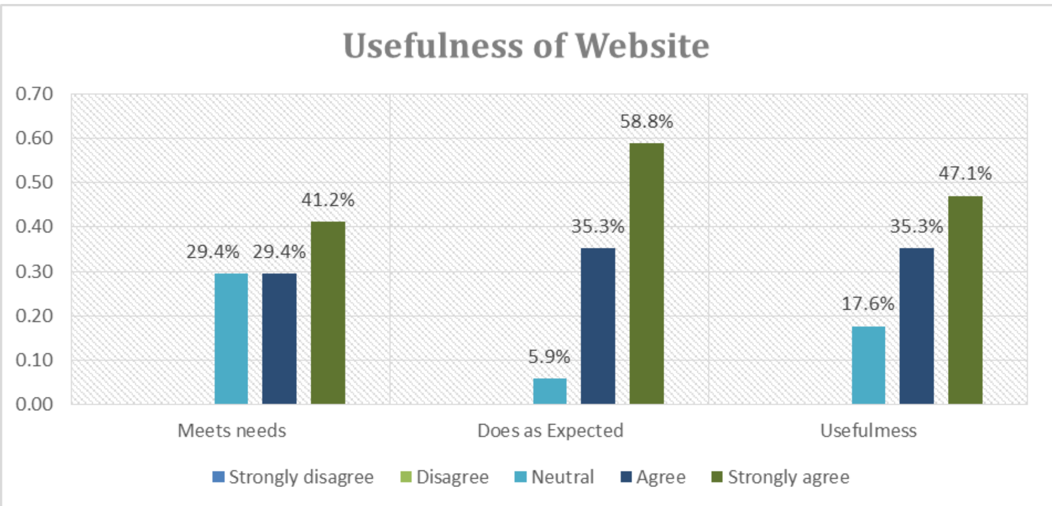


**Figure 10**

*The Usefulness of CDPIS Mobile-based Application Responses*

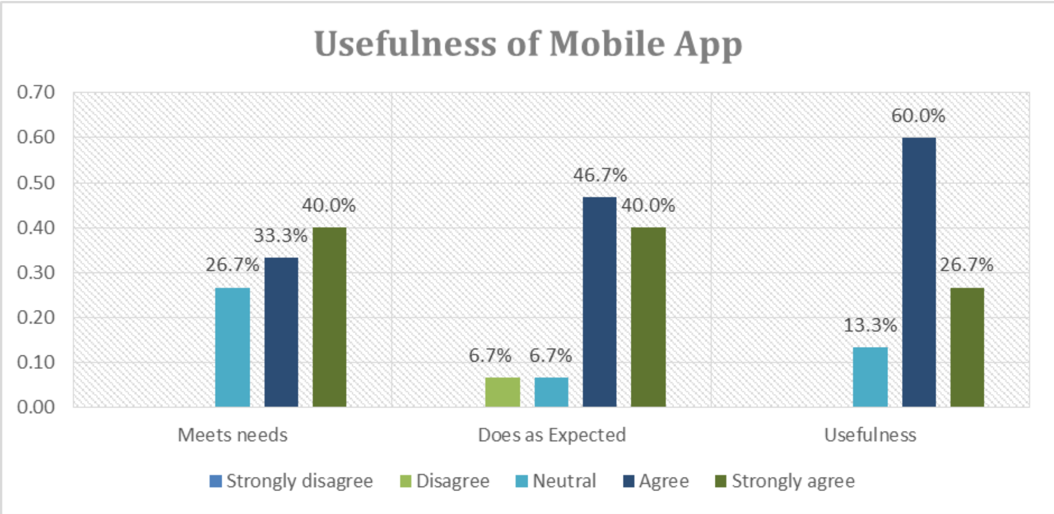



**Figure 11**

*The Ease of Use of CDPIS Web-based Application Responses*

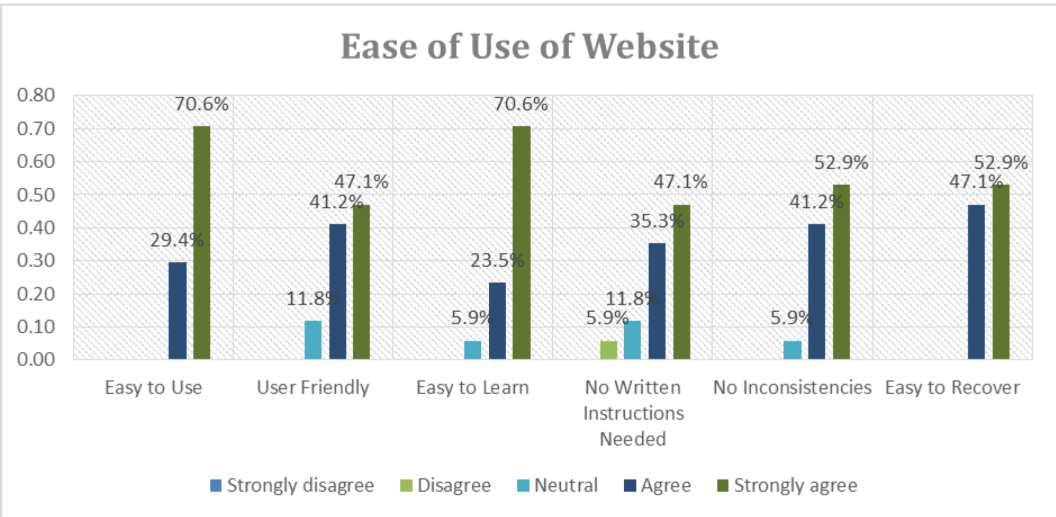


**Figure 12**

*The Ease of Use of CDPIS Mobile-based Application Responses*

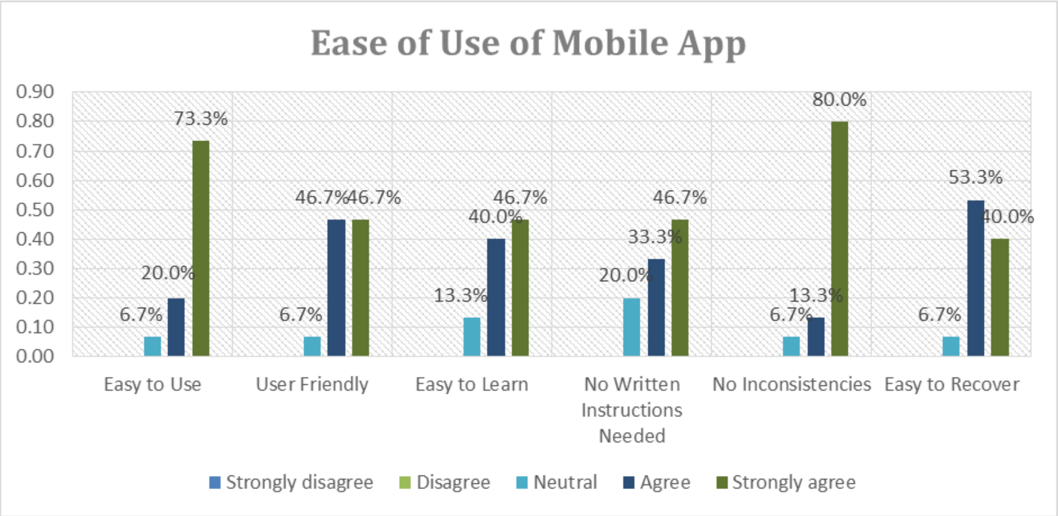



**Figure 13**

*The Satisfaction of CDPIS Web-based Application Responses*

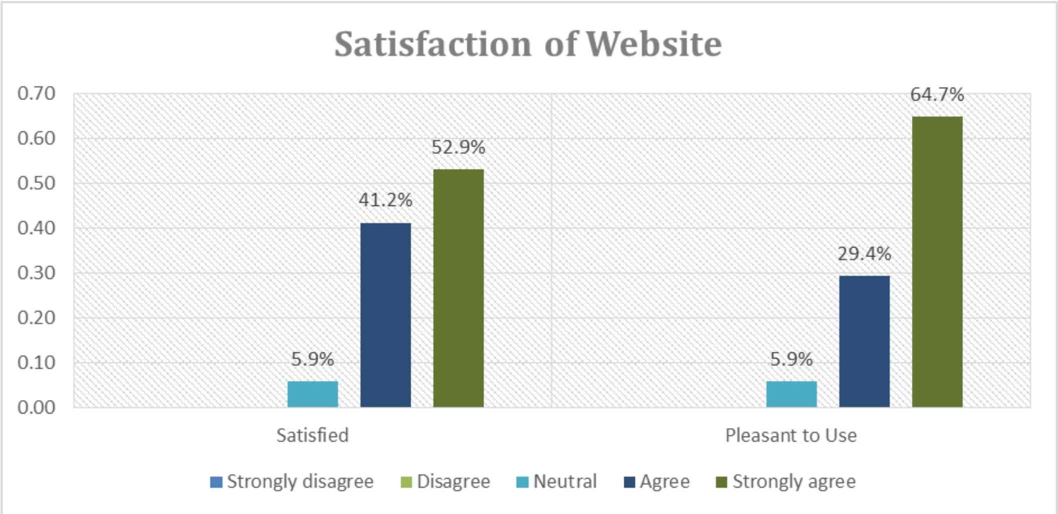
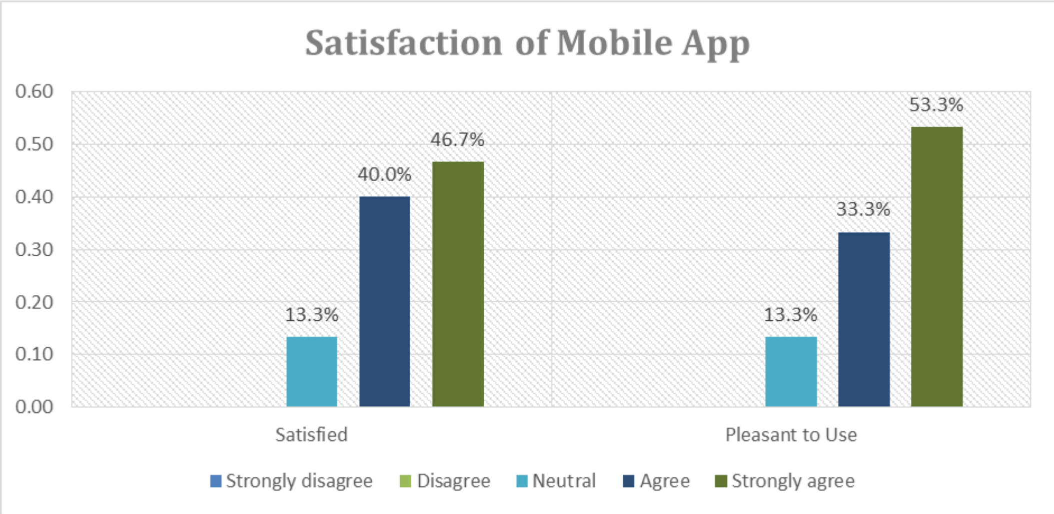


**Figure 14**

*The Satisfaction of CDPIS Mobile-based Application Responses*




Analysis of the participants' responses for each application was conducted, and it was found that most participants rated the three-, four-, or five scores for each question. However, a small % of mobile-based application participants, which is 6.7%, rated a score of two for the question “Does as expected” in the usefulness aspect. It was concluded that the mentioned participants did not conduct the testing for the web-based application as the application is the most significant part of the whole system. The participants may find that the mobile-based application's usefulness did not meet their expectations. Apart from that, a small % of web-based application participants, which is 5.9%, rated the two scores for the “No written instructions needed” in the ease-of-use aspect. It was concluded that the application has many functions, making it difficult for the participants to navigate and use it for the first time.

Overall, the evaluation's response indicated that both applications are helpful and easy to use. In addition, the participants rated the applications’ functions that assist them in managing durian plantations as satisfactory. Nevertheless, it was discovered that some mobile-based applications faced difficulties using them as the layout of some pages did not fit the aspect ratio of their devices. This problem was mainly reported by the participants who used a smaller ratio of the device than the programmed size.

## CONCLUSION AND FUTURE WORKS

Based on the results from the post-task questionnaire and the feedback obtained, some improvement is needed regarding the system's design. The problem is mainly with the layout of the mobile-based application, as it is reported that some pages on the mobile app do not fit the participants’ devices' aspect ratio, the participants who use devices with a smaller size ratio than the size set during the development. Overall, the system is ready to be implemented as the feedback given and the analysis conducted to show a positive result from the participants. With a properly written manual on how to use the system, the system can solve the problem statement of the project and thus contribute to the management of the users or farmers' plantations. Many aspects of the CDPIS can be studied to improve further the provision of the necessary aid in durian plantation management. Currently, the system can only manage and standardise the information about the durian plantation.

In the future, the functionality of the CDPIS can be expanded by adding new functions, such as a tree monitoring system. Through the application of sensors and Artificial Intelligence into the system, this function enables users to virtually monitor their plantation as it can determine the humidity and temperature of the soil, which is essential for the growth of the durian trees. Besides, a function such as an automated scheduling system can help produce a more marketable durian fruit. The function includes step-by-step durian cultivation and guidelines on actions to be taken when the trees are infected with diseases or pests. In conclusion, the commercialisation of durian plantations in Malaysia represents a dynamic and evolving sector within the agriculture industry. Web and mobile applications offer promising avenues for enhancing farm management practices, improving productivity, and meeting the demands of an increasingly discerning consumer base. By leveraging technology and embracing innovation, Malaysian durian growers can position themselves for continued success in the global market while promoting sustainable practices and preserving the rich heritage of durian cultivation.

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## ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

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|---|
| **Channels of distribution in Malaysian organic durian: Case study approach / Safari, S., Razali, N. A., Manickam, T., Mansor, H., & Yusof, R.** |
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# Channels of Distribution in Malaysian Organic Durian: Case Study Approach

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**Abstract**

Durian consumption is centred on the Asian market given the dominating growth of the commodity in the region. Due to the consistent and substantial demand for durians yearly, the use of excessive and non-permitted pesticides in farming practices and artificial chemical ripening agents to promote maturity for doubling up the yield has become a major concern in food safety. Over the long term, extensive and indiscriminate use could negatively affect both environment and human health. The National Agricultural Policies (NAPs) in Malaysia (NAP-1and NAP-2) emphasise organic agriculture, which is considered safe for human consumption and protects the environment. Malaysian Agriculture Research and Development Institute (MARDI) has been entrusted to develop a durian cultivation package using organic farming practices, as one of the high-value tropical fruit commodities. Therefore, this case study analyses the market information and its distribution and identifies issues and challenges mainly in the production and marketing aspects. Data were collected using an in-depth interview involving major industry players (i.e., farmers, wholesalers, and retailers). Currently, only six farms are classified as organic and certified through the myOrganic certificate in 2021 with the majority of organic durian farms being micro-to-small-scale. All data were analysed using content analysis. The majority of the marketing chain of organic durian in Malaysia involves a less-complex chain, so-called Zero-Level or Direct channel (production-to-final consumption), and only a respondent applied One-Level marketing channels (Production to retailing to final consumption). Organic durian is segmented as a premium and niche market as product attributes are claimed to be safer and entitled to offer higher market prices than non-organic. However, the organic durian market remains extremely limited compared to organic vegetables. This study provides preliminary supply chain information to be used as a basis for further research on organic durian targeting the export market.

**Keywords:** Marketing, Malaysian Tropical Supply Chain, High-Value Crop, Organic Fruit, Organic Durian

## Introduction

Durian consumption is centred on the Asian market as the commodity has dominated the region's growth. With its distinctively strong smell and sharp thorns on its shell, durian popularity and demand have skyrocketed. In 2021, durian export by country data depicted Thailand as the largest exporter with 81.3%, followed by Hong Kong, China (which is believed to be next exported into mainland China) (15.4%), Vietnam (2.5%) and Malaysia (0.7%). Despite export, demand for imported durian positively increased with the majority market to China (97%; annual growth 2016-2020; 55%), including Hong Kong. Since durian is targeted to be a high-potential commodity in the future, a study from the marketing perspective is important relative to organic durian, which is very new to the market. There is no doubt that the durian trade has increased significantly among producing countries, and durian is grown conventionally using chemical inputs (fertilizers and pesticides). Thus, given the global concern about pollution and the impacts of the COVID-19 pandemic, organic produce is becoming more relevant to consumers.

Singapore Food Agency (2021) voiced its concern about using excessive and non-permitted pesticides in farming for better yield and artificial chemical ripening agents to promote maturity in durian fruits exported to Singapore. In 2019, Thailand was also issued a warning letter from Japan due to the high pesticide residue in durian shipments (Karnjana, 2019) [16]. Besides, in another case in the same year, a thorough analysis by Thailand Pesticide Network (Thai-Pan) also found that 41% of 15 popular vegetables and nine fruits contained toxic chemical residue above the safe level. As Thailand is a big player in the global durian industry, Malaysian farmers may also equally overuse chemicals if strict control and approaches are lacking for the substitute organic products, which are safer for human consumption.

Chemical fertilizers, pesticides and fungicides are widely used in agriculture to improve crop yields. The substances are synthetic and they may cause environmental pollution and human health problems when overused (Duran-Lara *et al*., 2020) [9]. Several studies found that the use of chemicals did increase crop productivity, however extensive and indiscriminate use over the long term led to adverse impacts on environmental and human health (Chang *et al*., 2021 [8]; Leong, *et al*., 2017; Kamaruzaman *et al*., 2020 [15]). In a worse situation, humans can be affected through contact with the skin, ingestion, or inhalation, thereby leading to poor health statuses such as nutritional deficiencies and healthy/damaged skin (Nicolopoulou *et al*., 2016) [28]. Therefore, MARDI has been responsible for the development of a durian organic farming technology package, covering the entire value chain aspects from cultivation management (agronomy, fertilizer, pest and disease), post-harvest handling, economics and marketing. Nevertheless, this study focuses on marketing aspects to obtain market information along the supply chain and distribution. This study also attempts to identify issues and challenges, mainly in the production and marketing aspects.

## Literature Review

### a) Organics supply chains and distribution channels

The agriculture supply chain has been described widely by scholars as a supply chain where an agricultural product goes through different stages of production and distribution before reaching the final consumers. (Safari *et. al*., 2021; Aramyan, 2007; Bijman, 2002) [32, 4, 6]. The interconnected business process is involved directly or indirectly in all phases of satisfying the consumer's needs, consisting of producers, suppliers, distributors, transporter, warehouse, various types of intermediaries and customers (Tundys & Rzeczycki, 2015) [38]. In a broader sense, the supply chain includes new product development, marketing, operations, distribution, finance, and customer service (Food and Agriculture Organisation [FAO], 2007) [10]. While the distribution channel is the process flow from producers to end users through a series of marketing entities, and it depends on the number involved.

The supply chain of organic products is often considered an alternative supply chain, which is shorter, more locally oriented, and more tightly connected to producers and consumers than conventional food supply chains (Kottila *et al*., 2005) [19]. Tundys & Rzeczycki (2015) [38] demonstrated a clear difference in the construction supply chain for conventional and organic products, whereby the latter relies on the nature of the products, biodiversity, ecological process, and natural cycles. The organic supply chain assessment comprises three pillars of sustainability dimensions – environmental, economic and social (Zira *et. al*., 2021) [44]. In conjunction with the essence of safety and a sustainable environment, the organic supply chain seems most related to the green supply chain. It is also identified as a mitigation strategy to reduce global warming (Muller & Schader, 2009) and considering all elements with environmental risks and impacts (Zhu & Sarkis, 2004) [45].

Studies across different products and plants identified organic production had benefited stakeholders in the supply chain compared to conventional products. Organic production offers lower expenses for farm inputs, healthier soils, diverse source of income and higher prices (Alanzi, 2018) [2], more resource-efficient (Zira *et al*., 2021) [44], reduce the environmental effect (Longo *et. al*., 2017) [22], and producing lower carbon dioxide emissions (Brodt *et. al*, 2013) [7]. Despite having good impacts, organic production also faces challenges of the time-intensive process, higher cost, insufficient suitable land availability, and vulnerability to pest attacks. (Tundys and Rzeczycki, 2015) [38] and lower production (Longo *et al*., 2017) [22]. The products must thus reach end consumers as a necessity to maintain their freshness and quality in high expectations.

### b) Organic purchase consumption

Organic groceries consumption has been on the rise over recent years. Many countries have actively used and promoted organic technology to produce food. However, the overview landscape of organic consumption differs from one country to another. The growth of the organic food market has caused a significant change in food consumption patterns. This event began in 1989 in European countries, followed by North America and Japan (Nasir & Karakaya, 2014; Paul & Rana, 2012) [5, 29]. Nevertheless, the high-consumption countries are still leading in European countries, such as Switzerland, Denmark, Sweden, the United Kingdom, and Germany, as well as the United States of America and the Asian region, Japan, China and Australia (World Atlas, 2023) [41].

Globally, organic products have reached sales of US $ 90 billion (2016) and are expected to reach US $ 320.5 billion by 2025 (Jaffery & Annuar, 2023; Mustapha, 2018) [26]. A few attributes have been highlighted to influence the willingness to consume organic products such as consumers with a high level of education (Nasir & Karakaya, 2014; Roitner-Schobesberger *et al*., 2008; Zepeda & Li, 2007; Magnusson *et al*, 2001) [5, 30, 43, 24], female consumers (Urena *et al*, 2008, Krystallis *et al*., 2006; Lea and Worsley, 2005) [39, 18, 20], and higher-income levels (Govindasamy & Italia, 1999; Magnusson *et al*., 2001; Magnusson *et al*., 2003) [11, 24, 25]. Furthermore, organics products tend to be young buyers willing to pay higher premium prices (Ishak *et al*, 2021; Nasir & Karakaya, 2014; Jolly, 1991) [12, 5, 14].

While in Malaysia, organic sales value demand is increasing despite a limited local production supply. However, organic products are consistently imported, particularly from the US, Japan, Australia, New Zealand and China (Somasundram *et al*, 2016) [36]. As a result, the value of the organic food market increased by more than 100 % from RM 1 billion in 2001 to RM 12 billion in 2016 (Jaffery & Annuar, 2022 [13]; Willer & Lernoud, 2018), and it is expected to increase annually by 12.4% until 2030. Although organic food is more expensive in Malaysia, Abdullah *et al*. (2022) [1] found that 56% of consumers who earn more than RM 2,501 per month are willing to change their food choice preference to a healthier lifestyle and may buy some effort to buy organic products.

### c) Organic durian

The global durian fruit market is expected to grow by 7.1% (US$ 36.4 billion) in 2028, with Asia Pacific representing 92.3% of the worldwide durian market, predominantly driven by Chinese demand (Zanariyah, 2022) [42]. Undeniably, the organic market for fruits and vegetables is estimated to rise with a CAGR of 11.7% or US$ 55.86 billion by 2027 (Allied Market Research, 2020) [3]. Furthermore, the organic consumer population positively increases as they are concerned with antioxidants and overall health as evident in several scientific studies. The increase in lifestyle and healthy diet practices, especially for the younger generation living in cities, depicts that organic production is expected to increase by 12.4% annually (Song and Kanesh, 2020) [37]. Socioeconomic factors of consumers with a fixed income and purchasing power will influence the acceptance and purchase of organic consistently (Liuqing *et. al*, 2017) [21].

Looking at China's primary market, organic durian is not impossible to export penetration. In addition, Malaysia has gained several market accesses for durian to China in frozen forms pulp, paste and whole fruit. Notwithstanding, an effective marketing strategy is essential. Millennials are primarily relying on the Internet for information, while current, catchy, and exciting store website and social media platform is required to market the products. The marketing strategies for natural and organic are constantly changing, but the most important element is fitted to consumer-base. In durian organic, it may not be much different from conventional marketing, but testimonials of taste and health effects can be used as the main reason. Malaysia has the advantage of its famous Musang King or Mao Shan Wang clone. Apart from prioritising the export strategy, the proposal of durian tourism is also suggested for Malaysian farms that have received organic certification or My Organic. This strategy will lead to a long-term investment portfolio, capturing long-term economic returns with the offered eco-tourism package.

## Research Method

This study applied a case study approach using in-depth interviews involving major industry players in organic durian (i.e., farmers, wholesalers and retailers). The data were collected from 1st August 2021 to 25 October 2021 and the participants were obtained from the latest list (2021) of my Organic certificate farms from Malaysia's Department of Agriculture. About 89 organic farmers for vegetables and fruits have a planting area of more than 531.46 hectares. Of the 89 organic farmers, only 20.2% or 18 farms are involved fruit production. Meanwhile, for organic durian farms, only six farms are accredited and were selected as primary respondents in this study. The purposive sampling technique was used for other respondent groups (wholesalers and retailers), and direct information from the farmers. Nevertheless, only one respondent was involved because most farmers sell their fruits directly to consumers.

Case study approaches are widely used in qualitative research, quantifying, and analysing the presence, meanings and relationships of particular words, themes or concepts. The data on the supply chain, issues, and challenges along the supply chain, including production and marketing of durian organic, were then analysed using Content Analysis and ATLAS.ti 7 software.

## Result and Discussion

### Durian organic cultivation in Malaysia

In Malaysia, the local organic food industry is still small, as more than 60% of organic food products are imported. Most of the organic products are sold domestically, while some are exported to Singapore (Somasundram *et. al.*, 2016) [36]. The Ministry of Agriculture and Food Industry has always encouraged farmers to engage in organic farming in Malaysia. Organic farming focuses more on vegetable cultivation (93%), and only 3% is involved in organic fruit cultivation. Through the recycling concept, organic agriculture is planted with mixed crops between vegetables and fruits. The idea of mixed farming is not only for the biological management of disease and pests but also to increase soil fertility and maximise production. The area of organic as a whole is led by Sabah (42.53%), followed by Perak (18.62%), Johor (14.73%), Kedah (8.04%), and Pahang (6.17%) while other states contributed less than 5%.

The latest record by the Department of Agriculture revealed that only 89 farmers with an area of 531.46 hectares continued and validated until 2021. Out of 89 farms, only 18 (20.2%, with an area of 127.9 hectares) produce fruits, including durian, jackfruit, rambutan, banana, papaya and coconut. These crops are either the main or border crop, depending on the needs of the farmers. For organic durian, 15.4% or 19.76 hectares are planted, involving six (6) farms in Malaysia (Table 1). Organic Durians are currently cultivated in Johor (4.5 hectares), Sabah (3.9 hectares), Perak (3.1 hectares), Penang (2.9 hectares), Kedah (2.7 hectares) and Negeri Sembilan (2.6 hectares).

**Table 1:** Organic Durian Farms certified myOrganic by states and planted area (2021)

| Crop | State | Planted Area (Hectares) |
|---|---|---|
| Durian | Johor | 4.50 |
| | Sabah | 3.90 |
| | Perak | 3.15 |
| | Pulau Pinang | 2.93 |
| | Kedah | 2.71 |
| | Negeri Sembilan | 2.57 |
| | Total | 19.76 |

**Source:** Department of Agriculture Malaysia, 2021

Table 2 presents organic durian information based on the farmer's interviews. The planting area of organic durian is operated on a small scale and is not commercial. These involved farms operated by family and maintained as family heritage (more than 20-30 years of production). Some farms are trying to apply agrotourism elements. The common durian varieties include Musang King, D24, Duri Hitam and IOI. Organic plant growth is slow but suitable for plants without using chemicals that can damage the environment and health. Thus, the yield of organic durian trees is less than non-organic. For example, non-organic durian plants normally produce 100-150 fruits (1.5-2.0 Kg/fruit or 225 Kg/plant/season), whereas lower quantity ranging from 70-80 fruits are produced by organic durian plants (1.5 – 1.8 Kg/fruit or 144 Kg/plant/season). The efficiency of durian farms in production has been studied by Krasachat (2014) [17] in Thailand farms. The authors identified three factors relating to inefficiency: technical management in farming practices- lack of education and variability of fertilizer types, the application of organic farm systems and soil improvement practices, and the inefficiency of durian size.

From a pricing aspect, organic durian price is higher with an increment to 30-35% or RM 10-20/Kg. For example, the retail price of organic Musang King is RM 50-RM 60/Kg compared to non-organic at RM 35-40/Kg. Malaysian organic price of any products is well known to be more expensive than other countries- by as much as 100% to

300%, compared to only a 25% to 30% price gap in the US and European Union (EU) (Somasundram *et al*., 2016) [36]. However, in the case of durian, it is rarely found and at low perception among Malaysian. Therefore, the wholesale price of organic and non-organic durians becomes indistinguishable; hence both durians are offered at the same wholesale price. With no difference between organic or non-organic durians at the wholesale level, organic durian marketing remains unclear and segmented as a premium market with the upper market price unlike organic vegetables. Organic durian is currently unavailable at hypermarkets, supermarkets or roadside stalls - consumers willing to buy need to reserve through online or phone pre-order.

Eating durian might cause stomach discomfort, gas, diarrhoea, vomiting or allergic reactions in some people (RxList, 2021) [31]. From the feedback of experienced users of durian organic, consumers make repeat purchases due to its effect, which agrees that organic durian had no side effects such as stomach upset or high body temperature. However, there is insufficient evidence to confirm this claim except refereeing to the healthcare professional. Additionally, some consumers agreed that organic durian has a balance between bitterness and sweetness (less bitter and sweet). This mild taste may be good for people who dislike the strong flavour of durian. On the other hand, the responses were from a few persons and are not representative of all consumers. A comprehensive consumer study would yield different results.

**Table 2:** Current Status of organic durian farms in Malaysia

| Parameter | Description | Status |
|---|---|---|
| Planted area | 2-5 hectare/farmer | Small-scale farms: family/hobby or agrotourism farm |
| Variety and age of a tree | Holo, Anghe, Kampung, IOI, D24, Musang King (MK), Black Thorn | Old plants and maintained for ecological balance (20-30 years). Latest clone: MK and Black Thorn (5-6 years old) |
| Production | MK Organic: 70-80 fruit/tree/cycle<br>MK Non-organic: 130-150 fruit/tree/cycle | Organic yield is lower |
| Price | **Ex-farm**<br>MK Organic: RM 50-RM 60/ Kg<br>MK Non-organic: RM 35-40 /Kg<br>**Retail**<br>MK Organic: RM 60-70/ Kg<br>MK Non-organic: RM 40-50 /Kg | - A gap in retail price between organic and non-organic: RM 10-20 / Kg (direct-selling)<br>- There is no different price if selling at the commercial wholesale place. Organic fruit will sell at the same price as non-organic. |
| Market | Unavailable at retail markets-hypermarket and supermarket | Pre-order basis either online or by phone |
| Consumer acceptance | • Organic durian has a balanced taste between bitterness and sweetness.<br>• Stomach and body temperature tolerable | |

**Source:** Field study (2022)

### Durian Organic Supply Chain in Malaysia

The complexity of the supply chain involves few elements 1) various companies, 2) has a high number and variety of reactions, processes and interactions between and within companies, 3) processes and interactions are dynamic, 4) many levels of the system involved in each process and 5) the large amount of information needed to control the system (Serdarasan and Tanyas, 2012) [33]. Sivadasan *et al*. (1999) [34]; Sivadasan *et al*. 2002a [35] in their study agreed that 69% of complex structure in supply chain causes problems such as lower performance, higher costs, and lower profits. The organic durian supply chain is less complex than non-organic durians, which at the moment involves two marketing channels. 1) Zero-level channel or Direct channel (from the farm directly to final consumer); and 2) One-level marketing channel (from farm to retailer to final consumer) (Fig 1 and 2). In the Zero-level channel, booking is made using a pre-order basis through online platforms such as social media (example: Facebook and Instagram), private webs and group bookings (using WhatsApp). The delivery will be made directly by farmers to ensure quality and freshness. From the aspect of user groups, two main groups are either repeat users (regular customers) or new ones interested in organic produce.

While in the One-level channel, organic durian is sold from the farm to retailers and final consumers through physical stores. The pre-order from customers is needed to obtain orders through retailers. The two main groups of consumers are identified - regular customers and new customers who are interested in trying organic durians. As consequences, complexity reduction helps organizations focus on business benefits, consumer value and eliminate unnecessary activities, expenses and potentially even products. This is supported by Serdarasan and Tanyas (2012) [33] whereby majority of the companies indicated that they take action to manage or reduce the complexity for business expansion.

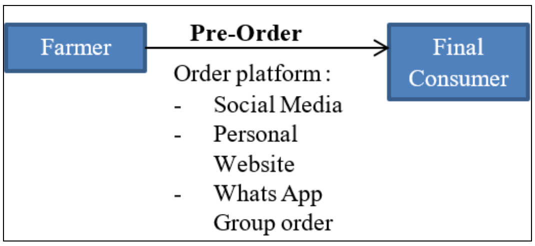


**Fig 1:** Zero-level channel for Organic Durian

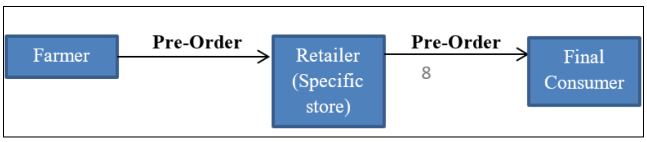


**Fig 2:** One-level channel for Organic Durian

### Issue and Challenges

Since organic durian in Malaysian can be said to be very new in the market, there are several issues and challenges to be faced as follows:

**Low production and small-scale farming**

A study by Krasachat (2014) [17] on organic durian farms in Thailand found that the efficiency of organic durian farms is highly dependent on technical expertise and optimal farming scale. Those factors could reduce it by 48% of farm production. While in Malaysia, organic durian farms are also in small scale size and unable to produce fruits commercially. Therefore, it makes production limited and unable to grow economically. Moreover, organic farm cultivation requires a long period of planning. Hence, it is an undoubtful plan as a long-term investment and is expected as good economic return in future. The cultivation of durian requires a long period and commercial scale.

**Limited market place**

Less complexity of the organic durian supply chain resulted in a niche market. However, in the sense of creating a different market, it also makes a limited market. This is because the supply chain does not involve many industry players (wholesalers, distributors and retailers); the marketing is straightly at zero and one-level distribution channel. To make this industry attractive, thus the involvement of industry players needs to be more active so that consumers obtain more information and promotions.

**Pest and disease**

Apart from that, the issue of disease and pest attacks is the most challenging issue since no chemical use is permitted except by using biological or organic control. The most acute disease is stem cancer caused by the insect (Phytophthora palmivora). The disease will damage the branches and roots. Therefore, continuous research studies should be made to ensure that there is applicable organic pest control to overcome this issue from time to time.

***Differences in taste and nutrients***

Scientifically, there is no significant difference between organic and non-organic products regarding taste. However, this is backed by many experienced consumers which consumed for long time. The acceptance of taste attributes is complex among consumers. The justification of non-organic side effects cannot be proven and tends to be influenced by other factors. However, it is well known that organic is safer and healthier. Thus, apart from validating myOrganic, effective marketing strategies and consumers' awareness are important to enhance in this industry.

**Conclusion**

Market information and supply chain of durian organic under the package of Tropical fruits cultivation carried out by MARDI has been carried out under technical and economic research activity. Durian has been chosen due to its high demand and potential in the domestic and export markets. The study found that the organic durian industry in Malaysia is very new, produced by small-scale farms under the myOrganic scheme. Only 20.2% (or 18 farms) are involved in organic fruit cultivation; out of these, only six (6) farms grow durian. Technically, organic production is lower than non-organic but safer for the environment and consumer health. To balance the production costs and farmers' income, the price of organic should be higher. Yet, Malaysian organic durian, specifically Musang King clone only a bit higher at RM 10-15 than the non-organic. This portrait of organic durian marketing remains unclear, unlike organic vegetables, segmented as a premium market with the upper market price. Consumers' feedback on taste and health benefits makes it more acceptable to encourage them to repeat purchases for the next season.

In terms of supply chain structure, organic durian only involves two channels: a Zero-level channel or Direct Channel (from farm to consumer); and a One-level channel (from farm to retailer to consumer). The potential of organic durian is a promising future for consumers' demand in creating a high-value product for domestic and export markets, especially to Asian and preferably to China markets. Understanding the supply chain and integrating the packaging technology is expected to overcome the issue and challenges, mainly production and pest and disease attacks. Thus, it is expected to increase farm production efficiency with commercial farm planning in the future.

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## ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

**Durian disease classification using vision transformer for cutting-edge disease control / Mat Daud, M., Abualqumssan, A., Nor Rashid, A., Hanif Md Saad, M., Mimi Diyana Wan Zaki, W., Safie Mohd Satar, N., & Malaysia, K.**

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# Durian Disease Classification using Vision Transformer for Cutting-Edge Disease Control

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***Abstract*—The durian fruit holds a prominent position as a beloved fruit not only in ASEAN countries but also in European nations. Its significant potential for contributing to economic growth in the agricultural sector is undeniable. However, the prevalence of durian leaf diseases in various ASEAN countries, including Malaysia, Indonesia, the Philippines, and Thailand, presents formidable challenges. Traditionally, the identification of these leaf diseases has relied on manual visual inspection, a laborious and time-consuming process. In response to this challenge, an innovative approach is presented for the classification and recognition of durian leaf diseases, delves into cutting-edge disease control strategies using vision transformer. The diseases include the classes of leaf spot, blight sport, algal leaf spot and healthy class. Our methodology incorporates the utilization of well-established deep learning models, specifically vision transformer model, with meticulous fine-tuning of hyperparameters such as epochs, optimizers, and maximum learning rates. Notably, our research demonstrates an outstanding achievement: vision transformer attains an impressive accuracy rate of 94.12% through the hyperparameter of the Adam optimizer with a maximum learning rate of 0.001. This work not only provides a robust solution for durian disease control but also showcases the potential of advanced deep learning techniques in agricultural practices. Our work contributes to the broader field of precision agriculture and underscores the critical role of technology in securing the future of durian farming**.

***Keywords*—Vision transformer; durian disease; deep learning; disease control***

## I. Introduction

The durian fruit's popularity has surged in recent years, primarily driven by increased consumer demand, notably from China [1]. Moreover, it has found a substantial export market in Southeast Asian countries, Hong Kong, Australia, and Western nations such as United States. This upswing in the durian market can be attributed in part to the cultivation of premium varieties renowned for their exceptional flavor and consistent pulp quality. Notably, varieties like D24, D197 (Musang King), and D200 (Black Thorn) from Malaysia, as well as traditional Thai cultivars such as Monthong, Chanee, and Kanyau, have garnered significant attention and are in high demand, painting a promising future for the fruit.

Thailand maintains its position as the primary producer and exporter of durians, with other countries like Malaysia, Indonesia, Vietnam, Cambodia, and the Philippines also cultivating this unique fruit [2]. The global durian fruit trade is characterized by a dominant duopoly, with China taking the lead in imports, while Thailand leads in exports. In 2021, Thailand's durian exports reached an impressive value of 3,920 million USD, making up a significant 82.7% of the total global trade. In contrast, Malaysia's contribution ranked fourth, comprising about 0.67% of the trade volume, with a total value of 31.8 million USD. Simultaneously, China asserted its dominance in global durian imports in the same year, with an astonishing 4,240 million USD, constituting a substantial 89.4% of the overall trade. Additionally, notable participants in the market, following China's lead, included Hong Kong, Vietnam, Chinese Taipei, and Singapore, accounting for 89.4%, 5.37%, 2.43%, 0.72%, and 0.36% of the trade, respectively [3]. Fig. 1 and Fig. 2 depict the top importer and exporter of durians, respectively.

The adoption of modern agricultural practices, including drip irrigation, enhanced fertilizer formulations and application techniques, and improved cultural and postharvest methods, has significantly contributed to the increased productivity of durian farms [4]. Nevertheless, growers remain vigilant due to the persistent threat of diseases in the industry. Durian trees are susceptible to a range of diseases, such as spot cancer, base rot, base disease, seedling disease, dead tip disease, fungal infections, leaf spots, leaf blight, and fruit rot. Among these, stem rot disease, primarily caused by P. Palmivora, stands out as a particularly perilous ailment. This disease severely impairs the tree's nutrient transport system within the stem.

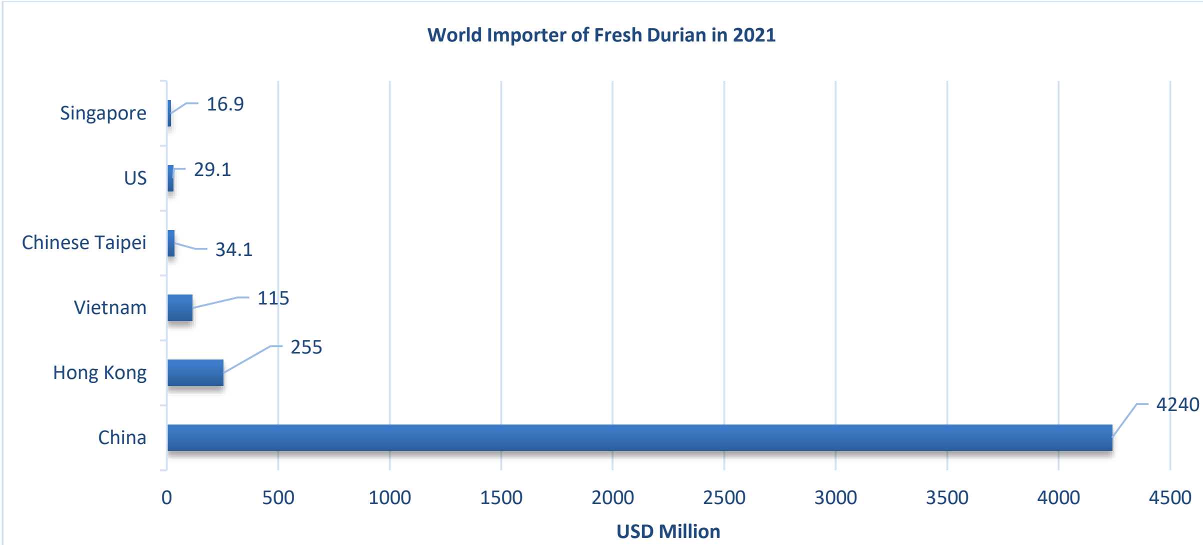



Fig. 1. World importer of fresh durian in 2021.

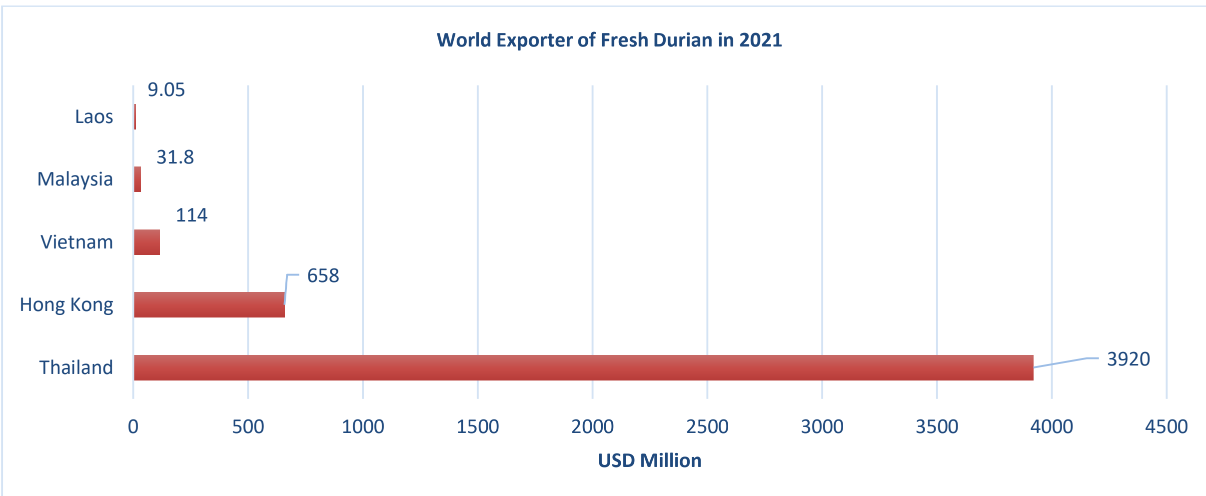



Fig. 2. World exporter of fresh durian in 2021.

Durian trees are susceptible to various diseases, such as algal diseases caused by cephaleuros virescens, characterized by the appearance of orange, rust-colored velutinous spots on the upper surfaces of leaves, twigs, and branches. Another concern is anthracnose, resulting from Colletotrichum gloeosporioides, which manifests as dark lesions on fruit and premature fruit drop. Moreover, Phomopsis leaf spot, induced by diplodia heobromae and C. Gloeosporioides, presents as necrotic, brown circular spots, approximately 1 mm in diameter, featuring dark margins and yellow halos on leaves. The sinister pink disease, attributed to erythricium salmonicolor, is marked by pinkish-white mycelial threads that envelop branches and shoots.

Additionally, postharvest fruit rots caused by Phyllosticta sp. and curvularia eragrostidis result in irregular necrotic patches in varying shades of brown. Rhizoctonia leaf blight, originating from Rhizoctonia solani, leads to water-soaked spots on leaves that coalesce to form larger, irregular, water-soaked patches, eventually drying into light brown necrotic lesions. Lastly, sooty mold and black mildew, caused by Black Mildew fungi, form a hard, lumpy crust on twigs and leaf petioles, and on fruit, they create a spongy crust on the surface. However, a particularly dangerous ailment is stem rot disease, resulting from P. Palmivora, which damages the tree's nutrient transport system in the stem.

A significant aspect of the challenges that arise in agricultural areas can be addressed by computer vision [5]. Traditionally, the detection of plant diseases heavily relied on manual inspections conducted by farmers or laborers, typically with the naked eye (Singh et al., 2017 & Petrellis, 2015). Table I presented traditional disease monitoring procedure for disease management with limitations, such as visual inspection, scouting, weather-based disease forecasting and etcetera. This method can be both laborious and repetitive, especially when dealing with tall Durian trees. However, the advent of artificial intelligence (AI) has revolutionized disease detection in various tree types, including Durian.

TABLE I. TRADITIONAL DISEASE MONITORING PROCEDURE FOR DISEASE MANAGEMENT

| Disease Monitoring Procedure | Description | Limitations |
|---|---|---|
| Visual Inspection | Regular visual assessment of crops for symptoms of disease. | - Subject to human error and bias.<br>- May miss early or subtle symptoms.<br>- Time-consuming for large fields. |
| Scouting by Field Observers | Trained personnel systematically inspecting fields for signs of disease. | - Labor-intensive and costly.<br>- Limited coverage and potential variations in observer expertise. |
| Weather-Based Disease Forecasting | Using weather data to predict disease outbreaks based on favourable conditions for pathogen development. | - Accuracy depends on the quality and availability of weather data.<br>- Doesn't account for all factors affecting disease. |
| Sampling and Lab Testing | Collecting plant or soil samples for laboratory analysis to identify and confirm disease presence. | - Requires specialized equipment and expertise.<br>- Results may not be available quickly enough for immediate action. |
| Disease Severity Rating Scales | Assigning numerical scores to rate disease severity, helping quantify disease progression. | - Subjective and dependent on the assessor's judgment.<br>- Can be time-consuming, especially for large areas. |
| Trap Crops and Indicator Plants | Planting susceptible species near valuable crops to serve as early warning indicators of disease presence. | - May not always provide timely detection.<br>- May require additional land and resources. |
| Neighbouring Farm Communication | Exchange of information among neighbouring farms about disease outbreaks or observations. | - Relies on the willingness of nearby farmers to share information.<br>- Limited to local awareness. |

In agriculture, diseases are a common occurrence across different fruit varieties. When it comes to monitoring fruit diseases, researchers and practitioners often grapple with the challenge of finding a balance between the accuracy of deep learning models and the computational resources necessary for efficient monitoring. To tackle this challenge and enhance both precision and efficiency, various deep learning architectures and techniques have been explored.

Considering there are more pixels in an image than there are words in NLP applications, the use of the attention mechanism in vision applications has been considerably more constrained due to the high computing cost [6]. This means that typical attention models cannot be applied to visuals.

## II. RELATED WORKS

Transformer network applications in computer vision were recently reviewed in [7] and vision transformer (ViT) is a major step towards adopting transformer-attention models for computer vision tasks [8]. Compared to CNN-based models that consider picture pixels, using image patches as information units for training is groundbreaking. ViT uses self-attention modules to analyze the relationship between image patches included in a shared region. ViT was demonstrated to outperform CNNs in image classification accuracy given vast quantities of training data and processing resources [8].

State-of-the-art deep learning models can achieve impressive results and are well-suited for drone applications, but they come with a hefty need for computational resources during the training process. In contrast, Vision Transformer (ViT) offers a promising alternative [26]. ViT avoids using Convolutional Neural Networks (CNNs) and performs at a level similar to top-tier CNN models. ViT, a relative of the Transformer model, utilizes a smart technique called self-attention to establish a global reference for each pixel in an image during training. It breaks the image into smaller patches, assigns a position to each patch, and learns from them. In the final layers of the ViT model, the similarity between these patch representations significantly improves. Interestingly, adding more layers to the model doesn't enhance its performance [27]. Nevertheless, ViT does pose a challenge when dealing with high-resolution images due to its four-fold increase in memory requirements, making them more difficult to handle.

Numerous research studies have focused on mitigating the shortcomings of Transformer-based models which tend to fall into two main categories: hybrid models and pure Transformer enhancements. Table II illustrates both hybrid and pure transformer enhancements. Furthermore, by employing the Vision Transformer, researchers achieved a minimum of 1% higher accuracy in classifying cassava leaf diseases than well-known CNN models. They also effectively implemented this model on the Raspberry Pi 4, an edge device, showcasing the substantial potential for its application in the realm of smart agriculture [17]. To the best of our knowledge, only [19] has performed durian disease detection using deep learning approach. The durian disease classification was performed using Resnet-9 and VGG-19 where Resnet-9 was outperformed VGG-19 with accuracy of 100% and 99.11%, respectively. Recent advancements in plant disease detection have seen substantial enhancements using CNN-based models. Nevertheless, these models have limitations such as translation invariance, locality sensitivity, and a lack of comprehensive global image understanding.

TABLE II. HYBRID AND ORIGINAL VISION TRANSFORMER METHOD

| Paper | ViT Techniques | Results | Limitations |
|---|---|---|---|
| [9] | Ghost-Enlightened Transformer (GeT) | 98.14% | -Relies on large labelled data |
| [10] | PlantXViT | 98.33% | -unable to maintain a lower count of Gega floating operation points. |
| [11] | Convolution vision Trasnformer (CvT) | 87.7% | -higher accuracy will increase training and inference times and memory used. |
| [12] | Convolution-enhanced image Transformer (CeiT) | 99.1% | |
| [13] | LocalVit | 94.2% | |
| [14] | Swin Transformer | 81.3% | -larger resolution needed to increase the accuracy |
| [15] | k-NN attention (KvT) | 73.0% | -need to be paired up as the boosting agent for the vision transformer. |
| [16] | RegionViT | 83.8% | Not stated |

To overcome these challenges, this study introduces a novel approach that employs a Vision Transformer-based model for more effective plant disease classification. ViT results will be compared with ResNet-9 and VGG-19 [19] in results and discussion part. This approach combines computer vision and deep learning technologies to revolutionize agricultural production management, utilizing large-scale datasets to address current agricultural issues and improve the overall performance of agricultural automation systems, especially in Durian disease classification, thereby propelling agricultural automation equipment and systems toward a more intelligent future [18].

The paper is organized as follows: Section I presents a brief introduction to the type of durian diseases and current method used to detect the diseases. Section II delves into related works. Section III covers the methodology of ViT and how the experiment conducted. Then, Section IV presents the results and discussion of durian disease detected using ViT and Section V gives the conclusion and future work of the research.

## III. METHODOLOGY

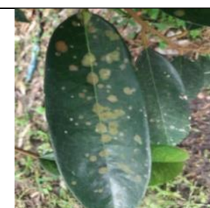
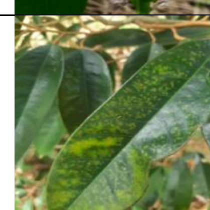
### A. Dataset Preparation

In this experimental study, our primary objective was to develop and train a robust deep learning model specifically Vision Transformer capable of accurately classifying diseases that affect durian plants. Our dataset included a total of 1,344 images, which were distributed across four distinct classes. The diseases aimed to precisely classify were ‘durian_leaf_spot’, ‘durian_leaf_blight’, ‘durian_algal_leaf_spot’, and ‘durian_ healthy’, as presented in Table III [20].

To effectively manage the dataset, the original dataset is divided into two sets: training and validation. This was achieved by applying a validation split ratio of 20%, meaning that 80% of the data was designated for training purposes, while the remaining 20% was reserved for validation.

Additionally, to enhance the model's generalization and diversify the training data, data augmentation techniques was implemented. The 'ImageDataGenerator' class is provided by Keras, which facilitated various augmentations of the training data. These augmentations included random rotations of up to 40 degrees, horizontal and vertical shifts of up to 20% of the image dimensions, shearing transformations up to 20%, random zoom adjustments that could expand or contract by up to 20%, and horizontal flipping to create mirror images. When generating new pixels, the 'nearest' method was utilized. This process resulted in the creation of four augmented versions of each original image, significantly expanding the size of the training dataset.

TABLE III. DURIAN DISEASE DATASET EXTRACTED FROM [20]

| Dataset | Description | Total number of images | Sample of images |
|---|---|---|---|
| 'durian___leaf_spot' | Images of durian leaves with leaf spot disease. | 336 |  |
| 'durian___leaf_blight' | Images of durian leaves with leaf blight disease | 336 |  |
| 'durian___algal_leaf_spot' | Images of durian leaves with algal leaf spot disease | 336 |  |
| 'durian___healthy' | Images of healthy durian leaves | 336 |  |

### B. Durian Disease Classification using Vision Transformer (ViT)

The ViT model consists of patch creation, patch encoding, multiple Transformer layers, and a final classification head, as shown in Fig. 3.

- Patch creation: Instead of processing entire images at once, the ViT model divides each image into smaller non-overlapping patches or tiles. This patch-based approach allows the model to process large images efficiently. Each patch is treated as a separate input and processed independently by the model.
- Patch Encoding: After splitting the image into patches, each patch is encoded into a numerical representation that the model can work with. This process typically involves linearly projecting the patch's pixel values into a lower-dimensional vector, allowing the model to learn spatial relationships and features within each patch.
- Multiple Transformer Layers: The heart of the ViT model consists of multiple Transformer layers. These layers process the encoded patches and capture contextual information, enabling the model to understand how different patches relate to one another. The self-attention mechanism in the Transformer architecture is particularly crucial for this step, as it helps the model weigh the importance of different patches when making predictions.
- Final Classification Head: At the end of the ViT model, there is a classification head. This part of the model takes the information from the previous Transformer layers and makes predictions based on the features learned during the earlier stages of processing. For tasks like image classification, this is where the model assigns labels or probabilities to different classes.

The ViT model employs two optimizers, Adam and SGD (Stochastic Gradient Descent), which include a regularization technique called weight decay. Weight decay is a regularization method used to prevent overfitting in deep learning models. It works by adding a penalty term to the loss function during training, encouraging the model to have smaller weight values. Smaller weights can make the model more robust and less prone to overfitting.

To improve training efficiency, a learning rate schedule is defined. In this schedule, the learning rate, which determines how much the model's parameters are updated during training, is reduced by 50% every 10 training epochs. This gradual reduction in learning rate is a common strategy to help the model converge to a good solution without making overly large updates to its weights, which can cause instability.

During training, the ViT model periodically saves its current state as checkpoints. These checkpoints capture the model's parameters, allowing you to resume training from where you left off or use the model for inference. The saving of model checkpoints is typically based on validation accuracy, meaning that the model's performance on a separate validation dataset is used as a criterion to determine when to save a checkpoint. This ensures that the saved models are based on their ability to generalize to unseen data.

Furthermore, the training data is divided into two parts: the main training data (90%) and a validation set (10%). The main training data is used to train the ViT model, while the validation set is used to monitor the model's performance during training. This split is important for assessing how well the model is learning and for tuning hyperparameters like the learning rate. After the model has been trained, it is evaluated on a separate test dataset that the model has never seen during training. This evaluation assesses the model's performance on unseen data and provides an indication of how well it can generalize to real-world scenarios. The evaluation reports two metrics: accuracy, which measures the overall correctness of predictions, and top-5 accuracy, which indicates how often the correct label is among the top five predicted labels.

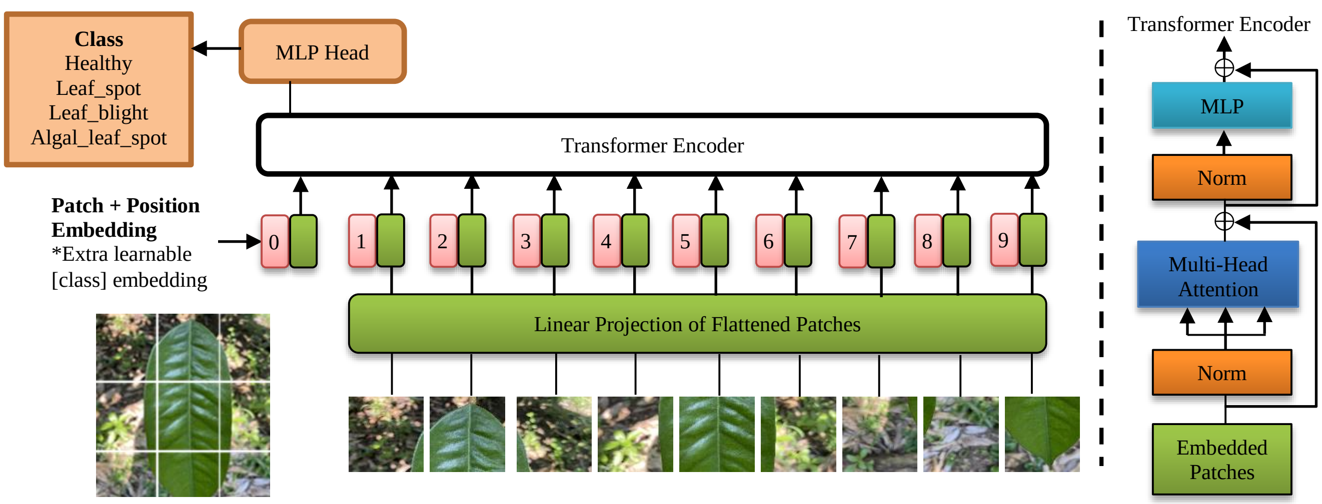



Fig. 3. Vision transformer architecture.

## IV. Results and Discussion

In this study, ViT has been deployed and fine-tuned it to perform Durian Disease classification using two well-known optimization algorithms, namely, Stochastic Gradient Descent (SGD) and ADAM optimizer. The experiments encompassed a range of hyperparameters, including different learning rates (0.001, 0.005, and 0.01) and various epoch settings (20, 30, and 40). The outcomes provide valuable insights into how the model's performance varies with alterations in these key hyperparameters, shedding light on the most effective configurations for the task.

As revealed in Table IV, a validation accuracy of 94.12% was attained with the utilization of the ADAM optimizer, a maximum learning rate of 0.01, and an extended training period of 400 epochs. In contrast, Table V displays the outcomes with the SGD optimizer, where a comparable learning rate and epoch setting yielded an accuracy of 85.82%. ADAM's superior performance in this context can be attributed to its adaptability and the fusion of techniques from both momentum and RMSprop optimization. ADAM excels in scenarios involving intricate loss surfaces and fluctuating learning rates. It dynamically tailors the learning rate for each parameter, guided by historical gradient information. This adaptability often results in swifter convergence and enhanced generalization capabilities. In contrast, SGD adheres to a more conventional optimization approach. Achieving parity with ADAM's performance, particularly with complex models like ViT, often necessitates manual fine-tuning of the learning rate and other hyperparameters.

In many cases, the maximum learning rate of 0.01 might lead to faster convergence but might also make the model diverge or not settle into the optimal solution. By reducing the maximum learning rate during training (e.g., from 0.01 to 0.001), the model is allowed to fine-tune and reach a more stable and accurate solution. This phenomenon can be observed where both optimizers are performed well with maximum learning rate of 0.001 compare to 0.01.

Certainly, our training approach involved the incorporation of a learning rate schedule to foster training stability and mitigate overfitting. Simultaneously, data augmentation proved instrumental in enhancing the model's robustness by enabling it to adapt to a broader range of image conditions. Techniques such as resizing, flipping, rotation, and zooming effectively contributed to this augmentation strategy.

However, in Table VI, ResNet-9 is outperformed the other two methods, ViT and VGG-19. When evaluating why ViT might not be as good as the accuracy of ResNet-9 and VGG-19 [19], various factors come into play. First, ResNet-9 and VGG-19, as convolutional neural networks (CNNs), have been explicitly tailored for image classification tasks, boasting a proven track record in this domain. ViT, on the other hand, is a relatively newer architecture that demands substantial fine-tuning for optimal performance.

Additionally, ViT models often require more extended training schedules, specialized initialization methods, and specific architectural considerations, necessitating higher computational resources. Moreover, ViT's capacity to generalize might be challenged when confronted with smaller datasets, as its architecture is not as well-suited to such scenarios. Comparatively, ResNet-9 and VGG-19 [19] models tend to deliver robust performance with limited data, given their established history in this context.

Furthermore, the availability of pretrained weights customized for specific tasks can provide a performance advantage to ResNet-9 and VGG-19 over ViT. It's important to note that ViT is relatively more susceptible to overfitting, especially in cases involving smaller datasets or exceptionally large models. In addition to these considerations, our dataset for durian leaf disease classification is relatively small, posing a challenge for ViT's generalization capabilities. Addressing this issue would necessitate the utilization of larger models, fine-tuning with different hyperparameters, and more extensive tuning.

TABLE IV. VIT WITH ADAM OPTIMIZER

| Maximum Learning Rate | Epochs | Train Loss | Validation Loss | Validation Accuracy |
|---|---|---|---|---|
| 0.001 | 100 | 0.0647 | 0.2388 | 0.8447 |
| 0.001 | 200 | 0.0167 | 0.1010 | 0.9118 |
| 0.001 | 400 | 0.0400 | 0.0873 | 0.9412 |
| 0.005 | 100 | 0.7316 | 0.7451 | 0.6471 |
| 0.005 | 200 | 0.7406 | 0.7898 | 0.6765 |
| 0.005 | 400 | 0.7406 | 0.7898 | 0.7353 |
| 0.01 | 100 | 1.0367 | 1.1862 | 0.4706 |
| 0.01 | 200 | 1.0376 | 1.1377 | 0.4982 |
| 0.01 | 400 | 1.0270 | 1.0367 | 0.5010 |

TABLE V. VIT WITH SGD OPTIMIZER

| Maximum Learning Rate | Epochs | Train Loss | Validation Loss | Validation Accuracy |
|---|---|---|---|---|
| 0.001 | 100 | 0.1200 | 0.2689 | 0.8009 |
| 0.001 | 200 | 0.0951 | 0.2564 | 0.8511 |
| 0.001 | 400 | 0.0894 | 0.2416 | 0.8582 |
| 0.005 | 100 | 0.8766 | 0.9394 | 0.5843 |
| 0.005 | 200 | 0.8105 | 0.8324 | 0.6056 |
| 0.005 | 400 | 0.7791 | 0.8289 | 0.6082 |
| 0.01 | 100 | 1.1245 | 1.3457 | 0.3943 |
| 0.01 | 200 | 1.1369 | 1.3363 | 0.3973 |
| 0.01 | 400 | 1.2046 | 1.2298 | 0.4085 |

TABLE VI. COMPARISON OF VIT, RESNET-9 AND VGG-19 [19] USING ADAM AND SGD OPTIMIZER

| Maximum Learning Rate | Adam Optimizer | | | SGD optimizer | | |
|---|---|---|---|---|---|---|
| | VGG-19 | ResNet-9 | VIT | VGG-19 | ResNet-9 | VIT |
| 0.001 | 0.8271 | 0.9521 | 0.8447 | 0.8542 | 0.8113 | 0.8009 |
| 0.001 | 0.8500 | 0.9797 | 0.9118 | 0.8542 | 0.8447 | 0.8511 |
| 0.001 | **1.0000** | **0.9911** | **0.9412** | 0.8875 | 0.8896 | 0.8582 |
| 0.005 | 0.8438 | 0.9667 | 0.6471 | 0.8708 | 0.8081 | 0.5843 |
| 0.005 | 0.8708 | 0.9792 | 0.6765 | 0.8771 | 0.8447 | 0.6056 |
| 0.005 | 0.8812 | 0.9792 | 0.7353 | 0.8708 | 0.8792 | 0.6082 |
| 0.01 | 0.8500 | 0.9729 | 0.4706 | 0.8542 | 0.7934 | 0.3943 |
| 0.01 | 0.8604 | 0.9896 | 0.4982 | 0.8542 | 0.8073 | 0.3973 |
| 0.01 | 0.8438 | 0.9896 | 0.5010 | 0.8812 | 0.8358 | 0.4085 |

## V. CONCLUSION AND FUTURE WORKS

This research represents a significant advancement in the field of durian leaf disease detection and recognition, addressing a critical issue faced by durian farmers in ASEAN countries and beyond. The traditional manual identification of leaf diseases has been a labor-intensive and time-consuming process, posing substantial challenges to the agricultural sector's sustainability. Through the application of cutting-edge deep learning techniques and the utilization of well-established models like ViT, an automated system has been successfully developed and capable of accurately classifying and recognizing durian leaf diseases. Notably, our results demonstrate the remarkable performance, achieving an impressive accuracy rate of 94.12% when utilizing the Adam optimizer. Moreover, this research underscores the broader implications of utilizing cutting-edge machine learning techniques in agriculture. It opens the door to the development of precision agriculture systems that can revolutionize crop management practices. The implementation of ViT-based disease control not only safeguards the economic stability and food security of the Southeast Asian region but also paves the way for further advancements in the field of agriculture. With technology as a key ally, durian farmers and the agricultural sector as a whole are better equipped to overcome the challenges posed by disease and secure a more prosperous future.

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## ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

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|---|
| **Durio Zibethinus L plantation intelligent web-based irrigation system using fuzzy logic (DuWIMS) based on IoT / Ahmad, Z. A., Chow, T. S., Jack, S. P., Abdullah, A. H., Ahmad, M. I., & Daud, S.** |
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# Durio Zibethinus L Plantation Intelligent Web-Based Irrigation System using Fuzzy Logic (DuWIMS) Based on IoT

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**ABSTRACT**

In response to the challenges posed by the recent pandemic on traditional farming in Malaysia, this paper proposes DuWIMS, an innovative smart irrigation system that integrates a modern web interface with an IoT-based system. Utilizing an array of sensors for real-time data collection, the system enhances irrigation efficiency through a dual-mode operation: manual remote control and automated irrigation via a fuzzy logic model. This system, tested on a durian farm in Kedah, Malaysia, significantly reduced irrigation time from two hours to approximately 50 minutes for 65 trees and decreased water usage by about 25%. Furthermore, durian trees irrigated with this system exhibited improved growth compared to those under traditional irrigation methods. Operational efficiency was bolstered with remote irrigation control and reliable performance, as evidenced by no system downtime over a three-month period. The deployment of the fuzzy logic model on a cloud server, serving as a backend API, also proved cost-effective by negating the need for on-site computing units. These findings underscore the potential of DuWIMS to revolutionize agricultural practices, particularly in challenging times, by optimizing resource usage and promoting sustainable farming.

## 1. Introduction

Food security was a trending topic in Malaysia for many years. Food security is important as it shows that all people in Malaysia have enough food to eat [1]. Recent pandemic of Covid-19 had caused a major problem for Malaysia's food security. The problem faced by Malaysia is not in terms of individual health nutrition, but economic development. When the Covid-19 pandemic hit Malaysia, plantation export hit an all-time low. Malaysia's major plantations like palm oil and durian had a reduction in total export due to the lockdown. Malaysia's plantation industry relies on manual workers. When the lockdowns happen during the pandemic, the plantation work had to be halted. According to Malaysia research in 2019, Malaysia plantations lay off a lot of their workers due to

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MCO rules like the lockdown which prevent the worker to travel to the field to carry out their work. [2] Sabah is one of the largest palm-oil plantations producing states, had its plantation activity stops in six districts. This caused a heavy impact on Malaysia's economy, where Malaysia suffers a 20% export output loss [3]. Based on the research on Malaysian Labor, during the pandemic, Malaysia was short of 500,000 jobs for the agriculture sector. This caused the production of plantations to drop. Malaysia's palm oil production lost roughly seven hundred thousand tons of product in the year 2020. This greatly affects Malaysia's food security status as the economy plummeted [4]. As Covid-19 got controlled and Malaysia's economy started to recover, it exposed 2 major problems that the traditional way of the plantation was facing.

The traditional way of plantation consists of manual activity irrigation, fertilization, and more. This activity usually requires human labour which starts with farmers going to their plantation site. The farm activity includes monitoring, irrigation, fertilization, soil preparation, and yield collection. Most of the farming time (70%) will be used for monitoring and irrigation [5]. Every plantation needs different water levels, temperatures, and soil conditions to obtain its optimum yield. Hence, specific monitoring had to be carried out at the plantation site to obtain optimal yield production [6]. The traditional way of monitoring and irrigation was carried out where farmers had to go to their plantation site to manually record their plantation status and decide whether it is suitable to water those plantations. As the Covid-19 pandemic started, farmers were unable to travel to their plantation sites due to the lockdown rules. This caused 70% of the farming activity to be halted, thus reducing yield production. Without proper monitoring and an irrigation system, the plantation is unable to produce healthy crops with an optimum yield. Furthermore, the irrigation level that was determined from the monitoring activity suffers from human error. The farmer had to manually record the characteristics data of each plantation in a large area. This data was vulnerable to error as the recording is carried out gradually throughout the plantation site. This problem shows that the traditional way of farming not only was costly as it relied on manual labour work, but it also suffered from inconsistent and deferred data.

Recent growth in technology, especially on the Internet of Things (IoT) sector has helped the traditional way of farming to solve its problems. IoT has grown over the years and affected a wide range of applications branching from manufacturing, health, communication, and agriculture [7]. IoT can be defined as a network that connects physical devices like sensors and actuators with the internet allowing the devices to communicate with each other, exchange data, and process the data [8]. In agriculture sectors, various sensors would be used to detect and record the unique data of plantations. This data will be a further process depending on the application. IoT also reduces manual labour, as the IoT nodes record and send data automatically. Thus, farmers do not have to travel physically and regularly to the plantation site to carry out their farming activity. Moreover, all the detected plantation data will be transmitted in real-time, hence solving the inconsistent and deferred data of the traditional farming method. There is various research regarding the IoT application in agriculture sectors. As the most important activity for farming is irrigation, an IoT-automated irrigation system would help improve plantation productivity.

Recent researchers have designed different irrigation systems featuring different sensors and network setups. Krishnan *et al.,* [9] designed a smart agriculture system featuring an irrigation control system. The system contains an Arduino controller, GSM, motor, soil moisture sensor, temperature sensor, and humidity sensor. The sensors connected to the Arduino controller will detect their respective data and transmit it to a coordinator node using GSM. The coordinator node will then upload the data to the web server and display it in the Android application. The system will turn on the irrigation valve based on the fuzzy logic controller output. A fuzzy logic system is deployed on a controller to compute the sensor input data and determine the motor status. The proposed system was able to reduce the time needed for irrigation by 7% when compared to the manual irrigation system. Although the system proposed by Krishnan *et al.,* [9] did enhance the traditional irrigation system, it has stability issues as the irrigation output depends on the fuzzy logic controller deployed on site. A Smart Irrigation system proposed by Keswani B utilizes a different approach compared to the previous irrigation system [10]. The proposed system combines IOT wireless sensor network with a neural network. The neural network will be used to predict soil moisture content based on the farm history. The soil moisture content data, sensor data, and weather data will be entered into fuzzy logic modelling system. The fuzzy logic model will command the valve status based on the input data. The proposed system was able to water the plantation under different weather conditions. Based on the proposed irrigation system, the system solved the fuzzy logic system problem of the previous irrigation system as the computing unit was a computer. The data collected will be stored in a server, and the computing computer will access the data and process it using the fuzzy logic model and produce the valve command output. It still has the same weakness as the previous irrigation system as the user had no control over the irrigation system.

Hassan et *al.,* proposed a smart irrigation system with a photovoltaic supply [11]. This proposed system carries similar features to the previous research's system. Multiple sensors like light, temperature, humidity, soil moisture, and water flow sensor were connected to a microcontroller. The unique feature that this proposed system had is the PWM solar charge controller that charges the battery for the microcontroller. The PWM solar charge controller controlled the input voltage received by the solar panel. The proposed system was able to prolong the battery life of the controller, with the battery holding off for 3 days without charging. Recent research on smart irrigation system from the year 2019 to 2022 [9-11], shows that IoT smart irrigation system was able to replace traditional irrigation system. All the previous proposed system had their unique features but still faced the same problem. The previously proposed system was missing a proper web system that allows farmers to interact with the irrigation system. Thus, we proposed to develop a modern irrigation system that had both monitoring and control mechanisms displayed and usable on a web system and a fuzzy logic computing system on a cloud server.

The main purpose of this study is to develop an intelligent irrigation system containing both monitoring and control mechanisms. The proposed irrigation system combined both web system and irrigation system. The proposed system implements fuzzy logic system that interact with the web system. Multiple sensors were used to collect data from the farm, and these data were used in the fuzzy model. The fuzzy model will compute the volume of irrigation and time needed for irrigation. The proposed system would also reduce manual labour during irrigation process by allowing user to remotely control the water valve through the web system. This helps to reduce the needs of manual labour during irrigation process. Through the precise computed volume of irrigation and time needed for irrigation, the proposed system could reduce irrigation time and water consumption.

## 2. Methodology

The proposed system features two main parts. The first part is the web system while the second part is the irrigation mechanism. The web system could display real-time sensor data in graphs, providing real-time irrigation control, and managing plantation information. The real-time sensor data will allow the farmer to monitor their farm condition from their residence. The real-time irrigation mechanism let farmer control the irrigation valve straight from the web instead of traveling to their plantation field to stop the water pump for irrigation. Furthermore, the system also labels each of the plantations on the plantation site. This allows farmers to update information regarding the individual plantation and monitor its growth condition. The architecture of the web system was shown in Figure 1.

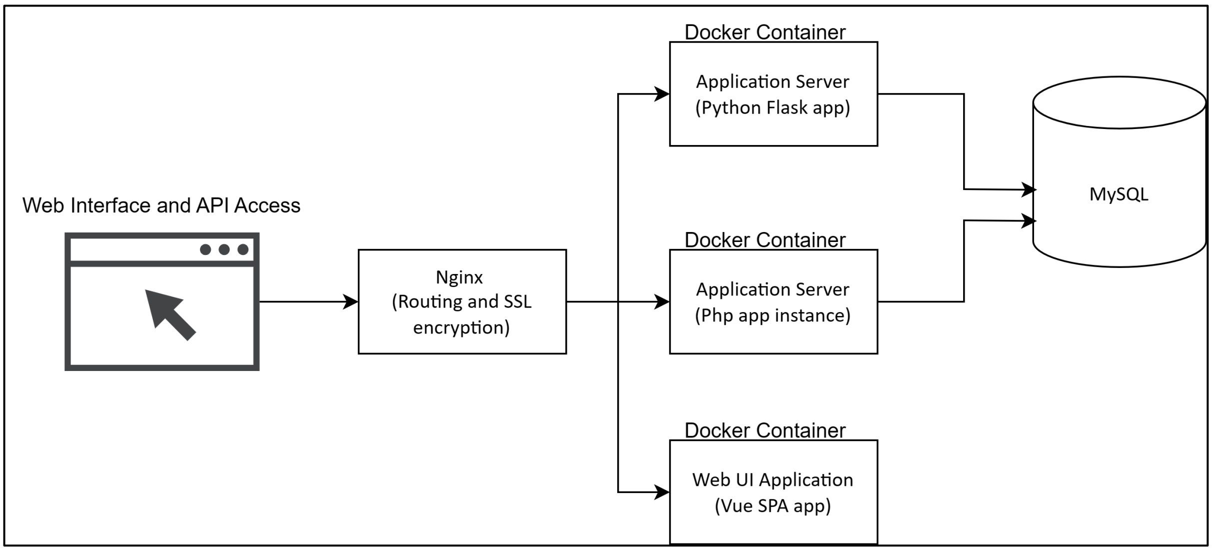


**Fig. 1.** Web system Architecture

### *2.1 Web System*

The web system was separated into two main parts, the frontend part, and the backend part. The web system was deployed on a docker container which served in a webserver. Docker container is a standalone package of software that runs on docker [12]. Docker isolates the application from the underlying operating environment, which enhances the performance of the application. Both the frontend part and backend part of the web system was deployed in a different docker container. The frontend part was developed with the Vue JavaScript framework. It was deployed as a docker container which served as the web UI application. The user will access the front end of the web system with a webpage routed by the Nginx web server. Nginx is a web server that routes all the HTTP requests by the user to the correct container. The Nginx web server used in the system was configured with Secure Sockets Layer (SSL) protection. SSL protects the network from an active, man-in-middle attacker, which ensures the communication between client and server was guaranteed to be secure [13]. The backend part of the web system contains two different application servers running on their docker container. The first application server will handle all the browser APIs that access the MYSQL database. This server was running with a PHP server script. It also handles the request from the sensor node for the irrigation system on both monitoring and irrigation control mechanisms. The second application server was running on the FLASK server. This server holds the fuzzy logic model. As the fuzzy logic model was running on a server, it allows real-time processing. Both application servers will access the same database. The database used here was the MYSQL database.

### *2.2 Irrigation System*

The irrigation part contains both monitoring and controlling mechanisms. The system has two major units: the sensor node and the control node. The sensor node contains the ESP32 controller, WIFI module, humidity sensor, light sensor, soil moisture sensor, soil temperature sensor, and ambient temperature sensor. The control node contains an ESP32 controller, WIFI module, ultrasonic sensor, water flow sensor, soil moisture sensor, soil temperature sensor, and electronic water valve. The sensor device node handles the monitoring mechanism. The block diagram of the irrigation system is demonstrated in Figure 2.

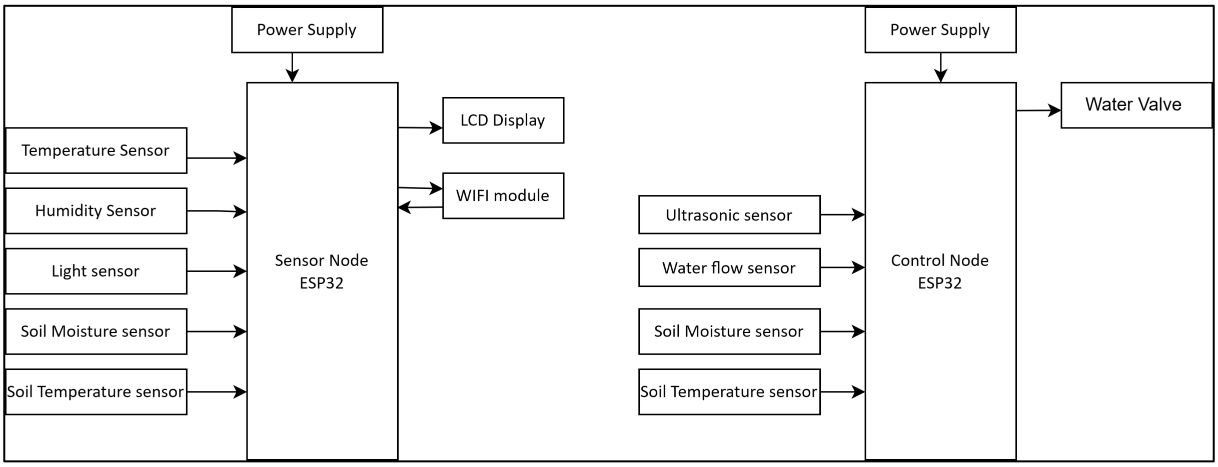


**Fig. 2.** Block diagram of proposed irrigation system

Multiple sensors re connected to the ESP32 controller. The controller collects the sensor data and uploads it into the database through a WIFI connection. The ESP32 uploads sensor data to the database by using the API provided by the PHP application server. The sensor data stored in the database will be accessed by the Web UI application, thus providing real-time monitoring of plantation parameters. The Web UI application can be viewed in a browser on every platform. The control node handles the irrigation mechanism. An ESP32 controller was connected to the electronic water valve. The controller will receive instructions from the Application server to switch on or off the water valve. The water flow sensor was also connected to the controller. This sensor will detect the water flow rate. The controller will generate the total water volume of water flow based on the water flow rate. The soil moisture sensor and soil temperature sensor will record the soil condition when the water valve was operating. The last sensor connected to the controller was the ultrasonic sensor. This sensor was used to measure the water tank volume. Both nodes were powered by solar energy. A solar panel was connected to a charging controller which generate 12V. The 12V was further stepped down to 5V by using a regulator connected to the ESP32 controller. Figure 3 shows the block diagram of the solar panel connection.

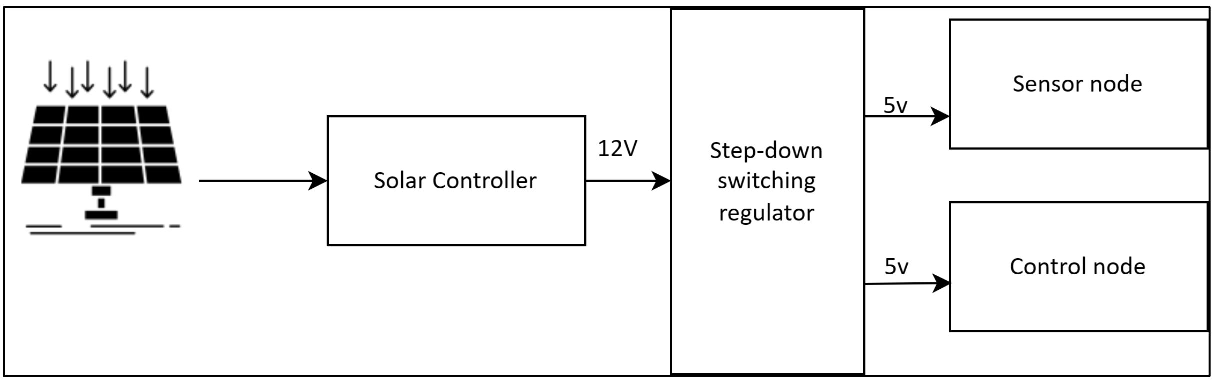


**Fig. 3.** Solar panel connection

### *2.3 Working Principle*

The system works as per the flowchart given in Figure 4 and it involves the following steps.

i. Admin register sensor node and controller node in the web system.
ii. A one-time setup sensor node that initializes the sensor node to start sending data to the database.
iii. Continuous data sensing and uploading data into the database.
iv. The web system fetches data from the database to display on the dashboard.
v. The user manually controls irrigation or selects the fuzzy logic auto mode.
vi. The control node opens or closes the water valve based on the decision data.

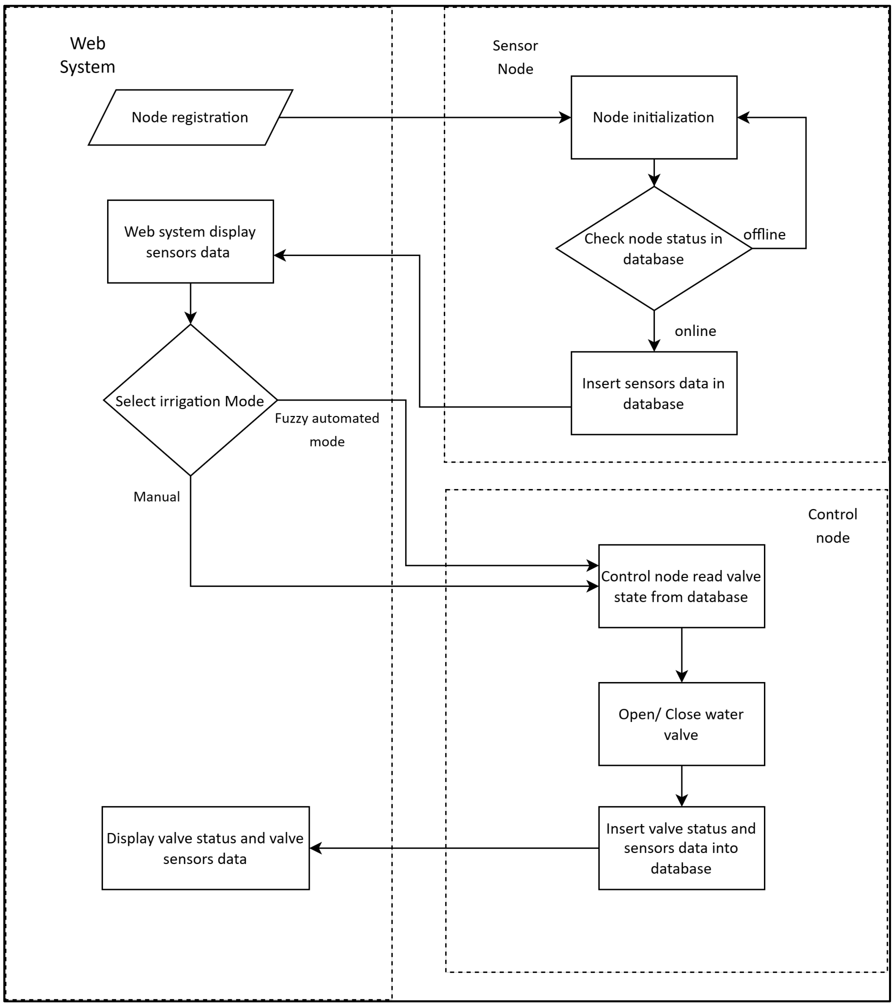


**Fig. 4.** Workflow of the proposed system

As shown in the flowchart, the system starts with registering the sensor node and control node in the web system. The sensor node and control node represent the area they were placed in. Once registered, the sensor node will initialize and upload test data into the database. Once the web system receives the test data from the sensor node, the sensor node will be confirmed to be online in the web system. The sensor node will start to collect sensor data and upload it into the database, while the web system will fetch the data from the database and display it in the dashboard. The web system will have a section that shows the irrigation control panel. By accessing this panel, farmers will be able to remotely control the water valve, either through manual control or using the fuzzy logic system to automate the irrigation control. Once the farmer changes the valve state to ON or OFF, the web system will record the valve condition in the database. The control node will read the newest valve status in the database. Based on the valve status, the controller will switch on or off the water valve. When the water valve was triggered, the controller will initiate sensors to start sensing data and insert the valve status, sensor data, date, and time into the database. The web system will display the data transmitted by the controller node including the valve status and the soil moisture, and temperature value. This allows users to know the condition of their plantation site while irrigation is running in real-time. Furthermore, users could also use the fuzzy logic system to automate irrigation control.

### *2.4 Fuzzy Logic System*

The fuzzy logic system had been used in different systems such as remote sensing systems [14] and control systems. The fuzzy logic system was primarily used in the decision-making stage of a system. It contained 3 different stages which were fuzzification, interference, and defuzzification [15]. The fuzzy logic system that was implemented in this project was shown in Figure 5. A fuzzy logic system starts with fuzzification where it takes in input variable and converts it into linguistic values that represent the fuzzy sets. Next, a knowledge base will be built based on farmer knowledge of the farming domain. The knowledge base contains membership functions and fuzzy rules. The membership functions make up the definitions that define the input variable. The fuzzy rule was used to define the control goals and policy of the output. Both membership functions and fuzzy rules were built with the data from farmers. Defuzzification was performed last to map the range of values of output into quantitative information. The input used in the proposed system were ambient temperature, humidity percentage, soil temperature, soil moisture, and light intensity. The system will compute the output for irrigation which contains the irrigation level, volume of irrigation, and time needed to finish the irrigation.

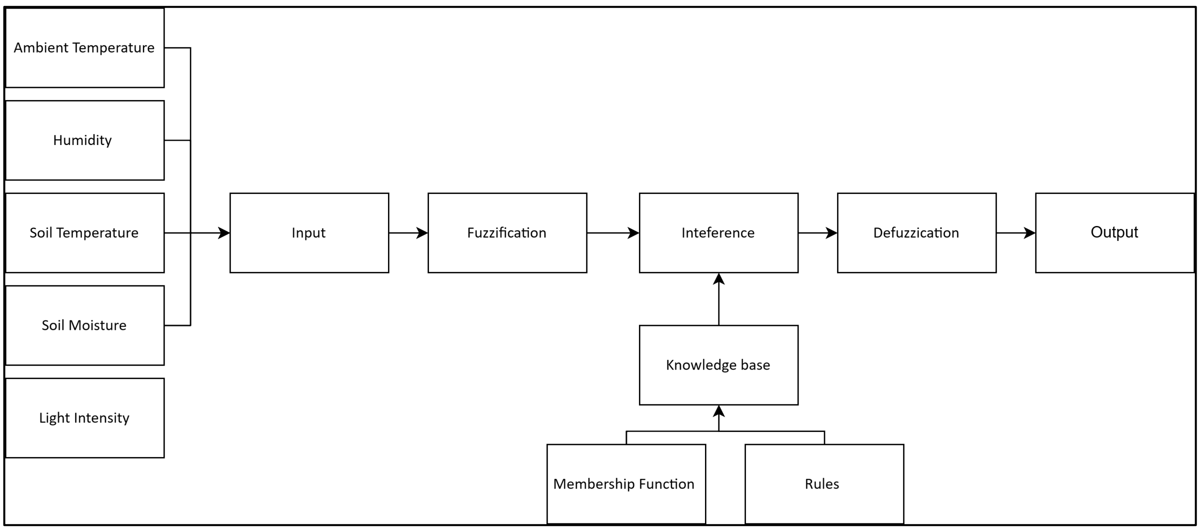


**Fig. 5.** Fuzzy Logic System

Ambient temperature affects the efficiency of irrigation, as the high temperature required more water to be used in irrigation. Thus, a temperature sensor was used to collect ambient temperature data. Figure 6 shows the membership functions of the ambient temperature. As Malaysia's temperature varies between lower 20°C to upper 40°C, thus we classified the temperature into 4 categories. The very low section of temperature rarely happens in Malaysia, as Malaysia is a tropical country. The mean ambient temperature in Malaysia varies from 28°C to 30°C [16], hence the medium class of the temperature was in between the mean temperature of Malaysia. The membership function equation was represented below.

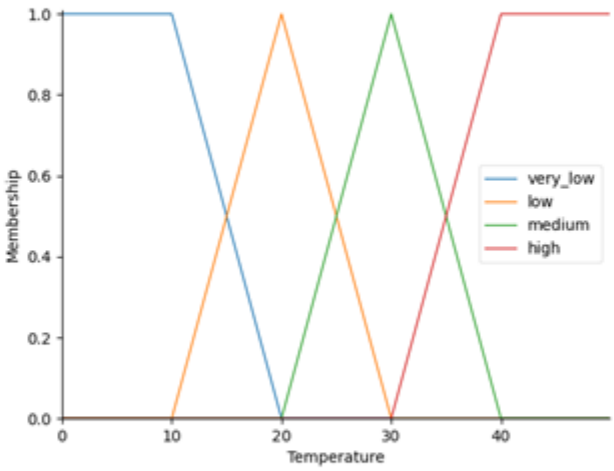


**Fig. 6.** Ambient temperature membership function

$$Temp_{\textbf{very}\ low}(x) = \begin{cases} 1, x \leq 10 \\ \frac{20-x}{10}, 10 < x \leq 20 \end{cases} \tag{1}$$

$$Temp_{low}(x) = \begin{cases} 0, x \leq 10 \\ \frac{x-10}{10}, 10 \leq x \leq 20 \\ \frac{30-x}{10}, 20 \leq x \leq 30 \\ 0,30 \leq x \end{cases} \tag{2}$$

$$Temp_{low}(x) = \begin{cases} 0, x \leq 10 \\ \frac{x-10}{10}, 10 \leq x \leq 20 \\ \frac{30-x}{10}, 20 \leq x \leq 30 \\ 0,30 \leq x \end{cases} \tag{3}$$

$$Temp_{high}(x) = \begin{cases} \frac{x-30}{10}, 30 \leq x \leq 40 \\ 1,40 \leq x \end{cases} \tag{4}$$

The next input parameter for the fuzzy system is the soil temperature. Soil temperature is one of the major parameters that affect the growth of plantations. Based on Frey's research on soil temperature response [17], the soil temperature was affecting the microorganism in the soil which affects the growth of the plantation. The research revealed that the optimum soil temperature for plant growth was 10°C to 25°C, as the microorganism in the soil were more active. The research was carried out in different countries and compared to Malaysia; Malaysia had a higher ambient temperature. Hence, the soil temperature used in the system was separated into 4 categories. The optimum soil temperature was increased by 10°C, thus resulting in between 20°C to 35°C. Figure 7 shows the membership function for soil temperature. The membership function equation was represented below.

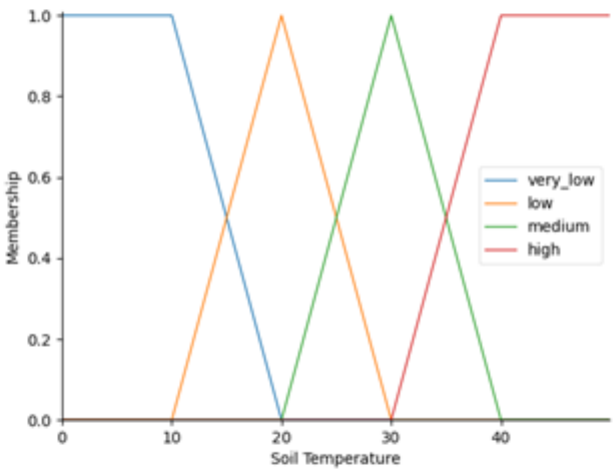


**Fig. 7.** Soil temperature membership function

$$Soil\ Temp_{very\ low}(x) = \begin{cases} 1, x \leq 10 \\ \frac{20-x}{10}, 10 < x \leq 20 \end{cases} \quad (5)$$

$$Soil\ Temp_{low}(x) = \begin{cases} 0, x \leq 10 \\ \frac{x-10}{10}, 10 \leq x \leq 20 \\ \frac{30-x}{10}, 20 \leq x \leq 30 \\ 0{,}30 \leq x \end{cases} \quad (6)$$

$$Soil\ Temp_{medium}(x) = \begin{cases} 0, x \leq 20 \\ \frac{x-20}{10}, 20 \leq x \leq 30 \\ \frac{40-x}{10}, 30 \leq x \leq 40 \\ 0{,}40 \leq x \end{cases} \quad (7)$$

$$Soil\ Temp_{high}(x) = \begin{cases} \frac{x-30}{10}, 30 \leq x \leq 40 \\ 1{,}40 \leq x \end{cases} \quad (8)$$

Humidity or ambient humidity was used as an input parameter in the fuzzy system. Humidity or relative humidity often affects soil water repellence. Water repellence of soil prevents water to infiltrate soil [18]. Doerr research on water repellence shows that the soil had high water repellence when the soil was exposed to 98% relative humidity in a brief period [19]. The water vapor from the surrounding was absorbed into the soil, thus increasing the water repellence of the soil. If the relative humidity of the surroundings increased, the soil would sustain its wettability which decreased the chances of water infiltrating into the soil. The humidity percentage was separated into 4 categories, with the highest humidity being more than 70%. Malaysia's average humidity was between 75% to 95 %, hence instead of keeping the highest humidity level at a relative 98%, the highest humidity for the fuzzy system was set at 75 [20]. Figure 8 shows the membership function for soil temperature. The membership function equation was represented below.

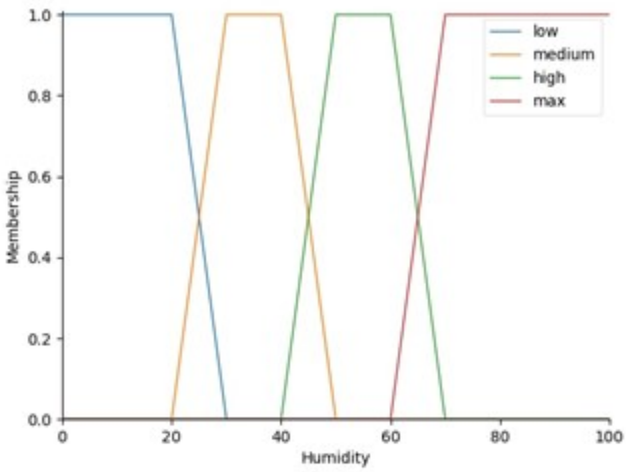


**Fig. 8.** Humidity membership function

$$Humidity_{low}(x) \quad = \begin{cases} 1, x \leq 20 \\ \frac{30-x}{10}, 20 < x \leq 30 \end{cases} \tag{9}$$

$$Humidity_{medium}(x) = \begin{cases} 0, x \leq 20 \\ \frac{x-20}{10}, 20 \leq x \leq 30 \\ 1, 30 \leq x \leq 40 \\ \frac{50-x}{10}, 40 \leq x \leq 50 \\ 0, 50 \leq x \end{cases} \tag{10}$$

$$\text{Humidity}_{high}(x) \quad = \begin{cases} 0, x \leq 40 \\ \frac{\text{x}-40}{10}, 40 \leq x \leq 50 \\ 1, 50 \leq x \leq 60 \\ \frac{70-x}{10}, 60 \leq x \leq 70 \\ 0, 70 \leq x \end{cases} \tag{11}$$

$$\text{Humidity}_{max}(x) \quad = \begin{cases} \frac{x-60}{10}, 60 \leq x \leq 70 \\ 1, 70 \leq x \end{cases} \tag{12}$$

Soil moisture was also used as an input parameter for the fuzzy system. Soil moisture represents the amount of water content in the soil. It also controls the groundwater storage of soil as it determines the amount of water that infiltrates into the soil [21]. Soil moisture is often affected by soil temperature. Based on Venkat's research on the relationship between soil moisture and temperature, there was a linear relationship between soil moisture and soil temperature [22]. It also states that an increased in ambient temperature and soil temperature would reduce soil moisture [22]. Soil moisture also affects soil evaporation, as low soil moisture caused lesser water to be evaporated. This affects the evapotranspiration of plantations, where their growth was limited by the lack of water, and energy from evaporation [23]. The soil moisture data were measured in percentage, and it was classified into five categories which are very low, low, medium, high and maximum. Relative humidity and ambient temperature affect the soil moisture; hence the optimum soil moisture was assumed to be at between 20% to 90%. Very low soil moisture was set at below

10% as Malaysia's relative humidity was high, it was rare to have soil moisture be dry. Malaysia's ambient temperature was high; hence soil moisture rarely reaches 90% throughout the day. Figure 9 shows the membership function for soil temperature. The membership function equation was represented as below.

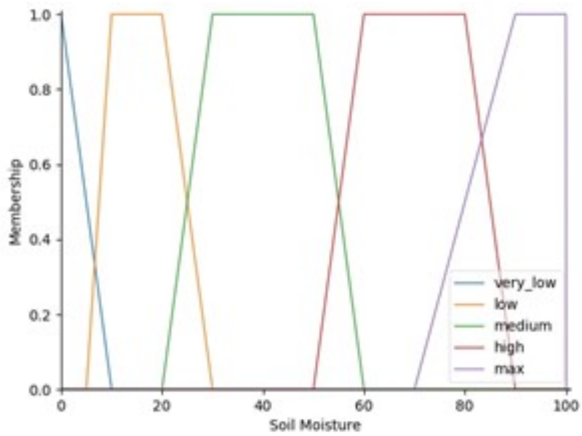


**Fig. 9.** Soil Moisture membership function

$$SoilMoisture_{very\ low}(x) = \begin{cases} \frac{10-x}{10}, 0 \le x \le 10 \\ 0, 10 \le x \end{cases} \quad (13)$$

$$SoilMoisture_{low}(x) = \begin{cases} 0, x \le 10 \\ \frac{x-5}{5}, 5 \le x \le 10 \\ 1, 10 \le x \le 20 \\ \frac{30-x}{10}, 20 \le x \le 30 \\ 0, 30 \le x \end{cases} \quad (14)$$

$$\text{SoilMoisture}_{medium}(x) = \begin{cases} 0, x \le 20 \\ \frac{\text{x}-20}{10}, 20 \le x \le 30 \\ 1, 30 \le x \le 50 \\ \frac{60-x}{10}, 50 \le x \le 60 \\ 0, 60 \le x \end{cases} \quad (15)$$

$$\text{SoilMoisture}_{high}(x) = \begin{cases} 0, x \le 50 \\ \frac{\text{x}-50}{10}, 50 \le x \le 60 \\ 1, 60 \le x \le 80 \\ \frac{90-x}{10}, 80 \le x \le 90 \\ 0, 90 \le x \end{cases} \quad (16)$$

$$\text{SoilMoisture}_{max}(x) = \begin{cases} \frac{x-70}{20}, 70 \le x \le 90 \\ 1, 90 \le x \end{cases} \quad (17)$$

The last input parameter was light intensity. Light intensity is the amount of light that is exposed to the plantation. Light intensity affects the transpiration rate of the plant, where the rate of at the plant releases its water vapor depends on the light intensity [24]. The light intensity also scales with the ambient temperature. High light intensity will result in high ambient temperature. Based on the research on coffee arabica leaf at different irrigation and light intensity levels, a plantation that is exposed to a medium light intensity environment and high irrigation level has the highest growth rate [25]. If the plant is exposed to a high light -light-intensity environment, its water evaporation rate would increase. This caused the plant to reduce its photosynthesis rate, which reduce the growth rate of the plant. Malaysia's daily average light intensity reading is in between sixty thousand lux to eighty thousand lux [26]. The light intensity level was classified into three categories, where the medium light intensity was in between forty thousand to sixty thousand lux. High light intensity was in between fifty thousand and hundred thousand lux Figure 10 shows the membership function for light intensity. The membership function equation was represented as below.

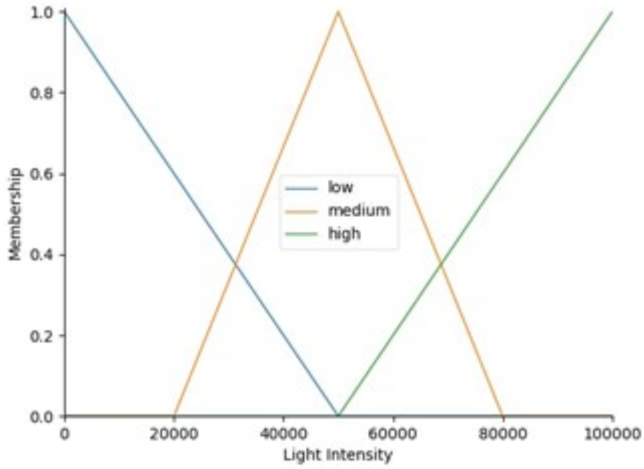


**Fig. 10.** Light Intensity membership function

$$LightIntensity_{low}(x) \quad = \begin{cases} \frac{50000-x}{50000}, x \leq 50000 \\ 0{,}50000 \leq x \end{cases} \tag{18}$$

$$LightIntensity_{medium}(x) = \begin{cases} 0, x \leq 20000 \\ \frac{x-20000}{30000}, 20000 \leq x \leq \ 50000 \\ \frac{80000-x}{30000}, 50000 \leq x \leq 80000 \\ 0{,}80000 \leq x \end{cases} \tag{19}$$

$$\text{LightIntensity}_{high}(x) \qquad = \begin{cases} \frac{\text{x}-50000}{50000}, 50000 \leq x \leq 100000 \end{cases} \tag{20}$$

The output of the fuzzy system is the irrigation level. The irrigation level starts from 0 to 100%. Based on the irrigation level output, the backend API will compute the time needed and volume of water needed to fulfil the irrigation level. These outputs will then be displayed at the frontend website. The irrigation was classified into five different categories. Figure 11 shows the membership function for the irrigation level. The membership function equation was represented below.

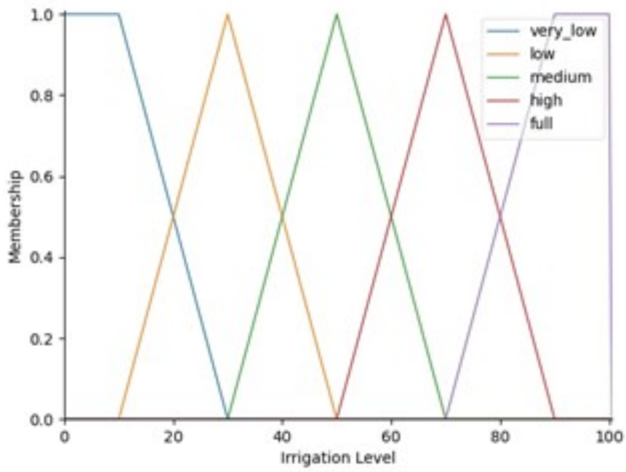


**Fig. 11.** Irrigation Level membership function

$$IrrigationLevel_{very\ low}(x) = \begin{cases} 1, x \leq 10 \\ \frac{30-x}{20}, 10 < x \leq 30 \end{cases} \tag{21}$$

$$IrrigationLevel_{low}(x) = \begin{cases} 0, x \leq 10 \\ \frac{x-10}{20}, 10 \leq x \leq 30 \\ \frac{50-x}{20}, 30 \leq x \leq 50 \\ 0{,}50 \leq x \end{cases} \tag{22}$$

$$\mathrm{IrrigationLevel}_{medium}(x) = \begin{cases} 0, x \leq 30 \\ \frac{\mathrm{x}-30}{20}, 30 \leq x \leq 50 \\ \frac{70-x}{20} 50 \leq x \leq 70 \\ 0{,}70 \leq x \end{cases} \tag{23}$$

$$\mathrm{IrrigationLevel}_{high}(x) = \begin{cases} 0, x \leq 50 \\ \frac{\mathrm{x}-50}{20}, 50 \leq x \leq 70 \\ \frac{90-x}{20}, 70 \leq x \leq 90 \\ 0{,}90 \leq x \end{cases} \tag{24}$$

$$\mathrm{IrrigationLevel}_{max}(x) = \begin{cases} \frac{x-70}{10}, 70 \leq x \leq 90 \\ 1{,}90 \leq x \end{cases} \tag{25}$$

The output of the fuzzy system was computed using the pre-set fuzzy rules shown in Table 1. The fuzzy rules were determined based on the previous research data and farmer's data.

**Table 1**
Fuzzy rules example for proposed fuzzy logic system

| Number | Rule |
|---|---|
| 1 | If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “Low”) ^ (Soil Moisture is “Low” \| “Very Low”) ^ (Light intensity is “Low”), then (irrigation level is “Low”) |
| 2 | If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “Medium”) ^ (Soil Moisture is “Medium” \| “Low”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”) |
| 3 | If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “High”) ^ (Soil Moisture is “High”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”) |
| 4 | If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “Maximum”) ^ (Soil Moisture is “Maximum”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”) |
| 5 | If (Ambient Temperature is “Low”) ^ (Soil Temperature is “Low”) ^ (Ambient Humidity is “Low”) ^ (Soil Moisture is “Low” \| “Very Low”) ^ (Light intensity is “Low”), then (irrigation level is “Medium”) |
| 6 | If (Ambient Temperature is “Low”) ^ (Soil Temperature is “Low”) ^ (Ambient Humidity is “Medium”) ^ (Soil Moisture is “Medium”) ^ (Light intensity is “Low”), then (irrigation level is “Low”) |
| 7 | If (Ambient Temperature is “Low”) ^ (Soil Temperature is “Low”) ^ (Ambient Humidity is “High”) ^ (Soil Moisture is “High”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”) |
| 8 | If (Ambient Temperature is “Medium”) ^ (Soil Temperature is “Low” \| “Medium”) ^ (Ambient Humidity is “Low”) ^ (Soil Moisture is “Low” \| “Very Low”) ^ (Light intensity is “Low” \| “Medium), then (irrigation level is “High”) |
| 9 | If (Ambient Temperature is “Medium”) ^ (Soil Temperature is “Low” \| “Medium”) ^ (Ambient Humidity is “Medium”) ^ (Soil Moisture is “Medium” \| “Low”) ^ (Light intensity is “Low” \| “Medium”), then (irrigation level is “Medium”) |
| 10 | If (Ambient Temperature is “Medium”) ^ (Soil Temperature is “Low” \| “Medium”) ^ (Ambient Humidity is “High”) ^ (Soil Moisture is “High” \| “Medium”) ^ (Light intensity is “Low” \| “Medium”), then (irrigation level is “Low”) |
| … | … |

## 3. Results

The system was implemented in on a real farm located at in Kedah, Malaysia. The farm was managed by TW Megastar. The primary plantation of the farm is the durian tree. The durian plantation is located at Muda Kuari, Tunjang Jitra, Kedah. The total farm area is 2.5 acres. Figure 12 shows the location of the durian farm. The farm currently had planted 65 durian trees. The placement of the tree was mapped in Figure 13.


**Fig. 12.** TW Megastar Durian Plantation Farm

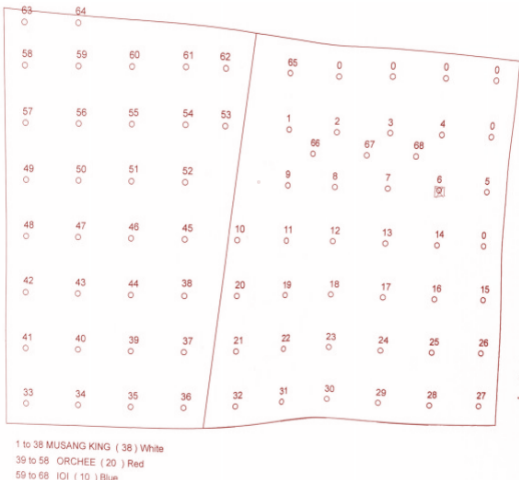


**Fig. 13.** Durian tree mapping

### *3.1 Hardware*

Based on the mapping of the durian tree, the irrigation system was implemented at the first tree row of the tree. The hardware setup of the irrigation system was like a traditional drip irrigation system where the water pipes were first connected to a water tank. The water pipes were then separated into different drip lines on each row of the durian tree. The control node was implemented at the main pipe that connects to each of the drip lines. It will control the valve connected to each drip line. The sensor node was installed at different sections of the farm. The current setup for the farm was two sensor nodes that were separately installed at the left and right sides of the farm. Figure 14 shows the durian tree plantation with drip piping. Figure 15 shows the irrigation piping at individual trees. The set-up of the control node was shown in Figure 16. Figure 17 shows the sensor node. The control and sensor nodes were ensembled before installing at the farm.

**Fig. 14.** Drip piping with the durian tree

**Fig. 15.** Piping at durian tree

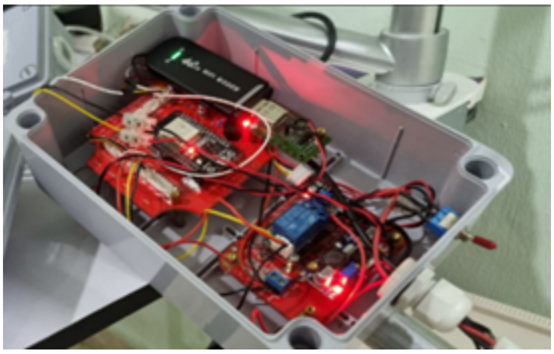

**Fig. 16.** Control node prototype

**Fig. 17.** Sensor node prototype

### *3.2 Web System*

The web system was deployed on a cloud server at www.twm.5ir.tech. The web system had zero downtimes since it was deployed. It also didn't suffer from digital attacks as the web system was encrypted with SSL. The data stored in the web system was well secured. The web system displays the real-time data collected from the sensor node and display in the dashboard form. The data can be viewed in hourly, daily, or monthly form. Data will be fetched from the database every 10 minutes, thus the data shown in the dashboard is always the newest data collected by the sensor node. In the dashboard, the newest data was displayed separately below the header. Each card represents each sensor's data. The body section of the dashboard had two graphs displaying humidity-ambient temperature data and soil moisture-soil temperature data. The button could switch the graph form based on its view form. The custom and search tab allows customize and query-based data views.

The web system also includes a tree registration system. The tree page shows a collection of planted tree data. It allows the farmer to record individual growth data of the durian tree. Figure 17 shows the login page of the web system. Figure 18 shows the main dashboard of the web system. Figure 19 shows the custom graph and Figure 20 shows the tree details page.

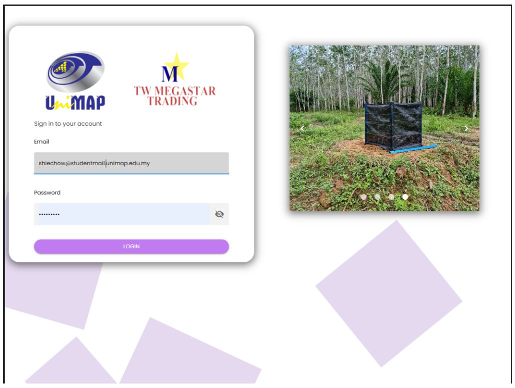


**Fig. 18.** Login page

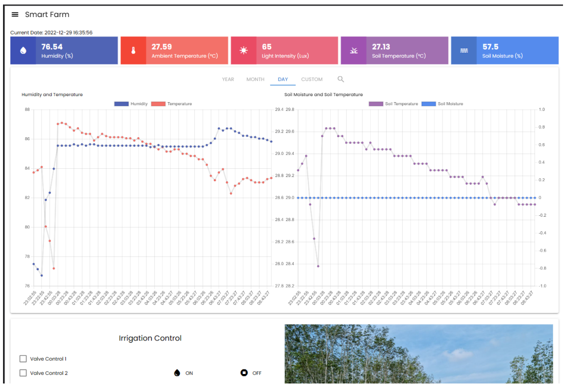


**Fig. 19.** Main dashboard


**Fig. 20.** Custom view of sensor data

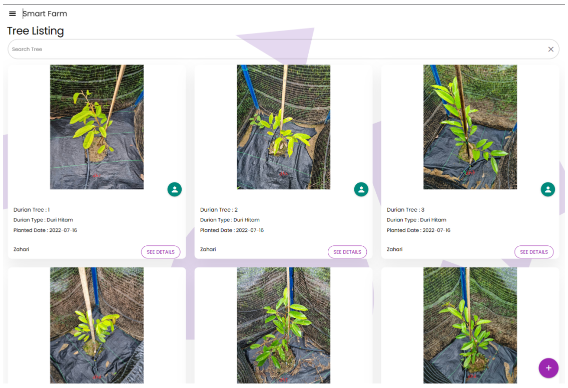


**Fig. 21.** Tree page

### *3.3 Irrigation System*

The fuzzy irrigation system was implemented in the web system. The bottom section of the main dashboard contains the irrigation control for the farm. By default, the irrigation controller is in manual mode. The farmer manually selects the valve that they want to open and close. When the farmer clicks the on button, the control node will listen to the changes and open the chosen valve. While the valve was opening, the control node will also record the current soil moisture and soil temperature value. The data will be displayed in the picture in the web system. Once the water valve was stopped, the soil moisture and soil temperature value will be updated to reflect the newest condition of the soil. The irrigation control section also featured a stopwatch that record the time for the ongoing irrigation. Figure 22 shows the irrigation control section of the web system and the current soil moisture and temperature data.

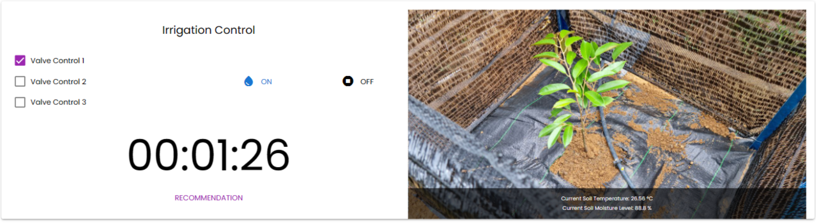


**Fig. 22.** Irrigation Control

The fuzzy irrigation system can be accessed at the recommendation button. The recommendation button is called the fuzzy logic API and passes the current sensor's data to the backend server. The backend server receives the current humidity, ambient temperature, light intensity, soil moisture, and soil temperature and inputs it to the fuzzy logic model to process it. The output of the fuzzy model is then passed back to the web system. The web system displays the result and changes the irrigation mode to automated mode. The irrigation will turn off automatically at the suggested time, which results in optimum irrigation time. Figure 23 shows the fuzzy output on the web system.


**Fig. 23.** Fuzzy model output

### *3.4 System Testing*

The system was deployed at the targeted farm from August 2022 to October 2022. One sensor node and three control nodes were installed at the farm. The sensor node record data from August 2022 to October 2022 without any down time. The data was recorded at the pace of every 10 minutes. The average of the recorded data was computed and displayed on the main dashboard. The average humidity around the farm was 82%, while the average ambient temperature was 29.85°C. The average soil temperature was 28.65°C, while the average soil moisture was 50%. The data shows that there was a relationship between the ambient temperature and the soil temperature as they had a similar reading. The average soil moisture throughout the month was lower as the average temperature was high and rain rarely happen; hence the soil moisture can't maintain its wetness throughout the day. Figure 24 and Figure 25 show the mean of the collected data.

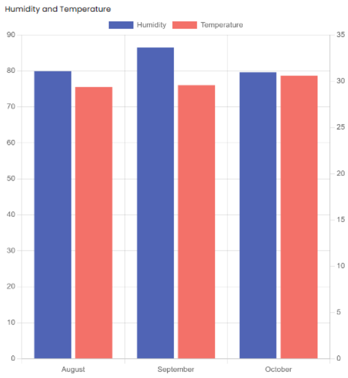


**Fig. 24.** Average humidity and ambient temperature data

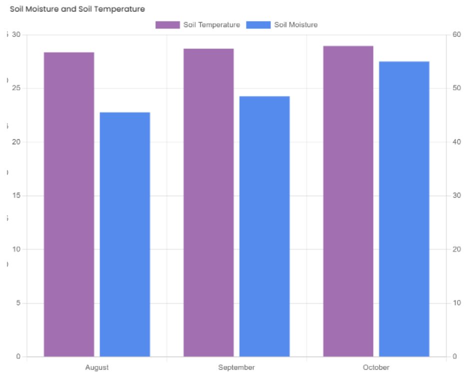


**Fig. 25.** Average soil temperature and soil moisture data

The farm site originally depends on manual irrigation, where farmers manually watered all the durian trees. The intelligent irrigation system replaces the traditional manual watering process, by allowing the farmer to remotely watered the durian tree with the exact volume of water that the tree needs. Compared to the traditional manual irrigation method, the fuzzy irrigation system shortens the time needed to complete the irrigation process. Data collection had been done throughout the 3-month trial period. The water volume consumption and the time taken for the irrigation was recorded and visualize in Figure 26 and Figure 27.

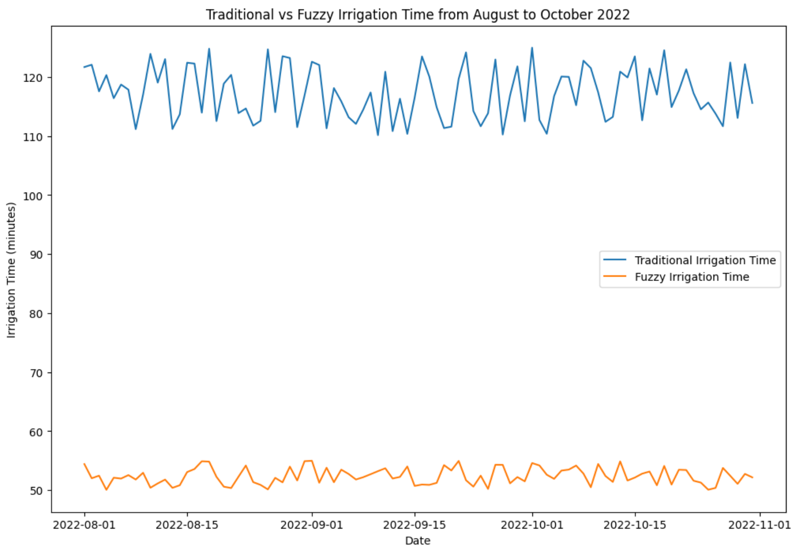


**Fig. 26.** Comparison between traditional and fuzzy irrigation time

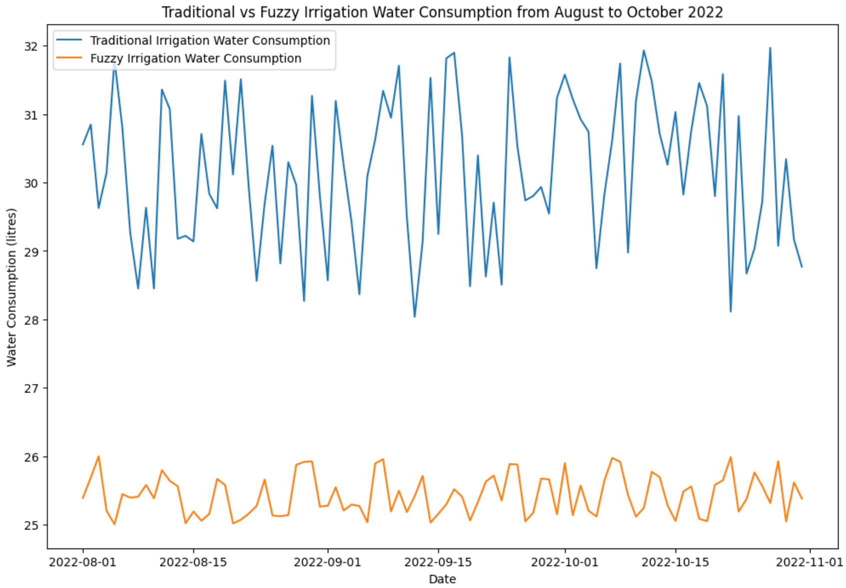


**Fig. 27.** Comparison between traditional and fuzzy water consumption

Based on the collected data, the average time needed for the farmer to finish irrigating all 65 trees took an average of two hours. The farmer reported that the average time to finish irrigation using fuzzy irrigation was 50 minutes. The volume of water that was used for irrigation was greatly reduced after the implementation of this system. Manual irrigation depends on the farmer's decision to turn off the water pipe, which caused the water volume used to become irregular. The fuzzy irrigation system stops the irrigation at a precise time thus the water used was more consistent. Based on the farmer from TW Megastar, a young durian tree needed 30-liter water to grow. As shown in Table 2, the fuzzy irrigation system was able to irrigate the durian tree with an average of 25 litres of water which didn't overflow the durian tree. While the irrigation time was reduced significantly, the water volume only dropped by 25% because watering plants is not a direct function of time alone. The efficiency and precision in the fuzzy system is apparent in both reduced time and water volume, but the volume reduction is not as dramatic because there's an optimal amount of water that the trees need, and going below that would compromise the health of the trees.

**Table 2**
Comparison between traditional irrigation and fuzzy irrigation system

| | Traditional Irrigation | Fuzzy irrigation |
|---|---|---|
| Time taken | 2 hours | 50 minutes |
| Water volume | Average of 35 litre | Average of 25 litre |

The first three rows of durian tree that utilized the intelligent irrigation system shows a better growth rate when compared to the durian tree that used traditional irrigation. Figure 28 shows the durian tree that utilizes the intelligent irrigation system, while Figure 29 shows the durian tree that used the traditional irrigation method. Each tree was planted in the same month in February 2022. The durian tree that used the fuzzy irrigation system has a higher height and better growth rate.

**Fig. 28.** Durian tree that used intelligent irrigation system

**Fig. 29.** Durian tree that used traditional irrigation method

## 4. Conclusions

The system was successfully developed and deployed at the farm. Throughout the 3-month testing, the system had zero down time. This shows that the developed intelligent irrigation system was able to replace the traditional irrigation method. The manual labour activity during the irrigation process was also replaced by accessing the web system. Farmers could access the web system through their smart phones or computer and turn on the irrigation. This system is also able to provide an accurate estimation of water volume and time needed for irrigation. The testing shows that this system saves up to 60% of irrigation time and 25% of the water used. The water consumption for this system is more efficient as compared to the traditional irrigation method. The fuzzy logic model was deployed on a cloud server, where it served as a backend API. This reduces the needs of setting up a computing unit at in the farm area which reduces the operation cost for the farm.

### *4.1 Future Works*

Although the system has been successfully implemented at the farm, future enhancements could include refining the fuzzy logic model by incorporating the evaporation and transpiration rate of water for more accurate water needs assessment. A significant advancement would be the integration of drones equipped with advanced sensors. These drones can capture high-resolution images, providing real-time data on land use, soil content, and vegetation health, including the Normalized Difference Vegetation Index (NDVI). This information can be integrated into the fuzzy logic model to further refine irrigation precision. Additionally, the introduction of a scheduler control mode would allow farmers to plan their irrigation up to 3 days in advance. Utilizing predictive models based on historical sensor data can also enhance the data used in the fuzzy logic model.

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**ARTICLES FOR FACULTY MEMBERS**

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

| |
|---|
| **Evaluation of morinda citrifolia leaf extract against phytophthora palmivora in controlling stem canker on durian (durio zibethinus) / Nor Danial, N. D., Asib, N., Sadi, T., & Ismail, S. I.** |
| ***Malaysian Applied Biology***<br>**Volume 54 Issue 1 (2025) Pages 24–37**<br>**https://jms.mabjournal.com/index.php/mab/article/view/2947/1004**<br>**(Database: Malaysian Society of Applied Biology)** |

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Research Article

# Evaluation of *Morinda citrifolia* Leaf Extract Against *Phytophthora palmivora* in Controlling Stem Canker on Durian (*Durio zibethinus*)

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**ABSTRACT**

Durian is an economically important crop in Malaysia and has been identified as a new source of agricultural wealth valued at USD 1.58 billion. However, *Phytophthora palmivora* has been reported in all areas where durian has been planted and continues to pose a significant challenge for durian growers. The crop losses and control costs were estimated at 11.7% in 2020. Durian farmers have applied oomycete fungicides for more than 20 years to control stem canker, and extensive use of fungicides has resulted in the development of resistant *Phytophthora* isolates. This study aimed to evaluate four different leaf crude extracts of mengkudu (*Morinda citrifolia*) extracted using methanol, acetone, ethyl acetate, and hexane solvents against *P. palmivora*. GC-MS analysis of *M. citrifolia* leaves crude extract revealed the presence of squalene. In-vitro screening of the *M. citrifolia* plant extracts, the crude extracts of acetone and ethyl acetate revealed effective concentration 50% ($EC_{50}$) values of 36.115 and 38.095 mg/mL, respectively. PDA supplemented with acetone solvent at 60 mg/mL altered the morphology and inhibited the mycelial growth of *P. palmivora*. In an in-vivo bioassay screening level, treated plants of *M. citrifolia* extract of ethyl acetate 76 mg/mL had a lesion growth of 30.24 mm on the stem. This treatment was not significantly different from the control positive treatment applied with Ridomil fungicide. *Morinda citrifolia* leaf extracts using methanol, acetone, and ethyl acetate revealed it could be used as an alternative biocontrol agent for foliar spraying to reduce disease severity in durian seedlings against *P. palmivora*.

**Key words:** Antifungal activity, canker, durian, mengkudu, *Morinda citrifolia*, *Phytophthora palmivora*

## INTRODUCTION

Durian (*Durio zibethinus*) is a sought-after fruit, especially in Asian countries. In Malaysia, durian has grown to be the most widely planted crop, occupying 41% of the country's total arable area, roughly 70,000 hectares. Durian, notably Musang King, is now regarded as a precious commodity and a new source of wealth for Malaysia. In Malaysia, this economically important crop, valued at USD 1.58 billion (Department of Agriculture, 2020), is the largest cultivated crop, making it a significant source of income for both small-scale and commercial farmers.

The stem canker disease caused by *Phytophthora palmivora* is notoriously challenging to control or eradicate. *P. palmivora* causes stem canker at nearly all phases of durian growth and is reported to have an estimated average loss of 20-30% in Malaysia (Misman *et al*., 2022). Many popular fungicide targets, like the process involved in ergosterol biosynthesis and cell walls made of chitin, are absent in the *Phytophthora* species (Kamoun *et al*., 2015). Several management measures, including phytosanitary, chemical control, cultural approaches, biological control, and genetic resistance, have been used to control the stem canker of durian. However, none have yielded satisfactory results or completely controlled the disease (Guest, 2007). Fungicide use necessitates precise control to avoid harm to human health and the environment and the emergence of fungicide resistance. Natural products, which are low toxicity and readily biodegradable into non-toxic products, offer a promising solution (Tripathi & Dubey, 2004). Plant extracts contain valuable secondary metabolites, which protect plants from oxidation and disease (Lima *et al*., 2019).

*Morinda citrifolia* is a medicinally valuable plant grown in the tropics for its fruits, leaves, and roots (Zin *et al*., 2002). The leaves are not only eaten as a vegetable (Zhang *et al*., 2016) but have also long been used to prevent various chronic diseases (Lim *et al*., 2016). Almost 200 phytochemicals have been identified and isolated from different parts of the *M. citrifolia* plant (Singh, 2012). *Morinda citrifolia* contains antifungal compounds such as anthraquinones (Takashima *et al*., 2007) and flavanols (Su *et al*., 2005). Both compounds inhibited *Phytophthora capsici* zoospores on cucurbits (Tala *et al*., 2018). This is in line with previous research showing that *M. citrifolia* can inhibit *Fusarium* sp. (Jayaraman *et al*., 2008), *Rhizoctonia solani* (Goun *et al*.,

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2003), and *Stagonosporopsis cucurbitacearum* (Fr.) Aveskamp (Mateus *et al*. 2017). Thus, the objectives of this study are to identify bioactive natural compounds in *M. citrifolia* leaf extracts extracted with methanol, acetone, ethyl acetate, and hexane and to evaluate in vitro and in vivo efficacy *of M. citrifolia* leaf crude extracts against mycelial growth of *P. palmivora* on durian seedlings, crude extracts against mycelial growth of *P. palmivora* on durian seedlings.

## MATERIALS AND METHODS

### Plant materials

Matured whole leaves of mengkudu (*Morinda citrifolia* L.) were collected from the landscaping area at Sultan Abdul Samad Library, Universiti Putra Malaysia, Serdang, Selangor, Malaysia (3.002492, 101.706151). MFI 0199/21 is a voucher specimen deposited at the Laboratory of Natural Products, Institute of Bioscience (IBS), Universiti Putra Malaysia. The preparation of plant materials followed the procedure of Zin *et al*. (2002) with minor modifications. The leaves were washed and cut into small pieces after being rinsed under running water. They were oven-dried for three days at 50°C before being ground into powder with a high-speed grinder machine. The powdered sample was kept at 28±1.5°C in an airtight container until further extraction processes.

### *Morinda citrifolia* leaf crude extract preparation

Extraction procedures use selective solvents to separate active compounds from plant tissues. Solvents diffuse into the solid plant material during extractions and solubilize compounds with similar polarities. Analytical grade (99% minimum purity) organic solvents of methanol, acetone, ethyl acetate, and hexane were used in this study. The solvents were chosen based on their relative polarity: methanol > acetone > ethyl acetate > hexane. The polarity of the solvents can influence the quality and quantity of secondary metabolites in an extract and their composition. Minor modifications were made to the procedure described by Krishnaiah *et al*. (2012). Sample powder to organic solvents of methanol, acetone, ethyl acetate, and hexane (1.5 w/v) were used to extract the ground powder for 24 hr on an orbital shaker machine (Model 720, Protech) at 240 rpm. The resulting suspensions were filtered through Whatman no. 1 filter paper and evaporated to dryness in a rotary evaporator at 60 rpm and 50 degrees Celsius (°C). The crude extracts were kept at 4°C in an airtight bottle until further use. The extract yield (%) was calculated according to Truong *et al*. (2019).

$$\text{Extract yield (\%)} = \frac{\text{Weight of the extract after evaporating solvent}}{\text{Dry weight of sample}} \times 100$$

### Gas Chromatography-Mass Spectrometry (GC-MS) analysis

The volatile chemical compounds in *M. citrifolia* crude leaf extract were investigated using gas chromatography-mass spectrometry (GC-MS). Natural Medicines and Products Research Laboratory, Institute of Bioscience, Universiti Putra Malaysia conducted the analysis. The crude samples were diluted to 50,000 ppm with the same solvent used in extraction. Shimadzu Gas chromatography GC-2010 Plus (Kyoto, Japan) equipped with a Shimadzu QP-2010 Ultra mass selective detector was used for gas chromatography and mass spectrometry. The system includes a Rxi®-5ms (5% diphenyl + 95% dimethylpolysiloxane) electron capture detector column measuring 30 m (length) × 0.25 mm (internal diameter) × 0.25 m (thickness). At a constant flow rate of 1.0 mL/ min, ultra-high purity helium was used as the carrier gas. The oven temperature was gradually increased from 50°C (initial) to 300°C (final) at a rate of 3°C/min. With an interface temperature of 250°C and an ion source temperature of 200°C, the sample was injected at 250°C. The total running time was 90 min. The GC retention time was used to identify and characterize the chemical compounds in the crude extracts. MS spectra of separated components were identified using FFNSC1.3.lib, WILEY229.lib, and NIST11s.lib data libraries.

### Preparation of *Phytophthora palmivora* isolates

Infected trees showing symptoms of water-soaking lesions were sampled. To obtain a pure culture of *P. palmivora* isolates, the outer layer of the bark surface was scrapped to obtain samples from the advancing lesion margin. Small pieces of bark containing the lesion margins were carefully removed using a machete. The small pieces (1 × 1 $cm^2$) were surface-sterilized in 0.5–1% sodium hypochlorite solution (NaOCl) for 30 s and washed three times using sterile distilled water. The tissue samples were blotted dry using sterile filter paper before being plated on $P_{10}$VP medium (Tsao and Ocana, 1969) containing 17 g/L corn meal agar (CMA), 0.4 mL/L pimaricin, 2 mL/L vancomycin and 100 mg powder pentachloronitrobenzene (PCNB). The plates were incubated for 2 days in the dark at 28±1.5°C. The growth of the hyphae was then cut and transferred onto V8 agar; 100 mL V8 vegetable juice; 1 g calcium carbonate; 16 g agar; and 900 mL distilled water to be incubated under the same conditions. Pure culture was viewed under a microscope for morphology characteristics. The morphology and molecular characteristics of *P. palmivora* were similar to the description of Latifah *et al*. (2018) and Bowman *et al*. (2007). For *in vitro* evaluation, the mycelium was used directly from the 7-day-old plate. As for the *in vivo* bioassay, the plates used were similar to the *in vitro* bioassay with the addition of zoospore preparation. This was done by pouring 5 mL of cold sterile distilled water onto the 14-day-old *P. palmivora* V8 plate. Zoospore was released with a sterile slide and counted using a hemocytometer to achieve 1 × $10^8$.

### *In vitro* screening of antifungal activities of *Morinda citrifolia*

*Morinda citrifolia*'s antifungal activity was evaluated in vitro using the poison agar technique described by Pham *et al*. (2021). Treatments were prepared using crude extracts from solvent methanol, acetone, ethyl acetate, and hexane at 20, 40, 60, 80, and 100 mg/mL concentrations. The extracts were diluted using the same solvents in the extraction procedure to obtain the correct concentrations. In a conical flask, 15 mL of autoclaved V8 agar was cooled to 40°C and mixed with treatments for 30 min. The mixture was poured into a sterile Petri dish to solidify. Petri dishes containing V8 agar with no added treatments were the negative control, while Petri dishes containing the fungicide Ridomil at 439 mg/mL were the positive control. The concentration of

Ridomil fungicide used in this study referred to the fungicide label for controlling stem canker disease on durian. A 5-mm mycelial plug from the leading edge of a 7-day-old *P. palmivora* culture was cut using a sterile cork borer and placed on treated plates. Plates were incubated in the dark at 28±1.5°C for 72 hr. Colony diameters were measured, and percent inhibition of radial growth (PIRG) was calculated according to Živković *et al*. (2010). The inhibition of zoospores or zoosporangium at 50% was estimated by effective concentration ($EC_{50}$) value calculated using Probit analysis.

$$\text{PIRG (\%)} = \frac{\text{R1 - R2}}{\text{R1}} \times 100$$

**Microscopic observation using a Scanning Electron Microscope (SEM)**

SEM was used to compare the mechanism of inhibition in treated and negative control plates. The analysis was conducted at the Microscopic Unit (EM), Institute of Bioscience, Universiti Putra Malaysia, by Heckman *et al*. (2007). Specimens were prepared by cutting a 1 cm × 1 cm × 0.2 cm block from an agar plate. The mycelia were fixed with glutaraldehyde for 5 hr at 4°C (2.5%). The fixed specimens were washed three times for ten min each with sodium cacodylate (0.1M) Buffer. After being post-fixed in osmium tetroxide (1%) for 2 hr at 4°C, the specimens were rewashed with sodium cacodylate (0.1 M) buffer for three changes of 10 min each. The specimens were then dehydrated in serially diluted acetone (35%, 50%, 75% & 95%) for 10 min each and 100% acetone for three 15-min changes. For 1.5 hr, the specimens were dried in a critical point dryer. The dried specimens were taped to stubs and coated with gold in a high vacuum chamber using an ion sputterer (Baltic SCD005). Finally, the specimens were examined using a Scanning Electron Microscope, JSM-IT100 InTouchScopeTM (Jeol Ltd., Tokyo, Japan).

***In vivo* bioassay**

*In vivo*, bioassays were performed on acetone and ethyl acetate plates that demonstrated the highest in vitro antifungal activities. The extracts were treated according to their $EC_{50}$ values. The treatment options were as follows: (i) the $EC_{50}$ value, (ii) half the $EC_{50}$ value, and (iii) double the $EC_{50}$ value. Acetone and ethyl acetate extracts were tested at 18, 36, 72 mg/mL, and 19, 38, and 76 mg/mL, respectively. The negative control was sterile distilled water, while the positive control was Ridomil fungicide at 439 mg/mL, as specified for *P. palmivora*-caused durian disease. Each treatment had four durian seedlings replicated. The experiment was conducted at Universiti Putra Malaysia's Agriculture Faculty's Rain Shelter 2B. Thirty-two healthy 6-month-old Mousang King (D197) durian seedlings were purchased from BBshoppe in MARDI Serdang, Selangor, Malaysia. A handheld pressure sprayer was used to apply 50 mL of treatment per seedling for each experimental unit. Zoospores were collected by soaking 14-day-old *P. palmivora* in sterile water using a handheld pressure sprayer and increasing the concentration to $1 \times 10^8$. Then, 24 hr after treatment, 200 uL zoospore suspensions were dropped onto wounded intact and attached durian leaves. Each durian seedling receives three inoculated leaves. Every three days for up to 15 days, the lesion size (mm) was measured using a digital Electronic Digital Solar Calliper. A single-point inoculation on the main stem of the durian seedlings was performed using modified procedures described by Mohamed Azni *et al*. (2019). The stem was inoculated seven days after the treatment onto the same durian seedling mentioned earlier. The main stem of a durian seedling was wounded with a 4-mm cork borer and then inoculated with a 4-mm diameter *P. palmivora* mycelial plug. The inoculation site was covered with moist cotton and wrapped in parafilm to maintain the humidity. The progression of the infection on the leaves was recorded every three days. After ten days, the destructive sampling of the stem was performed.

Disease incidence (DI) was evaluated 15 days after inoculation based on the equation from Tabet Zatla *et al*. (2017). The disease severity index (DSI) was determined using the equation from Yusoff *et al*. (2020) 15 days after inoculation. Disease severity was evaluated based on a 1 to 4 scale as described by Latifah *et al*. (2018). The following is the scale: 1 = healthy leaf (no visible symptoms); 2 = initial infection with a leaf lesion less than 5 mm long; 3 = lesion dispersed around the leaf with a lesion length of 5-10 mm; and 4 = lesion progressed to the entire leaf with discoloration of a lesion length of more than 10 mm).

$$\text{DI (\%)} = \frac{\text{Total number of infected sample}}{\text{Total number of sample assessed}} \times 100$$

$$\text{DSI (\%)} = \frac{\sum(\text{Number of samples in the scale} \times \text{Severity scale})}{\text{Total number of samples assessed} \times \text{Highest scale}} \times 100$$

## RESULTS

**Yield of crude extract**

Table 1 shows the percentage yield of crude extracts using methanol, acetone, ethyl acetate, and hexane. The extracts were dark green. Methanol crude extracts produced the highest percentage yield (11.07%), followed by ethyl acetate (3.43%), acetone (3.07%), and hexane (2.47%).

**Table 1.** Percentage yield of different crude extracts of *Morinda citrifolia* leaf

| Solvent extract | Weight of dried sample (g) | Weight of crude extract (g) | Yield (%) |
|---|---|---|---|
| Methanol | 100 | 11.07 | 11.07 |
| Acetone | 100 | 3.07 | 3.07 |
| Ethyl acetate | 100 | 3.43 | 3.43 |
| Hexane | 100 | 2.47 | 2.47 |

**Chemical constituent from *Morinda citrifolia* extracts by GC-MS analysis**

The most polar methanol extract of *M. citrifolia* leaves identified six chemical compounds contributing to the six peaks (Figure 1a). Squalene (peak five at 76.96 min retention time) and Hexadecanoic acid (peak two at 52.85 min retention time) were identified as the main chemical constituents, with an area of 41.5% and 15.1%, respectively. The acetone extract gave 12 peaks in the chromatogram (Figure 1b). The extract contains a mixture consisting mainly of squalene. The top five primary chemical compounds were identified as Squalene (Peak 7 at 77.08 min retention time), Hexadecanoic acid (Peak 3 at 53.11 min retention time), Linolenate (Peak 6 at 58.86 min retention time), Diacetone alcohol (Peak 1 at 6.26 min retention time) and Phytol (Peak 5 at 57.69 min retention time) with areas of 36.12%, 14.77%, 14.24%, 12.62% and 7.62% respectively. GCMS analysis of the crude extract of ethyl acetate led to the identification of 9 compounds (Figure 2a). The main constituents were Squalene (Peak 4 at 77.08 min retention time), Phytol (Peak 2 at 57.72 min retention time), and Alpha-Tocopherol (Peak 6 at 84.33 min retention time) with an area of 51.94%, 18.34%, and 11.00% respectively. The nonpolar hexane crude extract showed 17 peaks in the GC-MS chromatogram (Figure 2b & Table 2), identified according to their retention time. The compounds found comprised mainly of squalene at peak 12 with a retention time of 77.06, identified as a significant chemical constituent (51.3%), followed by Phytol (15.1% at 57.70 min retention time), Alpha-Tocopherol (7.52% at 84.31 min retention time), and Triacontane (4.55% at 83.46 min retention time). This result aligns with findings by Lima *et al*. (2019), where *M. citrifolia* leaves extracted with hexane had obtained squalene as the most significant component.

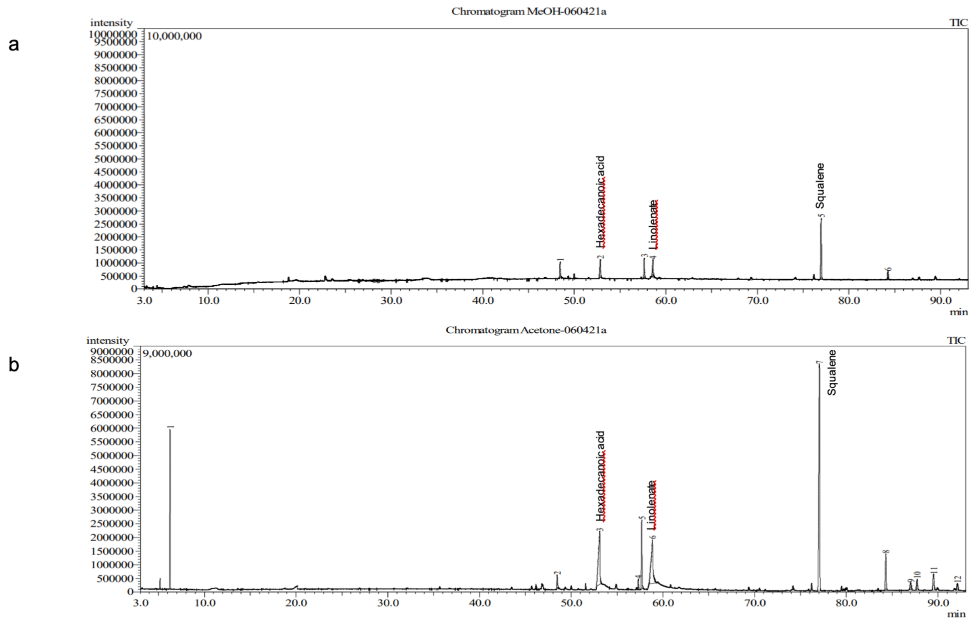


**Fig.1.** GC-MS chromatogram of *Morinda citrifolia* leaves extract using methanol (a) and acetone (b).

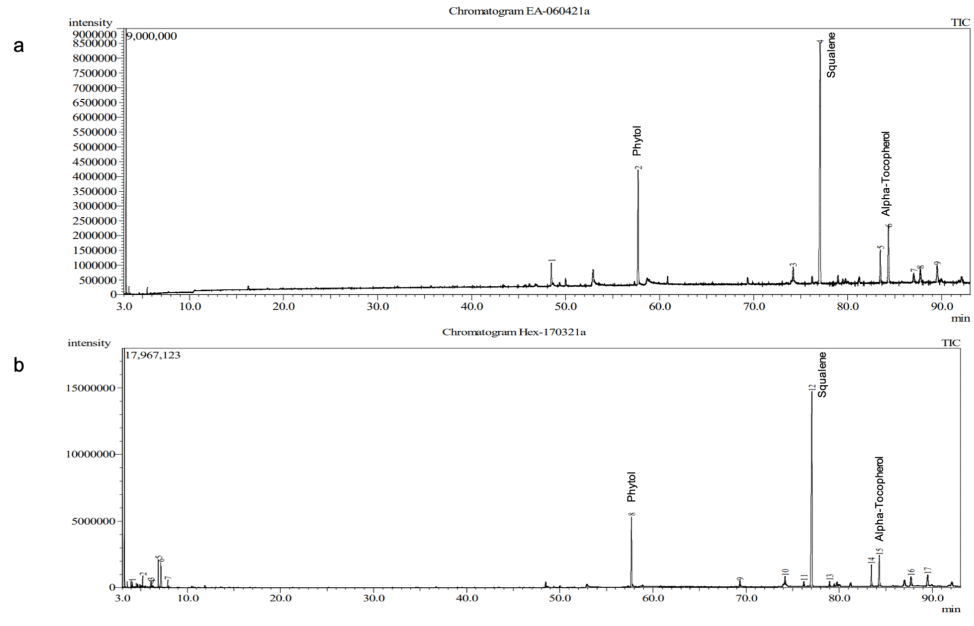


**Fig. 2.** GC-MS chromatogram of *Morinda citrifolia* leaves extract using ethyl acetate (a) and hexane (b).

**Table 2.** Chemical constituent of *Morinda citrifolia* leaf extracts

| Solvent | Peak | Compound | Molecular formula | Retention time (min) | Retention index | Area (%) | Chemical group |
|---|---|---|---|---|---|---|---|
| Methanol | 1 | Neophytadiene | $C_{20}H_{38}$ | 48.45 | 1836 | 10.06 | Diterpene |
| | 2 | Hexadecanoic acid | $C_{16}H_{32}O_2$ | 52.85 | 1963 | 15.05 | Fatty acid |
| | 3 | Phytol | $C_{20}H_{40}O$ | 57.64 | 2109 | 13.06 | Diterpene |
| | 4 | Linolenate | $C_{19}H_{32}O_2$ | 58.59 | 2139 | 14.38 | Fatty acid |
| | 5 | Squalene | $C_{30}H_{50}$ | 76.96 | 2815 | 41.50 | Triterpene |
| | 6 | Alpha-Tocopherol | $C_{29}H_{50}O_2$ | 84.25 | 3134 | 5.94 | Vitamin E |
| Acetone | 1 | Diacetone alcohol | $C_6H_{12}O_2$ | 6.26 | 843 | 12.62 | Ketones |
| | 2 | Neophytadiene | $C_{20}H_{38}$ | 48.47 | 1836 | 1.29 | Diterpene |
| | 3 | Hexadecanoic acid | $C_{16}H_{32}O_2$ | 53.11 | 1970 | 14.77 | Fatty acid |
| | 4 | 9,12,15-Octadecatrienoic acid | $C_{19}H_{32}O_2$ | 57.31 | 2098 | 1.04 | Fatty acid |
| | 5 | Phytol | $C_{20}H_{40}O$ | 57.69 | 2111 | 7.62 | Diterpene |
| | 6 | Linolenate | $C_{19}H_{32}O_2$ | 58.86 | 2148 | 14.24 | Fatty acid |
| | 7 | Squalene | $C_{30}H_{50}$ | 77.08 | 2820 | 36.12 | Triterpene |
| | 8 | Alpha-Tocopherol | $C_{29}H_{50}O_2$ | 84.31 | 3137 | 4.91 | Vitamin E |
| | 9 | Stigmast-5-en-3-ol | $C_{29}H_{50}O$ | 87.02 | 3247 | 1.30 | Phytosterol |
| | 10 | Stigmasterol | $C_{29}H_{48}O$ | 87.72 | 3273 | 1.82 | Stigmastane |
| | 11 | Stigmast-5-en-3-ol | $C_{29}H_{50}O$ | 89.51 | 3341 | 2.97 | Phytosterol |
| | 12 | 9,19-Cyclo-9.beta.-lanostane-3.beta.,25-diol | $C_{30}H_{52}O_2$ | 92.12 | 3440 | 1.31 | Triterpene |
| Ethyl acetate | 1 | Neophytadiene | $C_{20}H_{38}$ | 48.48 | 1837 | 3.19 | Diterpene |
| | 2 | Phytol | $C_{20}H_{40}O$ | 57.72 | 2111 | 18.34 | Diterpene |
| | 3 | Ethyl Linoleolate | $C_{20}H_{36}O_2$ | 74.19 | 2701 | 2.25 | Fatty acid |
| | 4 | Squalene | $C_{30}H_{50}$ | 77.08 | 2820 | 51.94 | Triterpene |
| | 5 | Triacontane | $C_{30}H_{62}$ | 83.47 | 3101 | 4.94 | Alkane |
| | 6 | Alpha-Tocopherol | $C_{29}H_{50}O_2$ | 84.33 | 3138 | 11.00 | Vitamin E |
| | 7 | Cholest-5-en-3-ol | $C_{27}H_{46}O$ | 87.02 | 3247 | 1.62 | Phytosterol |
| | 8 | Stigmasterol | $C_{29}H_{48}O$ | 87.73 | 3274 | 2.65 | Phytosterol |
| | 9 | Stigmast-5-en-3-ol | $C_{29}H_{50}O$ | 89.52 | 3342 | 4.07 | Phytosterol |
| Hexane | 1 | Cyclopentane | $C_7H_{14}$ | 4.08 | 755 | 0.27 | Alkane |
| | 2 | Octane | $C_8H_{18}$ | 5.21 | 810 | 1.00 | Alkane |
| | 3 | Cyclopentane | $C_8H_{16}$ | 6.08 | 838 | 0.46 | Alkane |
| | 4 | Cyclohexane | $C_8H_{16}$ | 6.18 | 841 | 0.38 | Alkene |
| | 5 | Ethylbenzene | $C_8H_{10}$ | 6.89 | 863 | 3.25 | Hydrocarbon |
| | 6 | Benzene | $C_8H_{10}$ | 7.16 | 872 | 4.00 | Hydrocarbon |
| | 7 | Benzene | $C_8H_{10}$ | 7.90 | 895 | 0.90 | Hydrocarbon |
| | 8 | Phytol | $C_{20}H_{40}O$ | 57.70 | 2111 | 15.10 | Diterpene |
| | 9 | Hexadecanoic acid | $C_{19}H_{38}O_4$ | 69.33 | 2512 | 1.20 | Fatty acid |
| | 10 | Methyl (Z)-5,11,14,17-eicosatetraenoate | $C_{21}H_{34}O_2$ | 74.18 | 2700 | 1.76 | Fatty acid |
| | 11 | 9-Octadecenamide | $C_{18}H_{35}NO$ | 76.19 | 2782 | 1.03 | Fatty acid |
| | 12 | Squalene | $C_{30}H_{50}$ | 77.06 | 2819 | 51.33 | Triterpene |
| | 13 | Nonacosane | $C_{29}H_{60}$ | 78.96 | 2899 | 0.89 | Hydrocarbon |
| | 14 | Triacontane | $C_{30}H_{62}$ | 83.46 | 3100 | 4.55 | Alkane |
| | 15 | Alpha-Tocopherol | $C_{29}H_{50}O_2$ | 84.30 | 3136 | 7.52 | Vitamin E |
| | 16 | Stigmasterol | $C_{29}H_{48}O$ | 87.70 | 3273 | 2.74 | Phytosterol |
| | 17 | gamma.-Sitosterol | $C_{29}H_{50}O$ | 89.49 | 3341 | 3.61 | Phytosterol |

A total of 44 compounds were identified from the *M. citrifolia* leaves extract obtained by the four solvents (Table 2). The identification of the compounds is arranged according to their elution order on silica capillary columns (Yusoff *et al.*, 2020). For all solvents, the dominant component is squalene. The second primary compound for methanol and acetone extracts was Hexadecanoic acid, followed by Linolenate. Both ethyl acetate and hexane extracts had Phytol compound as the second principal component, followed by Alpha-Tocopherol.

### *In vitro* screening of antifungal potential of *Morinda citrifolia*

Crude extractions of *M. citrifolia* using methanol, acetone, ethyl acetate, and hexane were tested against *P. palmivora* at seven different concentrations (Figure 3). As shown in Table 3, each type of crude extract had a different level of inhibition rate at different concentrations.

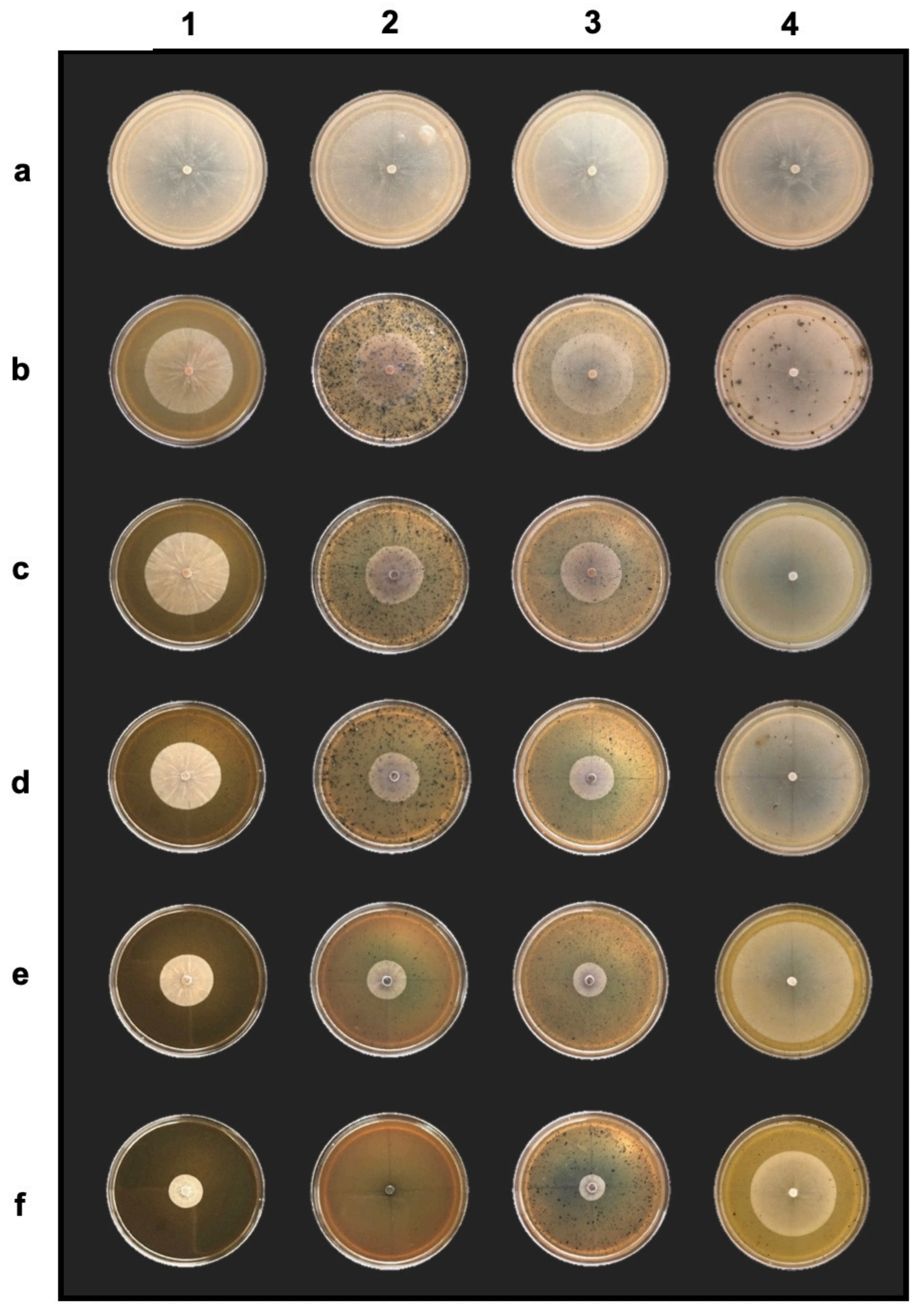


**Fig. 3.** *In vitro* antifungal activity of *Morinda citrifolia* leaf extracts against *Phytophthora palmivora* after three days of treatment. The numbers represent the solvents that were used. Methanol = 1, Acetone = 2, Ethyl acetate = 3 and Hexane = 4. The letters denote the concentration. a = 0 mg/mL; b = 20 mg/mL; c = 40 mg/mL; d = 60 mg/mL; e = 80 mg/mL; f = 100 mg/mL; f = 100 mg/mL.

**Table 3.** The effect of crude *Morinda citrifolia* extraction using methanol, acetone, ethyl acetate, and hexane at different concentrations on the PIRG of *Phytophthora palmivora* mycelial growth 3 days after incubation

| Concentration (mg/mL) | PIRG | | | |
|---|---|---|---|---|
| | Methanol | Acetone | Ethyl acetate | Hexane |
| 0 | 0.00 ± 0.00 [g] | 0.00 ± 0.00 [f] | 0.00 ± 0.00 [g] | 0.00 ± 0.00 [c] |
| 20 | 24.82 ± 0.61 [f] | 36.38 ± 0.40 [e] | 30.90 ± 0.97 [f] | 0.00 ± 0.00 [c] |
| 40 | 27.88 ± 0.39 [e] | 49.50 ± 0.52 [d] | 51.36 ± 0.98 [e] | 0.00 ± 0.00 [c] |
| 60 | 40.26 ± 0.52 [d] | 58.52 ± 1.85 [c] | 64.12 ± 0.81 [d] | 0.00 ± 0.00 [c] |
| 80 | 55.92 ± 1.12 [c] | 68.80 ± 1.78 [b] | 69.24 ± 0.90 [c] | 0.00 ± 0.00 [c] |
| 100 | 69.08 ± 0.78 [b] | 92.80 ± 0.00 [a] | 80.50 ± 1.52 [b] | 22.53 ± 4.87 [b] |
| Ridomil at 439 mg/mL | 92.80 ± 0.00 [a] | 92.80 ± 0.00 [a] | 92.80 ± 0.00 [a] | 92.80 ± 0.00 [a] |

PIRG is expressed as mean ± SE (standard error). Means with different letters within the same column are significantly different at $p < 0.05$ using Tukey's Studentized Range (HSD) Test.

Mycelial growth on V8 agar plates treated with Ridomil fungicide (positive control) had the highest PIRG of 92.8% for the entire crude extract and exhibited 100% inhibition in mycelium growth. The antifungal activity of crude extract acetone at 100 mg/mL was not significantly different from Ridomil, indicating that crude extract treatment had the most potent antifungal activity. Inhibition of *P. palmivora* mycelia growth was also observed in a concentration-dependent manner for crude extracts of methanol, acetone, and ethyl acetate (Figure 4).

The $EC_{50}$ for treatments using crude methanol, acetone, and ethyl acetate extracts is 66.52, 36.12, and 38.10 mg/mL, as shown in Table 4. However, the Probit analysis application could not compute the $EC_{50}$ for crude hexane extracts due to insufficient PIRG data. Crude extracts of acetone and ethyl acetate had the lowest $EC_{50}$ values. In a study by Choi (2017), crude extracts of *Dipsacur asper* extracted using acetone and ethyl acetate had the highest inhibition, suppressing the development of *Phytophthora infestans*.

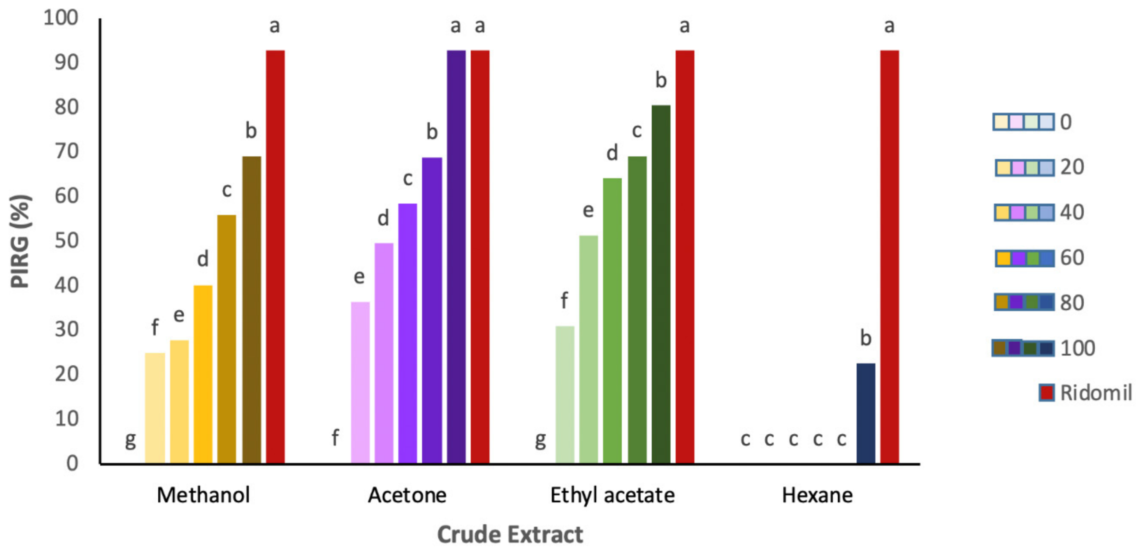


**Fig. 4.** Effect of crude extraction of Morinda citrifolia at different concentrations on the PIRG of *Phytophthora palmivora* after 3 days incubation. Means with the same letter within each crude extraction are not significantly different at p≤ 0.05 using Tukey's Studentized Range (HSD) Test.

**Table 4.** The mean effective concentration ($EC_{50}$) that inhibited mycelial growth by 50% for *Phytophthora palmivora* determined using Probit analysis

| Crude extract | $EC_{50}$ (mg/mL) | 95% Confidence Limits | |
|---|---|---|---|
| | | Lower | Upper |
| Methanol | 66.52 | 40.41 | 225.16 |
| Acetone | 36.12 | 0.25 | 63.60 |
| Ethyl acetate | 38.10 | 31.47 | 44.23 |

**Effect of *Morinda citrifolia* leaf crude extract on the mycelial morphology of *Phytophthora palmivora***

Microscopic observation on experimental plates using a scanning electron microscope helps obtain detailed information about mycelium morphology and interactions. Based on the results, crude extracted using acetone at 60mg/mL altered the morphology of *P. palmivora*. Figures 5c and d show SEM images of this fungus's mycelia, which were deformed, clumped, and had excessive branching. Furthermore, the mycelia surface had numerous hyphal tops, whereas the untreated plates in Figures 5a and 5b had a smooth shape and were evenly distributed.

**In vivo antifungal activities of *Morinda citrifolia* crude extract against *Phytophthora palmivora***

Acetone and ethyl acetate extracts were tested in vivo for antifungal activity against *P. palmivora* on wounded intact and attached durian leaves because they had the lowest $EC_{50}$ values for in vitro bioassay. The in vivo bioassay revealed that 100% of the leaves inoculated with *P. palmivora* developed symptoms (negative control treatment) (Table 5). Ethyl acetate treatment at 19 mg/mL reduced disease severity to 52.08%. Meanwhile, disease incidence ranged from 0 to 41.67% for the other treatments.

Table 5 shows leaf samples in the negative control treatment had a disease severity index of 56.25% on a scale of 2 to 3. As shown in Figures 6a, 6f, 6g, and 6h, the leaf samples exhibited symptoms of water-soaking lesions with a yellow halo discoloration around the lesion. *Morinda citrifolia* leaves treated with acetone (18, 36 & 72 mg/mL) and ethyl acetate (38 & 76 mg/mL) showed a significantly lower percentage of disease severity index when compared to the negative control. These treatments showed similar disease reduction using the commercial fungicide Ridomil. Thus, *M. citrifolia* leaf extract treatments could be an alternative fungicide, acting as a natural fungicide. Inoculation of *P. palmivora* onto the leaves of healthy durian seedlings resulted in water-soaking lesions three days later, as shown in Table 6. The developed lesions were limited to the inoculation site. *Phytophthora palmivora* water-soaking lesions were mainly small (0.19 - 4.03 mm) on day 15, as shown in Figure 6. The severity of the infection is affected by the rate at which the inoculum spreads (Drenth & Guest, 2004). After 15 days of inoculation, the lesion size of the control negative treatments measured 4.03 mm. This result was comparable to ethyl acetate treatment at 19 mg/mL with a lesion growth of 3.08 mm and no antifungal properties. At day 15, there was no disease development in the control-positive treatment, which used a commercial fungicide (Ridomil). Acetone treatment at 36 and 72 mg/mL effectively controlled *P. palmivora*, with lesion development of only 0.19 mm and 0.00 mm, respectively.

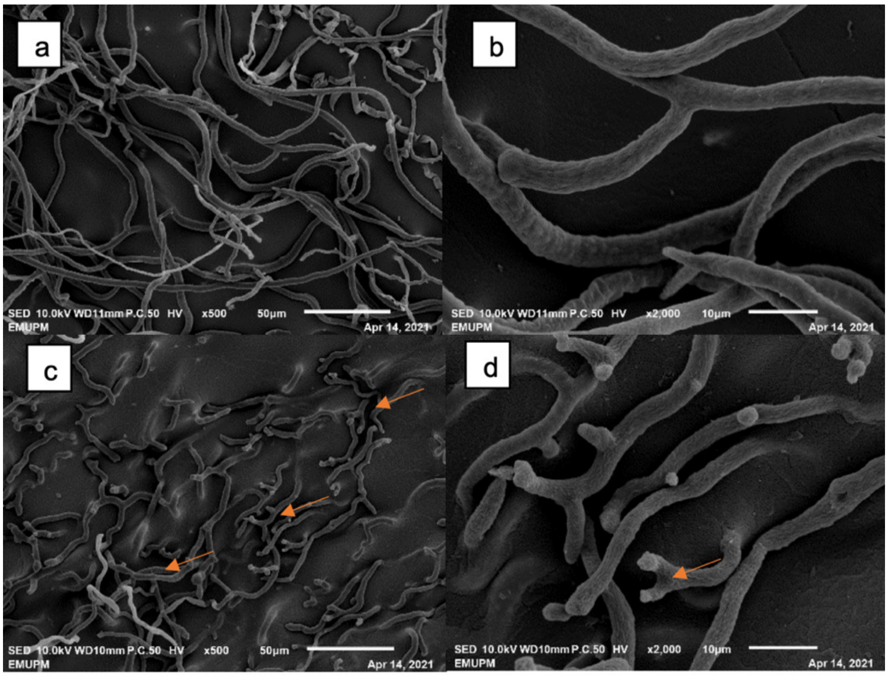


**Fig. 5.** SEM analysis of the effects of acetone crude extract on *Phytophthora palmivora* mycelial morphology at 60 mg/mL. Smooth surface, uniform and intact structure for the control negative plate at x500 (a) and x2000 magnification (b); Mycelial ruptured and deformed at x500 (c) and x2000 magnification (d).

**Table 5.** The incidence and severity of *Phytophthora palmivora* (mm) disease on treated durian seedlings 15 days after inoculation in a glasshouse

| Treatment | | Disease incidence (%) | Disease severity index (%) |
|---|---|---|---|
| T1 | Negative control (SDW) | 100.00 ± 0.00 a | 56.25 ± 2.08 a |
| T2 | Positive control (Ridomil) | 0.00 ± 0.00 b | 25.00 ± 0.00 b |
| T3 | Acetone 18 mg/mL | 25.00 ± 15.96 b | 31.25 ± 3.99 b |
| T4 | Acetone 36 mg/mL | 8.33 ± 8.33 b | 27.09 ± 2.09 b |
| T5 | Acetone 72 mg/mL | 0.00 ± 0.00 b | 25.00 ± 0.00 b |
| T6 | Ethyl acetate 19 mg/mL | 83.33 ± 9.62 a | 52.08 ± 6.25 a |
| T7 | Ethyl acetate 38 mg/mL | 41.67 ± 21.52 b | 37.50 ± 7.22 b |
| T8 | Ethyl acetate 76 mg/mL | 25.00 ± 13.61 b | 31.25 ± 3.99 b |

Disease incidence and disease severity index are expressed as mean ± SE (standard error). Means with different letters within the same column are significantly different at *p*< 0.05 using Tukey's Studentized Range (HSD) Test. SDW = sterile distilled water

**Table 6.** Size of the lesion caused by *Phytophthora palmivora* on durian leaves

| Treatment | | Lesion size (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Day 0 | Day 3 | Day 6 | Day 9 | Day 12 | Day 15 |
| T1 | Control negative (SDW) | 0.00 ± 0 a | 2.36 ± 0.31 a | 3.42 ± 0.44 a | 3.60 ± 0.45 a | 3.78 ± 0.46 a | 4.03 ± 0.44 a |
| T2 | Control positive (Ridomil 439 mg/mL) | 0.00 ± 0 a | 0.00 ± 0 d | 0.00 ± 0 c | 0.00 ± 0 d | 0.00 ± 0 d | 0.00 ± 0 c |
| T3 | Acetone 18 mg/mL | 0.00 ± 0 a | 0.31 ± 0.17 cd | 0.40 ± 0.21 c | 0.49 ± 0.26 cd | 0.50 ± 0.27 cd | 0.51 ± 0.27 bc |
| T4 | Acetone 36 mg/mL | 0.00 ± 0 a | 0.12 ± 0.17 d | 0.18 ± 0.18 c | 0.19 ± 0.19 d | 0.19 ± 0.19 d | 0.19 ± 0.19 c |
| T5 | Acetone 72 mg/mL | 0.00 ± 0 a | 0.00 ± 0 d | 0.00 ± 0 c | 0.00 ± 0 d | 0.00 ± 0 d | 0.00 ± 0 c |
| T6 | Ethyl acetate 19 mg/mL | 0.00 ± 0 a | 1.45 ± 0.47 b | 2.21 ± 0.57 b | 2.46 ± 0.64 b | 2.61 ± 0.67 b | 3.08 ± 0.63 a |
| T7 | Ethyl acetate 38 mg/mL | 0.00 ± 0 a | 0.99 ± 0.32 bc | 1.52 ± 0.48 b | 1.53 ± 0.60 bc | 1.58 ± 0.62 bc | 1.64 ± 0.63 b |
| T8 | Ethyl acetate 76 mg/mL | 0.00 ± 0 a | 0.31 ± 0.26 cd | 0.44 ± 0.30 c | 0.50 ± 0.34 cd | 0.54 ± 0.37 cd | 0.70 ± 0.39 bc |
| | | - | ** | ** | ** | ** | ** |

Lesion size (mm) on durian leaves is expressed as mean ± SE (standard error). Means with different letters within the same column are significantly different at *p*< 0.05 using Tukey's Studentized Range (HSD) Test. SDW = sterile distilled water

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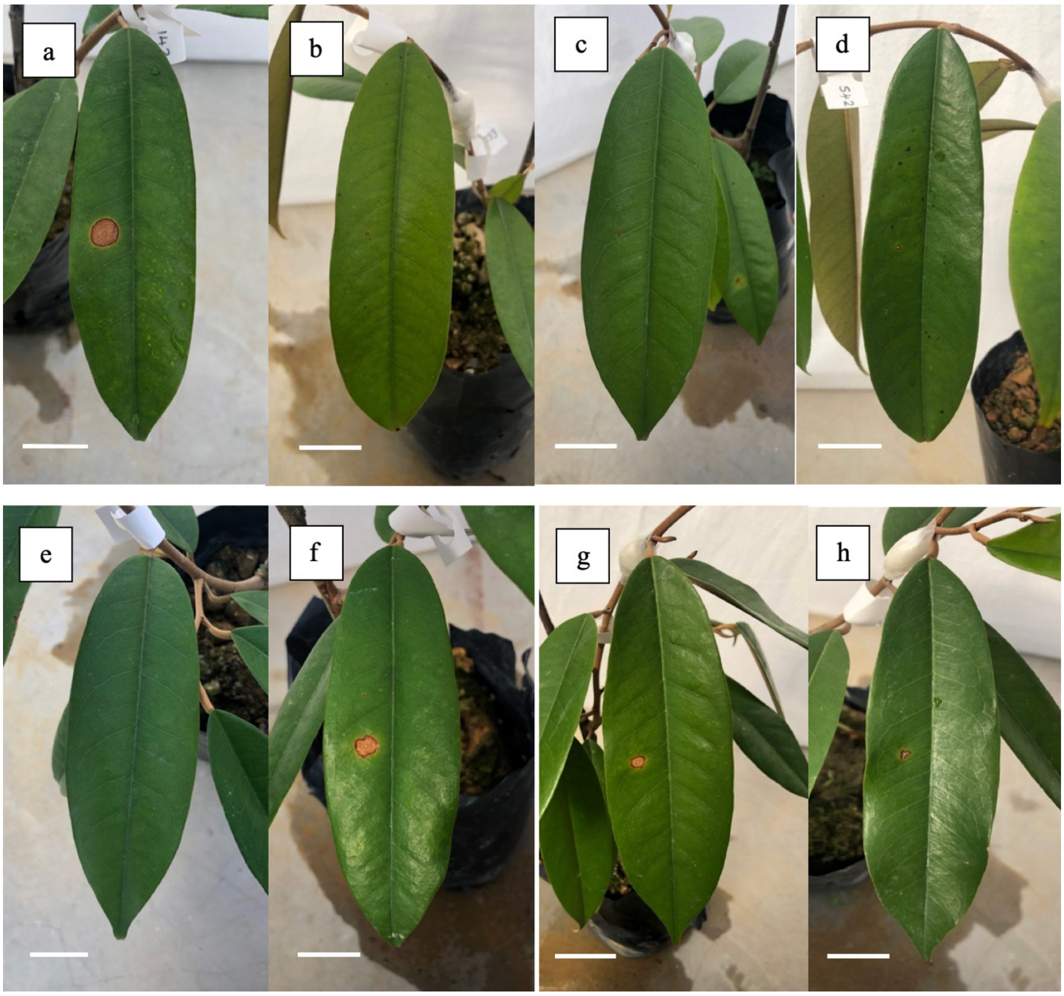


**Fig. 6.** *In vivo* test via artificial inoculation on durian leaves 15 days after inoculation. Inoculated leaves showed dark to light brown water-soaking lesions around the inoculation site. Control negative (a), Acetone 18 mg/mL (b), Acetone 36 mg/mL (c), Acetone 72 mg/mL (d), Control positive (Ridomil fungicide) (e), Ethyl acetate 19 mg/mL (f), Ethyl acetate 38 mg/mL (g) and Ethyl acetate 76 mg/mL (h). Scale bar 2 cm.

Inoculation on the main stem resulted in *P. palmivora* infection, with brown water-soaking discoloration at areas of mycelium insertion. Symptoms appeared seven days after inoculation. On day 10, the seedlings's outer bark layer was removed during destruction sampling to reveal lesion progression, as shown in Figure 7. According to Table 7, the control negative treatment on durian seedlings demonstrated significantly similar lesion progression to acetone treatment at 18 mg/mL. Both treatments increased pathogen colonization into epidermal tissues compared to *M. citrifolia* extracts of acetone 36 and 72 mg/mL and ethyl acetate 38 and 76 mg/mL. At the same time, Ridomil fungicide was used for positive control treatments.

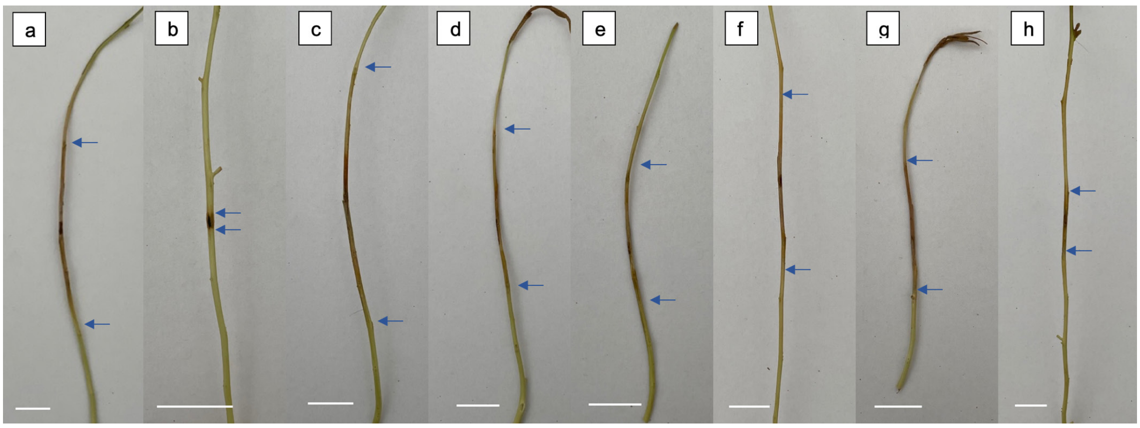


**Fig.7.** In vivo test via artificial inoculation on durian stem using destructive sampling. Symptoms developed on wounded stems caused by Phytophthora palmivora are indicated by dark brown necrotic lesions after 10 days of inoculation. Control negative (a), Control positive (Ridomil) (b), Acetone 18 mg/mL (c), Acetone 36 mg/mL (d), Acetone 72 mg/mL (e), Ethyl acetate 19 mg/mL (f), Ethyl acetate 38 mg/mL (g) and Ethyl acetate 76 mg/mL (h). Scale bar = 2 cm

**Table 7.** Lesion growth of *Phytophthora palmivora* (mm) on durian stem after 7 days of inoculation at glasshouse

| Treatment | | Lesion diameter (mm) developed on the stem |
|---|---|---|
| T1 | Control negative (SDW) | 104.81 ± 23.96 [a] |
| T2 | Control positive (Ridomil) | 9.49 ± 4.67 [d] |
| T3 | Acetone 18 mg/mL | 107.89 ± 9.60 [a] |
| T4 | Acetone 36 mg/mL | 58.62 ± 8.02 [bc] |
| T5 | Acetone 72 mg/mL | 52.08 ± 8.08 [bc] |
| T6 | Ethyl acetate 19 mg/mL | 85.43 ± 4.94 [ab] |
| T7 | Ethyl acetate 38 mg/mL | 56.21 ± 11.43 [bc] |
| T8 | Ethyl acetate 76 mg/mL | 30.24 ± 3.32 [cd] |

Lesion diameter (mm) developed on the stem is expressed as mean ± SE (standard error). Means with different letters are significantly different at $p< 0.05$ using Tukey's Studentized Range (HSD) Test. SDW = sterile distilled water

## DISCUSSION

The differences in yield percentage between the four crude extracts are due to the different solvents used for extraction, which may affect the solubility of extractable components due to the plant's varied chemical composition (Hsu *et al*., 2006). According to Turkmen *et al*. (2006) and McDonald *et al*. (2001), solvent is one of the most important parameters influencing yield percentage. This result is because differences in the polarity of the extraction solvents can result in a wide range of bioactive compound levels in the extract (Truong *et al*., 2019). Methanolic extract had a higher extraction yield than acetone, ethyl acetate, and hexane extracts, indicating that highly polar solvents have a higher extraction efficiency. In this study, the plant material *M. citrifolia* contains a higher yield percentage of polar compounds soluble in highly polar solvents such as methanol. This result is consistent with the findings of Jayaraman *et al*. (2008), who reported that the extraction yields obtained from *M. citrifolia* extracts were obtained in the following order: methanol > ethyl acetate > hexane. As a result, methanol with a relatively strong polarity has the best extraction efficiency (Zhu *et al*., 2020). Out of the four solvents used, extracts using hexane, a non-polar solvent, had the highest yield of 17 total compounds. This result might be because the compound extraction yield was affected not only by the solvent types but also by the chemical and physical structure of the plant samples (Zhu *et al*., 2020). The visible difference between the four solvents is that the presence of hydrocarbons is higher in hexane extract. The non-polarity of the solvent justifies this. According to Suchinina *et al*. (2011), the polarity and viscosity of the extraction solvents affect the composition and concentrations of the specific compounds in the plant material used. Thus, each solvent could extract different compounds, leading to different products and indicating different applications for the extracts (Lima *et al*., 2019).

A total of 44 compounds were found in the GC-MS analysis of *M. citrifolia* leaves crude extract using methanol, acetone, ethyl acetate, and hexane solvents. Squalene is reported to be the most abundant constituent of each crude extract. Similar findings by Lima *et al*. (2019) on leaves and fruit pulp of *M. citrifolia* also found squalene to be the most prominent compound in both plant samples. Squalene belongs to the chemical class triterpenes, which is a hyponym of terpene and plays a crucial role as an antioxidant (Micera *et al*., 2020), anticancer, antibacterial, and antifungal (Reddy & Couvreur, 2009). Squalene at a high concentration can disturb the structure of cellular membranes and thereby interfere with essential membrane functions (Gnamusch *et al*., 1992). Terpene compounds associated with antifungal activity against *Phytophthora* spp. In a study done by Camele *et al*. (2012), three Mediterranean aromatic plants (*Verbena officinalis, Thymus vulgaris, and Origanum vulgare*) consisting of mainly terpenes had a 100% inhibitory effect on *Phytophthora citrophthora*.

Hexadecanoic acid found in *M. citrifolia* leaves had a high area percentage from solvents of methanol and acetone. Hexadecanoic acid is a fatty acid with vital biological roles, such as being involved in β-oxidation for energy, cell membrane composition, and stress tolerance (Pang *et al*., 2015). As a result, genes involved in fatty acid metabolism may have essential biological functions such as regulating the growth and pathogenicity of the *Phytophthora* pathogen. A high level of hexadecanoic acid contributes to a decreased membrane fluidity and permeabilization. Thus, disrupting the normal function of the cell wall of *Phytophthora* (Liu *et al*., 2020)

Linolenate is a form of triglyceride ester of linolenic acid, a naturally occurring fatty acid. These fatty acids have excellent antioxidant and radical scavenging activity (Erasto *et al*., 2007). Linoleic acid is a substrate for the production of oxylipins thought to be involved in regulating fungal development (Herman, 1998). In 2004, Walters *et al*. tested linolenic acid against plant pathogenic fungi, *Rhizoctonia solani*, *Pythium ultimum*, *Pyrenophora avenae*, and *Crinipellis perniciosa,* and it showed that the biomass production of all tested pathogens reduced significantly. This finding is consistent with the findings by Kumar *et al*. (2013), *Ceriops decandra* leaves extracts had 8.62% linolenic and showed antifungal solid activity against *Pythium aphanidermatum*, *Rhizoctonia solani*, *Pyricularia oryzae*, *Curvularia oryzae*, and *Fusarium oxysporum*. Both studies used *Pythium* spp., an oomycete like *Phytophthora* spp. as test subjects in the mentioned screening. Hence, extracts containing this compound have the potential antifungal activity against *P. palmivora*.

Phytol belongs to the diterpene family and is a component that is relevant to the crude extract of *M. citrifolia*. Plant extract-derived diterpenoids reduce the number of fungal mitochondria, which could impact reactive oxygen species and ATP production (Haque *et al*., 2016). In a study on combating *Ganoderma boninense*, a disease in oil palm, a phytol component extracted from seaweed was highlighted to have remarkable potential as an antifungal property (Aziz *et al*., 2019). Phytol acts as an antimicrobial by leaking K+ ions from cells, directly disrupting the membrane tissue (Inoue *et al*., 2005). As a result, the fungus's mitochondria become dysfunctional. Masi and Evidente (2021) reported that a diterpene compound isolated from *Diplodia cupressi* completely inhibited the mycelial growth of *Phytophthora cambivora*.

Alpha-tocopherol is a naturally sourced vitamin E that is a free radical scavenger, preventing lipid peroxidation in biological systems (Rani *et al*., 2007). Due to this role, it can cause cell membrane perturbations, resulting in damage to essential components for the reliability of the membrane, thereby allowing an increase in permeability (Andrade *et al*., 2014). According to reports, tocopherols are critical in protecting against pathogens (Ghimire *et al*., 2017). The use of isomers of vitamin E was reported to distort the functions of bacteria *Staphylococcus aureus, Pseudomonas eaeruginosa*, and *Escherichia coli* (Andrade *et al*., 2014). In a study by Ghimire *et al*. (2017), the transgenic leaf extract of *Codonopsis lanceolate* had increased antimicrobial activity with the increase of Alpha-tocopherol content. For oomycetes specifically, reports of *Dittrichia viscosa* (L.) having high content of tocopherols (Rhimi *et al*., 2018) were able to control foliar disease caused by *Phytophthora infestans* (Wang *et al*., 2004).

Different solvents will extract a variety of compounds with varying polarities. Methanol solvent was used to extract the chemical groups of flavonoids, polyphenols, and glycosides. (Rauha *et al*., 2000). Acetone is an excellent solvent for extracting phenolics, flavonoids, alkaloids, and terpenoids (Truong *et al*., 2019). Hexane extracts semi-polar and nonpolar compounds like fatty acids, terpenoids, and fats (Tiwari *et al*., 2011). Both polar and nonpolar plant extract components contribute to antifungal activity against *P. palmivora*. Jayaraman *et al*. (2008) found that the plant's chemical makeup may account for the varying antifungal effectiveness of *M. citrifolia* leaf extract when employing different solvents.

Mycelial growth of *Phytophthora palmivora* was reduced significantly by crude extracts of methanol, acetone, and ethyl acetate in a concentration-dependent manner (Figure 4). This result is consistent with the findings of John *et al*. (2016) and Krzyko-upicka *et al*. (2019), who discovered that increasing the crude extract concentration increases the level of antifungal compounds. Such reduction in mycelia growth may be related to the enzymatic activity of the extract, which disrupts cell wall structure and blocks membrane synthesis (Li *et al*., 2014). The differences in antifungal activity of *M. citrifolia* leaf extracts extracted with different solvents could be attributed to differences in chemical composition (Ma *et al*., 2019). Studies have shown that extracts' secondary metabolites (such as phenolics, flavonoids, and terpenoids) play critical roles in antimicrobial action against various pathogenic microorganisms (de Araujo Gomes *et al*., 2020). The crude hexane extracts were ineffective in controlling *P. palmivora*, possibly due to the crude's lack of antifungal compounds. This result is consistent with an antifungal assay in which crude extracts of *M. citrifolia* fruit against nine pathogenic fungal strains in hexane solvent had the lowest percentage of inhibition (Jayaraman *et al*. 2008).

For *in vitro* bioassay evaluation, *M. citrifolia* leaves crude extracted with acetone and ethyl acetate had the best $EC_{50}$ values of 36.12 and 38.10 mg/mL, respectively, where the treatments have altered the morphology and restricted the growth of *P. palmivora* through microscopic observation using a scanning electron microscope, the fungus' morphological change is directly related to the secondary metabolites produced by the plant extract, which served as an antifungal agent to prevent fungal growth. There is a direct correlation between the morphological alteration of the fungus and the secondary metabolites generated by the plant extract, which functioned as an antifungal agent to restrict fungal growth (Pusztahelyi *et al*., 2015).

According to the *in vivo* bioassay, the negative control treatment developed 100% canker symptoms, while the other treatments had a disease incidence ranging from 0 to 41.67%. This result shows that the specific intracellular receptors are essential for the expression of the antifungal activity of the crude extract. These chemical constituents can detect sites of action in the pathogen. They would, therefore, bind on their receptors, thus inducing responses of fungicidal effects such as suppression of general metabolism or alteration of the fungus membrane and inhibition of respiration (Essomé *et al*., 2022). In this study, positive control using Ridomil commercial fungicide had 0% disease incidence, as did Acetone treatment at 72 mg/mL. This finding also demonstrates that the tested crude extract treatments have a bright future in developing a biological control product.

A study by Freeman and Beattie (2008) discovered that no infection was obtained at the inoculation site without wounding because the plant's outer barriers were still intact; hence, wounding will expedite disease infection. Unlike true fungi, oomycetes lack the melanin and septin necessary for producing appressoria. Instead, *P. palmivora* infiltrates its hosts by hyphal slicing through the host surface at an oblique angle (Bronkhorst *et al*., 2021). Therefore, in durian fields, wounds are thought to play a role in the natural infection of *P. palmivora* (Mohamed Azni *et al*., 2019).

## CONCLUSION

The two highest acetone and ethyl acetate concentrations resulted in significantly lower lesion development on the durian stem. The concentration of antifungal components in the plant extract was adequate for controlling the *P. palmivora* pathogen. Nevertheless, it is essential to note that the bioactivity of plant extracts can be attributed to the main constituents alone or in combination.

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## ETHICAL STATEMENT

Not applicable.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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## ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

**Factors affecting the durian production of farmers in the eastern region of Thailand / Thongkaew, S., Jatuporn, C., Sukprasert, P., Rueangrit, P., & Tongchure, S.**

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# FACTORS AFFECTING THE DURIAN PRODUCTION OF FARMERS IN THE EASTERN REGION OF THAILAND

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**ABSTRACT**

Thailand is the largest durian producer and exporter in the world market. In addition, durian is the most important fruit crop in Thailand because it can generate a higher income from exports with a value of approximately 45,349-million-baht, equivalent to an export quantity of 653,564 tons in 2019. The objective is to analyze the factors affecting the durian production of farmers in the eastern region of Thailand, namely Chanthaburi, Rayong, and Trad Provinces. The sample of 395 durian farmers underwent observation using simple random sampling via the questionnaire approach. The statistics consisted of mean, percentage, and multiple regression. The findings revealed that the positive factors affecting the durian production of farmers in the eastern region of Thailand are the experience of the farmers in growing durian, the size of the workforce, the planted area of durian, the number of durian trees, and the number of durian trees per planted area, while the negative factors affecting the durian production of farmers in the eastern region of Thailand are the age of the farmers and the cultivation of organic durian. The results will be beneficial to farmers, government, and related stakeholders, who can further apply these findings to enhance the efficiency of durian production to be the quality durian for domestic and foreign consumers.

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## INTRODUCTION

Fruit is an important agricultural product in Thailand. Since the country has a tropical climate, there are various high-quality fruits grown throughout the year, making Thai fruit very popular on both the domestic and international markets. Generally, fruit is an economic crop that has a higher value than rice farming and other field crops such as cassava, sugarcane, maize, etc. In addition, Thailand has a suitable area for cultivating tropical fruits, which are famous such as durian, longan, mangosteen, and rambutan for both domestic and international markets. Therefore, Thailand can export a lot of fruit and generate revenue for the country and domestic farmers. In 2019, Thailand's exports as a whole were worth 113,118 million baht; fresh fruit exports were worth 90,310 million baht or 79.84% (Ministry of Commerce, 2020a). Nowadays, the fruit consumption demand is predicted to rise due to the higher population, as well as behavioral changes in consumption resulting from higher incomes that lead people to consume fruit, which is not the main course, more than before. Durian, a tropical fruit, has its origin from Borneo Island, Brunei, Malaysia, and Indonesia. In Thailand, durian spread out to the southern part of Thailand from Malaysia in 1687 (Somsri, 2008). In many countries, durian was called the "King of Fruit" because of its excellent flavor, surprising smell, and marketing power. Today, Thailand is the biggest durian producer and exporter in the world. Thailand has the potential to export durian to the world market the most, more than 95% of the global export volume, followed by Malaysia (4%) and the others (<1%) (Durian Harvests, 2021). The durian season starts in March every year and ends in September. According to the records in 2019, 143,455 farming households planted durian on 937,607 rai (6.25 rai = 1 hectare). The outcome was up to 1,017,097 tons, 270,441 tons for domestic consumption, and 653,564 tons for international exports which were worth 45,349 million baht. Of these exports, 97.85% of fresh durian was exported to three countries: China, Vietnam, and Hong Kong. The majority was exported to China at 375,202 tons or 26,332 million baht, followed by Vietnam with 164,380 tons or 11,090 million baht, and Hong Kong at 99,932 tons or 6,990 million baht. Moreover, durian was transformed to make it easier to export; 25,987 tons of durian were transformed into a frozen product worth 5,371 million baht, 1,211 tons of durian were transformed to durian paste worth 132 million baht, and 215 tons of durian to freeze-dried durian worth 200 million baht. These products were exported to different countries: China, the United States, Russia, and Australia (Office of Agricultural Economics, 2020a, 2020c; Ministry of Commerce, 2020b). The main competitors are Vietnam and Malaysia since Vietnam has planted more and more durian every year, especially the Monthong type, which is the same species as Thailand. Even though Vietnamese Monthong durian has lower quality than the Thai species, Vietnam is now improving the previous species. On the other hand, Malaysia has started to negotiate with the Chinese government about fresh durian exports apart from frozen products. Therefore, the production of durian for export from these competing countries may cause Thailand to lose market share. In addition, this may affect the price and cause production volatility, although both current demands for durian and durian prices are likely to increase.

Most of the durian growing areas of Thailand are in the eastern and southern regions. The durian season in the eastern region each year starts from April to June, accounting for almost half of the country's production throughout the year. While the durian season for the southern regions each year is from July to September, it accounts for 42% of the country's production throughout the year. Hence, the eastern part of Thailand is the main cultivated area in Thailand, especially Chanthaburi, Rayong, and Trad Provinces which are mountainous and forested. The central part has mountainous plains, and the lower part has a river basin and coastal plain. The climate of the upper part of this region, Rayong Province, is a tropical savanna climate (Aw) and the lower part of this region, Chanthaburi Province, has a tropical monsoon climate (Am) with heavy rainfall. Within this region, Trad Province has the highest rainfall. In 2019, fruits that were significantly important to this region were durian, longan, mangosteen, and rambutan, with cultivated areas of 339,362 rai, 217,579 rai, 198,833 rai, and 113,004 rai, respectively. Planting durian in this region were 36,982 farmers on a cultivation area of 281,330 rai to gain 495,643 tons of durian. In this region, durian sales start in April and end in July every year. Over 50% of durian will be sold on the market in April and end in June. The famous durian species on the market are Monthong, Chanee, Kradum, and Puangmanee. The factors that influence consumers' decisions to buy durian in the eastern part of Thailand are consumer income, size of durian, consumers' satisfaction with the durian price, and the willingness of consumers to pay more for quality durian (Thongkaew *et al.*, 2017). In addition, the factors that influence entrepreneurs' decisions to buy durian for export include the age of entrepreneurs, methods of business operation, and entrepreneurs' satisfaction in terms of price and distribution channels (Thongkaew, 2018). These are the reasons for the study of factors that affect durian production in the eastern region of Thailand to provide farmers with the fundamental knowledge to improve durian production and respond to the domestic and international market demands effectively.

Over the past ten years, the demand for durian has been steadily increased following the reports of the Office of Agricultural Economics (2020c, 2020b) and the findings of Rueangrit *et al.* (2020). As a result, the durian price rose in line with the supply and demand mechanism; therefore, it was an incentive for domestic farmers to start growing durian in various areas across the country. This study will be particularly useful for durian farmers to be used as a guideline for the most efficient durian production, which will benefit exporters to obtain quality durian and meet the needs of the trading partners. The purpose of this study is to analyze the factors affecting durian production in the eastern region of Thailand as it is the most important durian growing area in the country due to the production efficiency both in quantity and quality of the durian fruits at a high level by comparing to other domestic and foreign production areas.

The results of this study will be the practical guidelines to farmers for producing quality durian in other production regions, that now farmers in Thailand have popularly grown durian throughout the country. In addition, the government and agricultural extension agencies can be used as information to create training course programs to support the durian production of farmers in the country as well as to prepare for further policy implications to enhance the efficiency of durian production in Thailand.

**LITERATURE REVIEW**

After all this time, many farmers are very interested in planting durian since durian can bring a high income and respond to consumer demand in the domestic and international markets. However, they still face problems in the production process. (1) Farmer problems: they still use the old techniques to produce durian, which requires a higher capital cost than competitors, they collect the product before the harvesting season, and they have no bargaining power to negotiate with agents and exporters. (2) Management problems: disease damage as a result of planting in the same cultivated area, residue, and ethephon problems. Even though ethephon can rapidly ripen green durian by up to 60-70%, the flavor is terrible. If these durians are exported to other countries, they can ruin the image of Thai durian quality. Another consideration is climate changes with increased temperatures and average annual rainfall but decreased relative humidity, while the number of rainy days also tends to decrease (Angyurekul and Soratana, 2014; Worakuldumrongchai, 2015). Furthermore, the traders who sell durian from country to country, mostly Chinese people, have indicated the highest price to buy durian or low quality of durian to export; low quality of durian mixed with green durian, or claiming market restrictions instead of tax as an excuse; sanitation, pesticides and residues, and other factors that were out of control such as disease. This can lead to rejection by trading partners in other countries and can also affect the farmers.

The study of factors that affect agricultural production reveals many studies, such as the work of DATEPUMEE *et al.* (2019), who analyzed factors that affect potential durian exports in Chanthaburi Province by using questionnaires to observe 393 farmers via the logit model for analysis. As a result, they found that the main factors were soil types, fundamental knowledge, fruit ripening experiments, chemical use to prevent diseases and pests, pruning, and using fertilizer. Hassan *et al.* (2010) studied a similar topic with wheat in a mixed cropping zone of Punjab in India by observing 200 wheat growers. As a result, the factors that positively affected wheat yield in the mixed cropping zone of Punjab were seed rate, fertilizers, weeding cost, rotavator, and farmer education level. On the other hand, the sowing period was a negative factor affecting wheat productivity. The study of Promchon *et al.* (2018) found that factors influencing table grape production in Thailand were income, labor, cultivated area, and water sufficiency to plant table grapes throughout the year by observing 89 farmers using multiple regression analysis. Suriya *et al.* (2017) performed a similar study with the bananas of Nong Suea district, Pathum Thani Province, by taking 212 farmers based on multiple regression analysis. According to the results, the factors that affected banana production were labor, total income, other income apart from planting bananas, capital, and fundamental knowledge. Furthermore, Tun and Kang (2015) found that farm mechanical tools were a significant factor in enhancing the efficiency of rice production in Myanmar using the data envelopment analysis and the stochastic frontier approach. Zhang *et al.* (2020) studied the production function in corn yields in Daqing City, China, using the Cobb–Douglas concept. The findings of this study showed that the rates of using fertilizer and pesticide, effective precipitation, and planted area of corn had a positive relationship in increasing corn yield. Zulu *et al.* (2019) analyzed sugarcane production by small-scale growers in Ndwedwe Local Municipality, South Africa, using ordinary least squares (OLS) based on the Cobb-Douglas function. This study found that the quantity of labor and amount of chemicals applied had statistical significance and positively correlated with sugarcane production. In recent studies of Guntukula and Goyari (2020), Pipitpukdee *et al.* (2020), Sarkar *et*

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*al.* (2020), and Shayanmehr *et al.* (2020) focused on the impact of climatic and non-climatic factors on the productivity of agricultural commodities using the panel data analysis. The findings from these empirical studies confirmed that climatic factors could be one of the most important factors in the efficiency of agricultural production. For example, Sarkar *et al.* (2020) analyzed the impact of climate change on oil palm productivity in Malaysia using multiple regression analysis. The results found that changes in annual average temperature, planted areas, and sea-level rise were associated with the efficiency of oil palm production in Malaysia.

## MATERIALS AND METHODS

The eastern region of Thailand consists of seven provinces in Table 1 classified by the Office of the Royal Society of Thailand, namely, Chanthaburi, Rayong, Trad, Prachin Buri, Nakhon Nayok, Chon Buri, and Sa Kaeo. The study area includes three provinces such as Chanthaburi, Rayong, Trad, covering almost all durian production in the eastern region. The population is 31,012 farmers who mainly grow durian in the eastern region of Thailand, in the provinces of Chanthaburi, Rayong, and Trad (Department of Agricultural Extension, 2016).

By using the formula of Yamane (1973) to find the sample size, it is determined that 395 farmers would be sufficient, and by using the quota selection method calculated from the ratio of farmers from each province, this gives the result of 267 farmers from Chanthaburi Province, 78 farmers from Rayong Province, and 50 farmers from Trad Province (Thongkaew, 2018). From the data above, this study used convenience sampling for observed samples, which included open-ended and closed-ended questions.

Five professionals were invited to check the content validity in order to correct and improve the questionnaires, and then trial tests were used with 30 durian farmers in Srisaket Province so that the reliability could be calculated using Cronbach's alpha coefficient, giving a result of 0.934, proving that it is in a high confidence range.

Table 1. Harvested area, production, and yield of durian in the eastern region of Thailand.

| Production area | Harvested area (rai) | | Production (ton) | | Yield (kg/rai) | |
|---|---|---|---|---|---|---|
| | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| - Chanthaburi | 181,960 | 190,728 | 279,075 | 339,292 | 1,533.716 | 1,778.931 |
| - Rayong | 61,005 | 64,469 | 85,880 | 108,093 | 1,407.753 | 1,676.666 |
| - Trad | 24,187 | 26,133 | 38,951 | 48,158 | 1,610.411 | 1,842.804 |
| - Prachin Buri | 1,243 | 1,569 | 1,047 | 1,623 | 842.317 | 1,034.417 |
| - Nakhon Nayok | 347 | 449 | 334 | 455 | 962.536 | 1,013.363 |
| - Chon Buri | 142 | 231 | 141 | 230 | 992.957 | 995.671 |
| - Sa Kaeo | 0 | 0 | 0 | 0 | 0 | 0 |
| Eastern region | 268,884 | 283,579 | 405,428 | 497,851 | 7,349.691 | 8,341.853 |
| Whole Kingdom | 676,249 | 724,730 | 759,828 | 1,017,097 | 1,123.593 | 1,403.415 |

Source: Office of Agricultural Economics (2020c)

To analyze the samples, descriptive and inferential statistics are employed, such as percentage, mean, and multiple regression, which is used for analyzing the factors that affect the durian production of farmers in the eastern region of Thailand using the production function, which can be presented in the form of equation (1) below;

$Q_i = f(X_1, X_2, X_3, \ldots, X_{12})$

$$Q_i = \alpha_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_{12} X_{12} + \varepsilon_i \quad (1)$$

where Q is the production of durian (unit: metric tons), f(.) is the production function, α is the constant, β is the coefficient of the variables, ε is the error, $X_1$ is the gender where 1 means male and 0 means female, $X_2$ is the age of farmers (unit: years), $X_3$ is the experience of farmers in growing durian (unit: years), $X_4$ is the size of the workforce (unit: persons), $X_5$ is the durian growing pattern where 1 means an integrated farming system and 0 is only growing durian, $X_6$ is the GAP standard where 1 means farmers have the GAP standard and 0 means farmers do not have the GAP standard, $X_7$ is the water resources for growing durian where 1 means farmers have sufficient water for growing durian and 0 means farmers have insufficient water for growing durian, $X_8$ is the growing organic durian where 1 means farmers are growing organic durian and 0 means farmers are not growing organic durian, $X_9$ is the planted area of durian (unit: rai), $X_{10}$ is the number of durian trees (unit: durian trees), $X_{11}$ is the number of durian trees per planted area (unit: durian trees/rai), and $X_{12}$ is the age of durian trees (unit: years).

The multiple regression analysis is considered using equation (1) by applying the Ordinary Least Squares (OLS) estimator to detect the size impact of the variables. To prevent the analysis results from being insufficiently reliable, this study will accompany the test of variance inflation factors (VIF) for checking the multicollinearity problem between the independent variables.

Next, the heteroskedasticity problem will diagnose using the Breusch-Pagan LM tests. Before explaining the relationships between the variables, any problems that may arise from the use of the OLS estimator must be addressed.

## RESULTS AND DISCUSSION

The basic information about durian farmers reveals that 61.77% of farmers are male with an average age of 49.89 years, mostly graduated from secondary school, and having experience in the production of durian of 19.98 years. The farmers have around 3.77 persons in their households and have 19.64 rai of the planted area, which includes durian planted on up to 15.48 rai. The workforce in durian production is approximately 2.61 persons. They mostly have their own source of funds at 66.76%. On the other hand, the farmers who are in debt have typically borrowed around 292,483.87 baht/household. The observed farmers have production costs of around 14,584.84 baht per rai with an income of approximately 94,133.64 baht per rai, while average durian production is 1,321.21 kilograms per rai.

Table 2. Factors affecting the durian production of farmers in the eastern region of Thailand.

| Variable | Coefficient | S.E. | t-ratio | p-value | VIF |
|---|---|---|---|---|---|
| Constant | -135.327 | 28.308 | -4.780 | <0.001 | - |
| $X_1$ | -3.742 | 2.599 | -1.440 | 0.150 | 1.050 |
| $X_2$ | -0.479 | 0.205 | -2.329 | 0.020 | 1.913 |
| $X_3$ | 0.466 | 0.250 | 1.861 | 0.063 | 2.552 |
| $X_4$ | 4.903 | 2.276 | 2.154 | 0.031 | 1.866 |
| $X_5$ | -0.040 | 3.416 | -0.011 | 0.990 | 1.113 |
| $X_6$ | 0.106 | 3.384 | 0.031 | 0.974 | 1.138 |
| $X_7$ | -3.341 | 3.461 | -0.965 | 0.335 | 1.050 |
| $X_8$ | -6.151 | 2.939 | -2.093 | 0.037 | 1.118 |
| $X_9$ | 11.736 | 1.535 | 7.641 | <0.001 | 7.552 |
| $X_{10}$ | 0.376 | 0.086 | 4.352 | <0.001 | 7.210 |
| $X_{11}$ | 8.749 | 1.351 | 6.475 | <0.001 | 1.293 |
| $X_{12}$ | -0.183 | 0.301 | -0.607 | 0.543 | 1.601 |

$\chi^2_{LM}$ = 4239.942 ($p < 0.001$)

The durian cultivation of farmers showed that the planted area is the plain area (54.68%), sandy loam (40.51%), using underground water (69.87%), with enough water throughout the year (84.81%). The diseases mostly found in durian cultivation are Pythium root rot and durian Psyllid. The farmers have mostly cultivated Monthong durian by digging plant holes (81.27%), using 93.67% of an 8*8-meter area with 18.29 trees per rai and with an average age of 14.75 years. When it comes to applying fertilizer, they use organic fertilizer (58.99%) after the harvesting season until the sprouting phase and also use chemical fertilizer (88.61%) (15-15-15, 16-16-16, and 17-17-17 solution). During the blooming stage, they use chemical fertilizer (90.89%) (8-24-24 solution). During the developing stage, the farmers use chemical fertilizer through leaves (13-0-46, 10-20-30, and 15-30-15 solution) at 29.11%, 24.56%, and 23.80%, respectively. During the fruit developing stage, they use chemical fertilizer through soil (8-24-24 and 12-12-17+2Mg solution) at 54.94% and 40.51%, respectively. In terms of the management and operation to increase durian quality and quantity, this study found 97.98% of farmers pruning their trees, 62.03% of them have spared two generations of durian, 98.64% of them pollinating flowers from 18.00 onwards, and 98.23% of them branching their trees. During the harvesting season, they all check their products by using the duration of time from blooming to the ripening of the durian. As a result, they will collect only 116.38-day-old durian. After all those previous processes, 66.84% of farmers have collectors and traders to export durian for them, and 58.99% of them accept wholesale business. Also, the farmers sell fresh durian productions, but only 29.87% were guaranteed by the GAP standard.

The factors affecting durian production in the eastern region of Thailand are presented in Table 2. The analysis of Table 2 reveals the avoidance of multicollinearity and heteroskedasticity problems by using the variance inflation factors (VIF) and Breusch-Pagan ($\chi^2_{LM}$) heteroskedasticity tests. According to the study, the factors affecting durian production include the age of the farmers ($X_2$), the experience of the farmers in growing durian ($X_3$), the size of the workforce ($X_4$), the growing organic durian ($X_8$), the planted area of durian ($X_9$), the number of durian trees ($X_{10}$), and the number of durian trees per planted area ($X_{11}$). The results can be explained as follows;

When farmers are one year older, the durian production will significantly decrease by 0.479 tons at the statistical significance level of 0.05. Thus, it can be inferred that when farmers become older, they will not know about technology changes compared to younger farmers. When the experience of farmers in growing durian increased by one year, the production would also significantly increase by 0.466 tons at the statistical significance level of 0.1. Thus, it can be implied that experience is very important for producing quality durian, and the application of new technology in a specific area can also help. When using one additional person in the labor force, the production will significantly increase by 4.903 tons at the statistical significance level of 0.05. Thus, it can be inferred that labor is the main factor in durian production since labor is mainly provided by people and still does not have to involve any technology to work instead of people who still do not possess the technology. This is consistent with the findings of Suriya *et al.* (2017) and DATEPUMEE *et al.* (2019), who found that farmer experience, including training attendance and agricultural knowledge, influenced productivity in case of banana and durian in Thailand as well as Suriya *et al.* (2017), Promchon *et al.* (2018), and Saisaard *et al.* (2021) found that increasing the number of the workforce could enhance the efficiency of production in case of banana, table grape, and rice in Thailand. Therefore, farmers with long experience in durian production will be able to produce durian well, which results in considerable labor required in the management of durian production. The farmers who produce organic durian will have fewer outcrops than the others who produce conventional (chemical) durian by around 6.154 tons at the statistical significance level of 0.05. Thus, it can be inferred that producing organic durian without using chemical fertilizer can cause nutritional deficiencies in the short term and leads to a longer time being needed to grow. When increasing the planted area by one rai, the production will increase by 11.736 tons at the statistical significance level of 0.01. With farmers planting one more durian tree, the production will increase by 0.376 tons at the statistical significance level of 0.01. In addition, increasing by one more durian tree per rai, the production will increase by 8.749 tons at the statistical significance level of 0.01. The planted area of durian, the number of durian trees, and the number of durian trees per unit of planted area affect durian production in the same direction; that is, if these factors increase, it will increase the production volume. The case of increasing planted area affecting yield is consistent with a study by Promchon *et al.* (2018), who found that planted area affected table grape production in Thailand. Even though the number of durian trees is very important in durian production, we still have to calculate the density of durian for a given area to receive the best outcomes. The model in Table 2 has described 98.932% of durian production in the eastern region of Thailand. On the other hand, the gender, the durian growing pattern, the GAP standard, the water resources for growing durian, and the age of the durian trees did not play any significant part in durian production.

## CONCLUSION AND RECOMMENDATIONS

In recent years, farmers are interested in growing durian instead of other crops such as Para rubber, oil palm, and other fruits because the demand for durian consumption in both domestic and foreign markets has been rising, and the price of durian fruits has increased as well. For this reason, farmers have expanded their growing areas from the past with the main growing areas in the eastern and southern regions, but nowadays, they have expanded their growing areas throughout all regions of Thailand, resulting in a continuous increase in the amount of durian in the country. Sometimes, there are some groups of farmers grow durian which focuses on producing too large quantities that sometimes they do not pay attention to the production of quality durian including variability of climate and weather, which causes production problems such as diseases and pests in durian, and fungi in durian both before and after production. As a result, the durian tree has deteriorated, and it affects the yield, which is not as expected, as well as the quality of the durian that does not meet the market demand.

Hence, this research aims to analyze the factors affecting durian production in the eastern region of Thailand, namely Chanthaburi, Rayong, and Trad Provinces which are the area where durian production is most efficient, both the high quantity and best quality of the durian that are acceptable for export in the global market. The samples were selected by 395 farmers who cultivate durian using a simple random sampling approach. Multiple regression analysis was employed using the production function concept. Multicollinearity and autocorrelation were considered to prevent the violation of the classical linear regression model. According to the results, positive factors that affect durian production are the experience of farmers in growing durian, the size of the workforce, the planted area of durian, the number of durian trees, and the number of durian trees per unit of the planted area. In contrast, negative factors are the age of the farmers and the growing organic durian. The experience of farmers in growing durian and the size of the labor force affects the production of durian, as durian cultivation has quite a lot of production details, starting from the preparation of durian varieties, the planting process, and the maintenance of the durian, watering, pruning, fertilizing, etc. However, it is important to consider the densities of the durian trees in a given planted area appropriately because if the number of durian trees in a given area is too high, it can lead to a decrease in production efficiency and result in higher production costs. The age of farmers has a negative effect on durian production as the older farmers may not be exposed to modern production technology or adjust the production patterns to suit modern durian production. In addition, when comparing organic durian production with conventional durian production, organic durian production was found to be less efficient than conventional durian production.

When it comes to the recommendations, farmers should be encouraged and provided training programs on increasing the efficiency of durian production to enhancing their knowledge and exchange experiences with successful durian growers as the increased experience of farmers will result in higher efficiency for durian production. There should also be research and development of durian production practices to reduce the workforce by using appropriate technology. Since durian production requires a lot of labor to take care of durian production at every step, using technology to replace labor is necessary to reduce production costs and increase production efficiency. Moreover, the government sector and related stakeholders should support fundamental knowledge of technology to improve the production process and improve durian production to respond to market demands, as well as managing the production process to receive quality products throughout the supply chain, following agricultural guidelines, quality controls and shipping from the plantations to the markets to increase reliability for domestic and international consumers. For the limitations, this study suggests that panel data analysis using Just and Pope's stochastic production should be considered to estimate the effect of climatic factors such as temperature series and precipitation on agricultural output and its variability as studies of Haile *et al.* (2017), Attiaoui and Boufateh (2019), and Sarker *et al.* (2017) including non-climatic factors such as agricultural land use, workforce, capital variables in order to find out suitable analytical solutions to support policy planning at both the micro and macro levels as well as to enhance the efficiency of agricultural production of the country.

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ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

Fungal and oomycete diseases of minor tropical fruit crops / Zakaria, L.

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# Fungal and Oomycete Diseases of Minor Tropical Fruit Crops

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**Abstract:** Minor tropical fruits are grown on a small scale and provide income to smallholder farmers. The cultivation of these fruit crops indirectly contributes to the economy of producing countries as well as to food and crop security. Dragon fruits, guava, passionfruit, lychee, longan, mangosteen, durian, and rambutan are common minor fruit crops. In recent years, the international trade of some of these minor tropical fruits, particularly dragon fruit, passionfruit, guava, and lychee, has increased due to their nutritional value, with various health benefits. Similar to other crops, minor fruit crops are susceptible to fungal and oomycete diseases. These diseases negatively affect the yield and quality of fruit crops, leading to substantial losses. In this context, the knowledge of disease types and causal pathogens is fundamental to develop suitable disease management practices in the field as well as appropriate post-harvest treatments.

**Keywords:** fungi and oomycete; diseases; dragon fruits; guava; passionfruit; lychee; longan; mangosteen; durian; rambutan



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## 1. Introduction

Minor tropical fruits are cultivated on a small scale and traded in small capacity, mostly at the local or regional levels. The consumption of these fruits is often limited to the local population [1]. Many minor tropical fruits, such as dragon fruits, guava, passionfruit, lychee, longan, mangosteen, durian, and rambutan, contribute to the economy of their respective producing countries. Nowadays, the production and trade of these minor tropical fruits have been rapidly expanding owing to their health benefits, and these crops have thus garnered much importance in the global market [2].

In many producing countries, minor tropical fruits have become a source of income, particularly for rural smallholder farmers. According to a survey by the FAO, earning from the cultivation and production of minor tropical fruits can contribute up to 75% of the total income. This may be due to the higher wholesale prices of these fruit crops, reaching around USD 4 per kilogram for lychee and guava and USD 13 per kilogram for durian, mangosteen, and passion fruit. Thus, minor tropical fruit cultivation is very profitable, provided that other factors, such as the handling and transportation of fruits, are well managed and cost effective [2].

In international markets, particularly in European countries and the US, minor tropical fruits are used primarily by Asian communities or ethnic markets and often by premium retailers for dietary and health preferences [2]. Familiar or popular minor tropical fruits in the international market include guava, passion fruit, and lychee. Additionally, some fruits, including dragon fruit, mangosteen, and rambutan, have been recognized as superfoods.

During 2015–2017, Asian countries were responsible for approximately 86% of minor tropical fruit production. The largest producers include India (24%) and China (22%), where these fruits are mainly available in local markets. Other major producing countries include Southeast Asian countries, including Thailand, Vietnam, Indonesia, and Malaysia, as well as South American countries, particularly Brazil [2].

Similar to other tropical fruit crops, however, diseases represent the most important constraint to minor tropical fruit crop production. Nearly all minor tropical fruit crops are infected by one or more plant pathogenic fungi and oomycetes, which are fungal-like organisms (Table 1). Thus, the knowledge of various diseases of these fruit crops is important to determine optimal cultivation regions and practices, post-harvest treatments, trade (market type or retail), and sustainability and profitability of their production [3]. In this context, the present review highlights the common fungal and oomycete diseases of popular minor tropical fruit crops, including dragon fruit, passion fruit, longan, lychee, rambutan, mangosteen, and durian.

**Table 1.** Fungal and oomycete diseases associated with minor tropical fruit crops reported in several countries.

| **Dragon Fruit (*Hylocereus* spp.)** | | | |
|---|---|---|---|
| **Disease** | **Causal Pathogen/ *Hylocereus* spp.** | **Country** | **References** |
| Anthracnose (fruit and stem) | *Colletotrichum gloeosporioides sensu lato* (stem of *H. undatus*; stem of *H. megalanthus*; stem and fruit of *Hylocereus* spp.) | Miami-Dade County, Florida, USA; Brazil, Malaysia | Palmateer et al. [4], Takahashi et al. [5], Masyahit et al. [6] |
| | *Colletotrichum gloeosporioides* (young stem and fruit of *H. undatus*) | China, Taiwan | Ma et al. [7], Lin et al. [8] |
| | *Colletotrichum siamense* (stem and fruit of *H. undatus*; stem of *H. polyrhizus*) | Thailand, China | Meetum et al. [9], Zhao et al. [10] |
| | *Colletotrichum karstii* (stem of *H. undatus*) | Brazil | Nascimento et al. [11] |
| | *Colletotrichum fructicola* (stem of *H. undatus* and *H. monacanthus*) | the Philippine | Evallo et al. [12] |
| | *Colletotrichum truncatum* (fruit of *H. undatus*, stem of *H. polyrhizus*) | Malaysia, China | Guo et al. [13], Iskandar Vijaya et al. [14] |
| | *Colletotrichum aenigma* (stem and fruit of *H. undatus*) | Thailand | Meetum et al. [9] |
| | *Colletotrichum siamense* (stem of *H. undatus*) | Andaman Islands, India | Abirami et al. [15] |
| Stem lesion/spot | *Curvularia lunata* (stem of *H. polyrhizus*) | Malaysia | Masratul Hawa et al. [16] |
| Storage fruit rot | *Gilbertella persicaria* (*H. costaricensis*) | China | Guo et al. [17] |
| Fruit blotch and stem rot | *Bipolaris cactivora* (*H. undatus*) | South Florida, Israel, Thailand, Vietnam | Tarnowski et al. [18], Ben-Ze'ev et al. [19], He et al. [20], Oeurn et al. [21] |
| Stem blight | *Alternaria* sp. (*H. undatus*) | South Florida, USA | Patel and Zhang [22] |
| Post-harvest disease | *Alternaria alternata* (*H. undatus*) | Brazil | Castro et al. [23] |
| Stem and Fruit Spot | *Aureobasidium pullulans* (*Hylocereus* spp.) | China | Wu et al. [24] |
| Stem blight | *Sclerotium rolfsii* (*H. undatus*) | China | Zheng et al. [25] |
| Stem reddish brown spot | *Nigrospora sphaerica* (*H. undatus*) | China | Liu et al. [26] |
| Stem reddish brown spot | *Nigrospora lacticolonia* and *N. sphaerica* (*H. polyrhizus*) | Malaysia | Kee et al. [27] |

**Table 1.** *Cont.*

| Dragon Fruit (*Hylocereus* spp.) | | | |
|---|---|---|---|
| **Disease** | **Causal Pathogen/ *Hylocereus* spp.** | **Country** | **References** |
| Stem reddish brown spot | *Nigrospora lacticolonia* and *N. sphaerica* (*H. polyrhizus*) | Malaysia | Kee et al. [27] |
| Stem canker, black rot, brown spot, fruit internal browning, fruit canker | *Neoscytalidium dimidiatum* (*H. undatus* and *H. monacanthus*) | Israel, Taiwan, Malaysia, China; Florida, USA; Puerto Rico | Chuang et al. [28], Lan et al. [29], Ezra et al. [30], Masratul Hawa et al. [31], Yi et al. [32], Sanahuja et al. [33], Serrato-Diaz and Goenaga [34] |
| Stem gray blight | *Diaporthe arecae*, *Diaporthe eugeniae*, *Diaporthe hongkongensis*, *Diaporthe phaseolorum*, and *Diaporthe tectonendophytica* (*H. polyrhizus*) | Malaysia | Huda-Shakirah et al. [35] |
| | *Diaporthe ueckerae* (*H. polyrhizus* and *H. undatus*) | Taiwan | Wang et al. [36] |
| Stem rot | *Fusarium proliferatum*, *Fusarium fujikuroi* (*H. polyrhizus*) | Malaysia | Masratul Hawa et al. [37], [38] |
| | *Fusarium solani* (*Hylocereus* sp.) | Bali, Indonesia Banyuwangi Regency, Indonesia | Rita et al. [39], Sholihah et al. [40] |
| | *Fusarium* sp. (*Hylocereus* sp.) | Lombok Utara and Central Bangka Regency, Indonesia | Isnaini et al. [41], Kurniasari et al. [42] |
| | *Neocosmospora rubicola*/*F. solani* species complex (*H. costaricensis*) | Dongfang, Hainan Province, China | Zheng et al. [43] |
| Basal rot | *Fusarium oxysporum* (*H. undatus*, *Selenicereus megalanthus*, *H. polyrhizus*) | Gran Buenos Aires, Argentina; Colombia, Bangladesh | Wright et al. [44], Salazar-González et al. [45], Mahmud et al. [46] |
| Stem blight | *Fusarium oxysporum* (*H. polyrhizus*) | Malaysia | Mohd Hafifi et al. [47] |
| Fruit rot | *Fusarium lateritium*, *Fusarium semitectum* | Vietnam | Le et al. [48] |
| | *Fusarium oxysporum*, *Fusarium dimerum* (*H. undatus*) | Shanghai, China | Zhi-Jing et al. [49] |
| | *Fusarium dimerum*, *Fusarium equiseti* (*H. undatus*) | Mekong, Delta, Vietnam | Ngoc et al. [50] |
| **Guava (*Psidium guajava* L.)** | | | |
| **Disease** | **Causal pathogen** | **Country** | **References** |
| Fusarium wilt | *Fusarium oxysporum* f. sp. *psidii* | India | Prasad et al. [51], Misra and Gupta [52] |
| | *Fusarium oxysporum*, *Fusarium solani* | India | Misra and Pandey [53] |
| | *Fusarium proliferatum*, *Fusarium chlamydosporum* | India | Misra and Gupta [52], Gupta and Misra [54] |
| | *Fusarium oxysporum* f. sp. *psidii*, *Fusarium solani* | India | Dwivedi and Dwivedi [55], Misra et al. [56,57], Misra [58] |
| | *Fusarium oxysporum* f. sp. *psidii*, *Fusarium falciforme* | India | Gangaraj et al. [59] |

**Table 1.** *Cont.*

| Dragon Fruit (*Hylocereus* spp.) | | | |
|---|---|---|---|
| **Disease** | **Causal Pathogen/ *Hylocereus* spp.** | **Country** | **References** |
| Decline | *Fusarium oxysporum* f. sp. *psidii*, *Fusarium solani* f. sp. *psidii* (no information on the nematode) | District of Punjab, Pakistan | Aftab [60] |
| | *Fusarium solani* (*Meladogyne mayaguensis*) | Brazil | Gomes et al. [61] |
| | *Fusarium oxysporum* (*Meloidogyne incognita*) | Haryana, India | Madhu et al. [62] |
| | *Fusarium oxysporum* f.sp. *psidii*(*Meloidogyne enterolobii*) | Ratlam district, India | Singh [63] |
| | *Fusarium solani* (*Meloidogyne enterolobii*) | Brazil | Veloso et al. [64] |
| | *Fusarium solani*, *Fusarium oxysporum* (no information on the nematode) | Pakistan | Khizar et al. [65] |
| Anthracnose | *Colletotrichum gloeosporioides* complex | Italy | Weir et al. [66] |
| | *Colletotrichum siamense* complex | India and Mexico | Sharma et al. [67], Rodríguez-Palafox et al. [68] |
| | *Colletotrichum abscissum*, *Colletotrichum simmondsii* | Brazil | Bragança et al. [69], Cruz et al. [70] |
| | *Colletotrichum guajavae* | India | Damm et al. [71] |
| | *Fusarium verticillioides* | India | Sanjeev and Brijpal [72], Baloch et al. [73] |
| Crown rot | *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus tamarii*, *Aspergillus japonicus*, *Aspergillus flavus* | Phillipine | Valentino et al. [74] |
| Fruit rot | *Fusarium oxysporum* | Egypt, Nigeria | Mathew [75], Amadi et al. [76], Embaby and Korkar, [77], Mairami et al. [78] |
| | *Aspergillus awamori* | Pakistan | Akhtar et al. [79] |
| | *Phytophthora nicotianae* | Bangladesh | Pervez et al. [80] |
| | *Neoscytalidium dimidiatum* | Malaysia | Ismail et al. [81] |
| | *Lasiodioplodia theobromae* | Malaysia | Zee et al. [82] |
| Canker | *Diplodia natalensis*, *Pestalotia psidii* | India | Misra 2012 [83] |
| **Passion Fruit (*Passiflora edulis* Sim.)** | | | |
| **Disease** | **Causal Pathogen** | **Country** | **References** |
| Wilt | *Fusarium oxysporum* f. sp. *passiflorae* | Brazil, North America, Portugal, New Zealand, | Rooney-Latham et al. [84], Garcia et al. [85], Melo et al. [86], Thangavel et al. [87] |
| | *Fusrium oxysporum* | Iksan and Jeju, Korea | Joa et al. [88] |
| | *Fusrium solani* | Zimbabwe | Cole et al. [89] |
| | *Fusarium incarnatum*, *Fusarium solani*, *Fusarium proliferatum* | Colombia | Henao-Henao et al. [90] |
| | *Fusarium nirenbergiae* | Italy | Aiello et al. [91] |
| Collar rot | *Fusarium solani* f.sp. *passiflorae* (*Fusarium solani*) | Brazil, USA, China, Uganda | Emechebe et al. [92], Ploetz [93], Li et al. [94], Ssekyewa et al. [95], Bueno et al. [96], Marostega et al. [97], Zhou et al. [98] |
| Canker | *Fusarium solani* *Fusarium oxysporum* f.sp. *pasiflorae* | Florida, USA | Manicom et al. [99], Ploetz [100], Anderson and Chambers [101] |
| | *Fusarium solani* | Taiwan and Uganda (reported as Nectria canker) | Emecahebe et al. [92], Lin and Chang [102] |

**Table 1.** *Cont.*

| Dragon Fruit (*Hylocereus* spp.) | | | |
|---|---|---|---|
| **Disease** | **Causal Pathogen/ *Hylocereus* spp.** | **Country** | **References** |
| Dieback | *Fusarium solani* | Kenya | Wangungu et al. [103], Power and Verhoeff [104] |
| | *Fusarium oxysporum. subglutinans*, *Fusarium pseudoanthophilum*, *Fusarium solani*, *Fusarium. semitectum* | Kenya | Amata et al. [105] |
| Stem bulging | *Gibberella fujukuroi*, *Fusarium* sp. | Sri Lanka | Wanniarachchi et al. [106], Rajapaksha et al. [107] |
| Anthracnose | *Colletotrichum boninense*, *Colletotrichum boninense*, *Colletotrichum truncatum*, *Colletotrichum gloeosporioides*, *Glomerella* sp. | Florida | Tarnowski and Ploetz [108] |
| | *Colletotrichum boninense* | Brazil | Tozze Jr. et al. [109] |
| | *Colletotrichum queenslandicum* | Northern Territory, Australia | James et al. [110] |
| | *Colletotrichum brevisporum* | Fujian Province, China | Du et al. [111] |
| | *Colletotrichum truncatum* | China and Taiwan | Zhuang et al. [112] Chen and Huang [113] |
| | *Colletotrichum brasiliense* | China | Shi et al. [114] |
| | *Colletotrichum constrictum* | Yunnan, China | Wang et al. [115] |
| **Lychee (*Litchi chinense* Sonn.)** | | | |
| **Disease** | **Causal Pathogen/Plant Parts** | **Country** | **References** |
| Anthracnose | *Colletotrichum gloeosporioides sensu lato* | | Fitzell and Coates [116], Coates et al. [117] |
| | *Colletotrichum gloeosporioides* (immature fruit and asymptomatic flowers) | Mexico | Martinez-Bolanos et al. [118] |
| | *Colletotrichum fioriniae* (fruit) | China | Ling et al. [119] |
| | *Colletotrichum karstii* (leaves) | Guangxi, China | Zhao et al. [120] |
| Pepper spot | *Colletotrichum gloeosporioides sensu lato* (fruit) | Australia | Cooke and Coates [121], Anderson et al. [122] |
| | *Colletotrichum siamense* (fruit) | Taiwan, China | Ni et al. [123] Ling et al. [124] |
| Blight of leaf, panicle and fruit | *Alternaria alternata* | Bihar, India | Kumar et al. [125] |
| Fruit rot (Brown rot) | *Fusarium incarnatum* | Hainan, China | Guo et al. [126] |
| Downy blight | *Phytophthora litchi* | Taiwan, Southern China | Kao and Leu [127], Wang et al. [128] |
| **Longan (*Dimocarpus longan* Lour.)** | | | |
| **Disease** | **Causal Pathogen** | **Country** | **References** |
| Downy blight (young leaves, panicles, flowers and fruits) | *Phytophthora litchi* | Taiwan | Ann et al. [129] |
| Inflorescence wilt, vascular and flower necrosis | *Fusarium decemcellulare* | Puerto Rico | Serrato-Diaz et al. [130] |
| Fruit rot (Brown rot) | *Phytophthora palmivora* | Thailand | Kooariyakul and Bhavakul [131] |
| | *Lasiodiplodia theobromae* | Puerto Rico | Serrato-Diaz et al. [132] |
| | *Lasiodiplodia pseudotherobromae* | Thailand | Pipattanapuckdee et al. [133] |

**Table 1.** *Cont.*

| **Dragon Fruit (*Hylocereus* spp.)** | | | |
|---|---|---|---|
| **Disease** | **Causal Pathogen/ *Hylocereus* spp.** | **Country** | **References** |
| Pericarp browning | *Phomopsis longanae*, *L. theobromae* | China | Chen et al. [134]<br>Sun et al. [135] |
| Dieback | *Lasiodiplodia hormozganensis*, *Lasiodiplodia iraniensis*, *Lasiodiplodia pseudotheobromae*, and *Lasiodiplodia theobromae* | Puerto Rico | Serrato-Diaz et al. [136] |
| Inflorescence blight | *Lasiodiplodia theobromae* | Puerto Rico | Serrato-Diaz et al. [132] |
| **Durian (*Durio zibethinus* L.)** | | | |
| **Disease** | **Causal Pathogen** | **Country** | **References** |
| Patch canker or stem canker, fruit rot, seedling dieback, foliar blight and root rot | *Phytophthora palmivora* | Malaysia, Indonesia, Thailand, Brunei, Vietnam | Pongpisutta and Sangchote [137], Lim [138], Lim [139], Sivapalan et al. [140], Tho et al. [141] |
| Stem rot | *Fusarium solani* and *L. pseudotheobromae* | Thailand | Chantarasiri and Boontanom [142] |
| Leaf blight | *Rhizoctonia solani* | Vietnam and Peninsular Malaysia | Thuan et al. [143], Lim et al. [144] |
| Foliar blight and Dieback | *Rhizoctonia solani* | Malaysia | Lim et al. [144] |
| Leaf spot | *Phomopsis durionis* | Thailand | Tongsri et al. [145] |
| Fruit rot | *Sclerotium rolfsii* | Malaysia | Lim and Kamaruzaman [146] |
| | *Colletotrichum gloeosporioides*, *Lasiodiplodia theobromae* | Thailand | Sangchote et al. [147] |
| | *Aspergillus* spp., *Penicillium* sp., *Fusarium equiseti* (secondary invaders or weak pathogens) | Brunei | Sivapalan et al. [148] |
| Durian decline | *Pythium vexans*, *Phytophthora palmivora* | Queensland, Australia and Indonesia | O'Gara et al. [149] |
| | *Phytophthora palmivora*, *Pythium cucurbitacearum*, *Pythium vexans* | Indonesia | Santoso et al. [150] |
| Root rot and canker lesion | *Phytophthora nicotianae* | Sabah, Malaysia | Bong [151] |
| Root and stem rot | *Pythium cucurbitacearum*, *Pythium vexans* (syn. *Phytopytium vexans*), *Pythium deliense* | Queensland, Australia; Malaysia, Thailand, Indonesia, Vietnam | Lim and Sangchote [152], Vawdrey et al. [153], Thao et al. [154] |
| **Rambutan (*Nephelium lappaceum* L.)** | | | |
| **Disease** | **Causal Pathogen** | **Country** | **References** |
| Fruit rot | *Botryodiplodia theobromae*, *Colletotrichum gloeosporioides*, *Gliocephalotrichum bulbilium*, *Pestalotiopsis* sp., *Phomopsis* sp., *Glomerella* sp. | Hawaii, Puerto Rico, Malaysia, Thailand and Sri Lanka, China | Farungsang et al. [155], Sivakumar et al. [156], Sangchote et al. [157], He et al. [158] |
| | *Lasmenia* sp., *Gliocephalotrichum* spp., *Pestalatiopsis virgatula* | Hawaii | Nishijima et al. [159], Keith [160] |
| | *Gliocephalotrichum bulbilium*, *Gliocephalotrichum simplex*, *Colletotrichum fructicola*, *Colletotrichum queenslandicum* | Puerto Rico | Serrato-Diaz et al. [161], Serrato-Diaz, et al. [162], Serrato-Diaz et al. [163] |
| | *Gliocephalotrichum bacillisporum* | Malaysia | Intan Sakinah and Latiffah [164] |
| Corky bark | *Dolabra nepheliae* | Malaysia, Hawaii, Puerto Rico and Honduras | Booth and Ting [165], Combs et al. [166], Rossman et al. [167] |
| Stem canker | *Dolabra nepheliae* | Hawaii, Puerto Rico and Honduras | Rossman et al. [168,169] |

**Table 1.** *Cont.*

| Dragon Fruit (*Hylocereus* spp.) | | | |
|---|---|---|---|
| **Disease** | **Causal Pathogen/ *Hylocereus* spp.** | **Country** | **References** |
| Corky bark and dieback | *Lasiodiplodia brasiliensis*, *L. hormozganensis*, *Lasiodiplodia iraniensis*, *Lasiodiplodia pseudotheobromae*, *Lasiodiplodia theobromae*, *Neofusicoccum batangarum*, *Neofusicoccum parvum* | Puerto Rico | Serrato-Diaz et al. [130] |
| Powdery mildew | *Oidium nephelii* | Sri Lanka, the Philippine, Thailand and Malaysia | Garcia [170], Coates et al. [171], Rajapakse et al. [172] |
| Inflorescence wilt, flower and vascular necrosis | *Fusarium decemcellulare* | Puerto Rico | Serrato-Diaz et al. [130] |
| Leaves necrosis of rambutan seedlings | *Pseudocercospora nephelii* | Brunei, Malaysia (Sabah and Selangor) | Peregrine et al. [173] |
| **Mangosteen (*Garcinia mangostana* L.)** | | | |
| **Disease** | **Causal Pathogen** | **Country** | **References** |
| Leaf blight | *Pestalotiopsis flagisettula* | Thailand, Malaysia, North Queensland, Australia, Hawaii | Lim and Sangchote [174], Keith and Matsumoto [175] |
| Brown leaf spots and blotches | *Pestalotiopsis* sp. | Hawaii | Keith and Matsumoto [175] |
| Diplodia fruit rot | *Diplodia theobromae* | Thailand | Lim and Sangchote [174] |
| Fruit rot | *Gliocephalotrichum bulbilium* | Guangzhou, China | Li et al. [176] |
| | *Gliocephalotrichum bulbilium*, *Graphium* sp. | Thailand | Sangchote and Pongpisutta [177] |
| | *Mucor irregularis* | Wujing Town, Shanghai | Wang et al. [178] |
| Black aril rot | *Lasiodiplodia theobromae* | Hawaii | Ketsa and Paull [179] |
| White aril rot | *Phomopsis* sp. | Hawaii | Ketsa and Paull [179] |
| Soft aril rot | *Pestalotiopsis* sp. | Hawaii | Ketsa and Paull [179] |
| Decline | *Lasidiplodia theobromae*, *Lasiodiplodia parva* | Bahia, Brazil | Paim et al. [180] |
| Brown root rot | *Phellinus noxius* | - | Lim and Sangchote [174] |
| Stem canker and dieback | *Pestalotiopsis* sp. | - | Lim and Sangchote [174] |
| Thread blight | *Marasmiellus scandens* | - | Lim and Sangchote [174] |

## 2. Fungal Diseases of Dragon Fruit

Dragon fruit (*Hylocereus* spp.) is a climbing cactus of the Cactaceae family. Due to the presence of scales or bracts on the surface of the fruit, it is often called pitaya or pitahaya meaning "scaly fruit" and has acquired the English moniker "dragon fruit." As dragon fruit flowers bloom only at night, they are also called the lady of the night, moonflower, belle of the night, and queen of the night [181].

Dragon fruit is presumably native to Mexico, Central America, and South America, specifically southern Mexico, the Pacific side of Guatemala and Costa Rica, and El Salvador [182]. Dragon fruit is now acclimatized to and cultivated in several countries in Central, South, and North America, including Mexico, Guatemala, Colombia, Costa Rica, Peru, Venezuela, and the United States (Florida, Hawaii, and southern California). In Asia, dragon fruit is widely cultivated in Vietnam, Thailand, Malaysia, Cambodia, Indonesia, the Philippines, India, and Taiwan [183], with Vietnam being the largest producer.

Only four species of *Hylocereus* are widely cultivated, depending on the country of origin: *Hylocereus undatus* (pink skin with white flesh), *Hylocereus monacanthus* (=*Hylocereus polyrhizus*; pink skin and red flesh), *Hylocereus costaricencis* (pink skin with violet-red flesh), and *Hylocereus megalanthus* (=*Selenicerus polyrhizus*; yellow skin with white flesh) [184].

### 2.1. Anthracnose

Various fungal pathogens affect dragon fruit crop. According to Balendres and Bengoa [185], 21 fungal species are associated with dragon fruit diseases. Among these, anthracnose is the most severe disease occurring on the fruit and stem. Anthracnose can occur in the field following harvest. Notable symptoms of anthracnose appear either on the fruit or the stem (Figure 1A,B), showing as reddish-brown irregular or round spots that later merge, enlarge, and turn into dark brown sunken lesions. In these sunken lesions, conidial masses appear, and the lesions are surrounded by chlorotic halos [11]. Although anthracnose has been reported in several producing countries, so far there is a lack of reports from Vietnam, Indonesia, and Sri Lanka even though these three countries are among the major producers of dragon fruits.

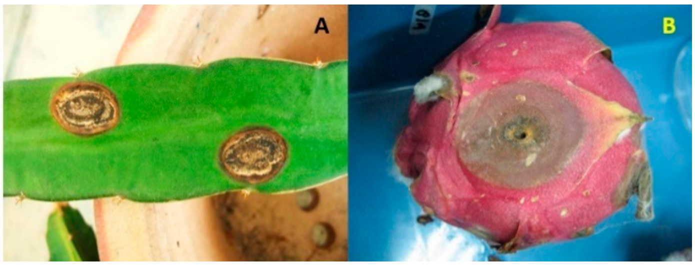


**Figure 1.** Anthracnose of dragon fruit. (**A**) Stem anthracnose. (**B**) Fruit anthracnose.

Before taxonomic revision of the *Colletotrichum* genus, *Colletotrichum gloeosporioides* was the most common species associated with dragon fruit anthracnose [4–6]. *Colletotrichum gloeosporioides* is a part of the *Colletotrichum gloeosporioides* species complex, comprising other species identified based on the molecular phylogeny of multiple genes [66]. Following taxonomic revision, *Colletotrichum gloeosporioides* was still identified as the causal pathogen of dragon fruit anthracnose in China and Taiwan [7,8]. Other species of *Colletotrichum* within the *Colletotrichum gloeosporioides* species complex causing dragon fruit anthracnose include *Colletotrichum siamense* [9,10], *Colletotrichum karstii* [11], and *Colletotrichum fructicola* [12]. In addition, *Colletotrichum truncatum* and *Colletotrichum boninense* have also been implicated in dragon fruit anthracnose [13,14] (Table 1).

### 2.2. Stem Rot

Stem rot of dragon fruit plants infected by *Fusarium* spp. has been reported in Malaysia and Indonesia (Table 1). Symptoms on infected *Hylocereus polyrhizus* (=*Hylocereus monacanthus*) include brown circular sunken lesions and etiological symptoms in the form of white mycelia and orange sporodochia. The causal pathogens include two *Fusarium* species, namely *Fusarium proliferatum* and *Fusarium fujikuroi* [37,38]. *Fusarium proliferatum* and *Fusarium fujikuroi* causing the stem rot of dragon fruit produce fumonisins, moniliformin, and beauvericin, and these mycotoxins contribute to the development and symptom expression of stem rot disease [186].

In Indonesia, the symptoms of stem rot include brown rot and wilting. *Fusarium solani* has been reported as the causal pathogen of stem rot in Bali [39] and Banyuwangi Regency [40]. Zheng et al. [43] reported *Hylocereus costaricensis* stem rot caused by *Neocosmospora rubicola* in Dongfang (Hainan Province, China).

Other stem rot diseases affecting dragon fruit include basal rot, stem blight, stem necrosis, stem canker, reddish brown spot, and stem gray blight (Table 1). Basal rot is caused by *Fusarium oxysporum* and has been reported in several dragon fruit species in Argentina, Colombia, and Bangladesh [44–46]. *Fusarium oxyporum* causes stem blight [47]. Stem necrosis is caused by *Curvularia lunata* [16] and stem canker by *Neoscytalidium dimidiatum* [37]. Two species of *Nigrospora*, namely *Nigrospora lacticolonia* and *Nigrospora sphaerica*, cause reddish brown spot [27]. Stem gray blight has been reported in Malaysia, and five *Diaporthe* species, namely *Diaporthe arecae*, *Diaporthe eugeniae*, *Diaporthe hongkongensis*, *Di-*

*aporthe phaseolorum*, and *Diaporthe tectonendophytica*, have been identified as the causal pathogens [35].

### 2.3. Fruit Rot

Anthracnose caused by *Colletotrichum* species is the most common post-harvest fruit rot of dragon fruit. In addition, *Bipolaris cactivora* and *Fusarium* spp. have been reported to cause fruit rot in dragon fruit. Infection often occurs in the presence of predisposing factors, such as wounds. According to literature, fruit rot caused *Bipolaris cactivora* is more prevalent than that caused by *Fusarium* spp. (Table 1). Pre- or post-harvest fruit rot has been reported in several countries, specifically in *Hylocereus undatus* [18–21,187,188]. Furthermore, *Fusarium oxysporum*, *Fusarium dimerum*, and *Fusarium equiseti* (Table 1) are associated with the fruit rot of dragon fruit [49,189]. Other fungal pathogens associated with dragon fruit disease are listed in Table 1.

## 3. Fungal Diseases of Guava

Guava (*Psidium guajava*) belongs to the myrtle family Myrtaceae and is widely distributed in tropical and subtropical regions of Asia, Africa, Oceania, and parts of the USA [190]. The origin of guava is not certain, but it is assumed that the plant originated from southern Mexico through Central and South America, probably from Mexico to Peru, as in these areas, guava is found in the wild as well as cultivated [182].

India is a major guava-producing country, accounting for approximately 56% of the total global production, followed by China, Thailand, Mexico, and Indonesia [2]. Similarly to other fruit crops, guava has multiple local names; it is called jambu batu in Malaysia, abas in Guam, and bayabas in the Philippines. The French refer to guava as goyave or goyavier, the Portuguese as goiaba, or goaibeira, and the Dutch as guyaba or goeajaaba [182]. Owing to their pleasant flavor, aroma, and nutritional content, guava fruits are well received by consumers.

Guava is susceptible to various fungal diseases, with wilt, fruit rot, dieback, styler end rot, stem canker, and fruit canker being the major diseases (Table 1). Among these, wilt is the most serious one, leading to substantial economic losses, particularly in India.

### 3.1. Wilt Disease

Guava wilt was first discovered in Taiwan in 1926 and later in the Allahabad district, India, in 1935 [191]. Most of the studies on guava wilt are from India, as the disease is considered a national problem owing to the economic importance of this fruit crop. The wilt disease has also been reported in several other guava-producing countries, including Pakistan [192], Bangladesh [193,194], South Africa [195] and Australia [196] (Table 1).

Partial wilting is a typical wilt of guava characterized by initial wilting of one side of the plant or some parts of the plants; later, other parts of the plant are also affected [58]. Guava wilts are categorized as quick and slow wilts. The quick-wilt-affected plants take approximately 2 weeks to 2 months to completely wilt after the appearance of initial symptoms. In a study by Misra and Pandey [53], guava plants with quick wilt required a minimum of 16 days for complete wilting. In the slow-wilt-affected plants, complete wilting takes approximately one year or more.

Guava wilt symptoms emerge after the rainy season, from October to November [197]. The fruits on infected plants remain undeveloped, hard, and stony. The infected guava plants appear yellow, with slight leaf curling, which leads to drooping and shedding of the leaves. Bark splitting can also occur in the wilted plants. Guava wilt infects both young and older trees bearing fruits, but older trees are more susceptible [198].

Comprehensive studies on the causal pathogens of guava wilt have been performed primarily in India. Various fungal pathogens, including *Fusarium oxysporum*, *Fusarium solani*, *Fusarium pallidoroseum*, *Fusarium decemcellulare*, *Fusarium equiseti*, *Gliocladium roseum*, *Gliocladium virens*, *Gliocladium penicilloides*, *Acremonium* sp., *Acremonium restrictum*, *Curvularia lunata*, *Curvularia pallescens*, *Chloridium virescens*, and *Pestalotiopsis dissieminata*, have been reported to be associated with guava wilt [53]. However, pathogenicity tests have indicated that only two species of *Fusarium*, *Fusarium oxysporum* and *Fusarium solani*, and two species of *Gliocladium*, *Gliocladium roseum*, and *Gliocladium penicilloides*, are the causal pathogens of guava wilt [53]. Prasad et al. [51] established *Fusarium oxysporum* as the causal pathogen of guava wilt and proposed the name *Fusarium oxysporum* f. ps *psidii* as a special form of *Fusarium oxysporum*. To date, the name *Fusarium oxysporum* f. sp. *psidii* is used when referring to the wilt disease of guava. *Fusarium solani*, in combination with *Microphomina phaseoli*, could also instigate the wilt of guava. Although more *Fusarium solani* isolates have been recovered from the roots of wilting guava and more have been found to be prevalent in the field, *Fusarium oxysporum* f. sp. *psidii* was found to be the most virulent. A study indicated that *Fusarium oxysporum* f. sp. *psidii* is the primary pathogen of guava wilt [52].

Two other *Fusarium* species, *Fusarium proliferatum* and *Fusarium chlamydosporum*, were found to be associated with this disease. These two species have been detected in severely affected guava orchards in India [52,199]. Pathogenicity tests were only performed on *Fusarium chlamydosporum* and confirmed it as a pathogen of guava wilt. Recently, Gangaraj et al. [59] reported *Fusarium oxysporum* f. sp. *psidii* and *Fusarium falciforme* as the causal pathogens of guava wilt in India.

### *3.2. Guava Decline*

Decline is another serious guava disease that has been reported in India, Pakistan, and Brazil (Table 1). Guava decline is a complex disease that involves a synergistic interaction between *Fusarium* spp. and nematodes. During the synergistic interaction, infection of the root by nematodes predisposes the guava tree to *Fusarium* infection, thereby causing root rot [60,200]. The synergistic interaction between nematodes and *Fusarium* spp. was supported by a greenhouse and field assessment [201]. Two *Fusarium* spp., *Fusarium solani* and *Fusarium oxysporum*, and several species of nematodes are commonly associated with guava decline.

An inoculation study of nematodes and several root fungal pathogens of guava, including *Fusarium*, by Aftab [60] indicated that root-knot nematodes initiate root infection, and that the severity of decline symptoms could be due to the activity of fungal pathogens causing root rot. The role of nematodes is not only to allow fungi to enter the roots through wounded sites but also to alter the physiology of the root as well as the entire guava plant [202].

Guava decline symptoms are similar to wilt symptoms, which include chlorosis, wilting, leaf browning, and leaf drop. Noticeable symptom of guava decline is infected roots showing numerous galls, mainly due to infection by nematodes. Decline symptoms start appearing from the upper part of the infected tree and progress downwards [61,200]. Guava decline is the main disease of guava trees in Brazil, particularly in Rio de Janeiro. Initially, Gomes et al. [61] demonstrated that *Meloidogyne mayaguensis* and *Fusarium solani* cause the decline disease in guava in Brazil. Later, Gomes et al. [200,203] reported that the species complex of guava decline disease interacts with *M. enterolobii*, which parasitizes guava trees and allows infection by *F. solani*, thereby causing rotting of the roots.

Recently, Veloso et al. [64] reported that the decline disease of guava in Brazil is also caused by *Meloidogyne enterolobii* and *Fusarium solani.* According to Gomes et al. [61], the root knot nematode *Meloidogyne enterolobii* is a weak pathogen, and guava decline only develops with infection by *Fusarium solani*. A survey by Madhu et al. [62] in Haryana, India, revealed the presence of *Meloidogyne incognita* and *Fusarium oxysporum* and showed that their synergistic interaction contributes to guava decline incidence and severity. Decline was more severe in old orchards than in young orchards. Singh [63] reported that guava decline in Ratlam, India, is associated with the wilt fungus of guava, *Fusarium oxysporum* f. sp. *psidii*, and *Meloidogyne enterolobii.* Numerous galls were observed on the roots of infected guava trees. The same study indicated that *F. oxysporum* f. sp. *psidii* can cause both wilt and decline in guava. However, a detailed study is required to confirm the actual fungal pathogen of guava decline in the district of Ratlam, India, as the pathogen was identified based on mycoflora study.

Guava decline is also a major problem in Pakistan, as the disease develops rapidly and causes severe infection in many guava orchards. Guava decline in Pakistan is caused by various fungal pathogens, including *Fusarium solani*, *Fusarium oxysporum*, *Botryodiplodia theobromae* (synonym *Lasiodiplodia theobromae*), *Colletotrichum gloeosporioides*, Helminthosporium spp., and Curvularia lunata, as well as an oomycete, Phythopthora parasitica [65].

### *3.3. Anthracnose*

Guava fruit rot is a serious disease that occurs in the field and during storage, transportation, and marketing. Various fungal pathogens can cause guava fruit rot in the field, as well as after harvest [58]. In this review, we focus on *Colletotrichum* which causes anthracnose (Table 1). The most obvious symptoms of anthracnose in guava are necrotic and sunken lesions on the surface of the fruits (Figure 2). Masses of spores are formed on lesions during the advanced stage of infection. Anthracnose not only infects the fruits but also the leaves and twigs of guava.

**Figure 2.** Anthracnose of guava.

Prior to taxonomic reevaluation of the genus *Colletotrichum*, *Colletotrichum gloeosporioides sensu lato* was considered the most common species associated with guava anthracnose in several guava-producing countries [204–207]. After identification based on the phylogeny of multiple markers, several species of *Colletotrichum gloeosporioides* and *Colletotrichum acutatum* complexes have been reported as the causal pathogens of guava anthracnose. Species of the *Colletotrichum gloeosporioides* complex have been reported as pathogens of guava anthracnose in Italy [66] and those of the *Colletotrichum siamense* complex in India and Mexico [67,68]. Within the *Colletotrichum acutatum* complex, so far, three species have been reported as the causal pathogens of guava anthracnose, *Colletotrichum abscissum* in Brazil [69], *Colletotrichum simmondsii* in Brazil [70], and *Colletotrichum guajavae* in India [71].

### *3.4. Crown Rot*

Guava crown rot, caused by *Fusarium verticillioides*, has been reported in India [72]. The disease was detected in the Thai guava variety, which is an introduced variety in India. Guava crown rot usually occurs at the cut ends and spreads to the crown area, with discolored spots of various sizes [74]. Later, a larger lesion appears and turns into necrotic black circular patches that cover the whole fruit. Whitish mycelia appear in the lesions, and the fruits become discolored and malformed [72]. In a study by Valentino et al. [74], guava crown rot was reported to be caused by *Aspergillus* spp., *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus tamarii*, *Aspergillus japonicus*, and *Aspergillus flavus*.

### *3.5. Fruit Rot*

In addition to crown rot, another post-harvest disease of guava is fruit rot. Similarly to other post-harvest diseases, fruit rot of guava can occur in the field or during harvesting, storage, transit, and marketing. Similar to anthracnose, guava fruit rot lesions appear as brown spots, which later coalesce and become larger and expand to the whole fruit.

Several fungal species have been reported as the causal pathogens of guava fruit rot (Table 1). However, in some of the studies, the pathogens were identified based on morphological methods, and there is a possibility that the species identity of the pathogens is not accurate.

*Fusarium* spp. have been isolated from the fruit rot lesions of guava, among which *Fusarium oxysporum* has been reported in three localities in Egypt [77] and in several markets in Nigeria [76–78]. In a study by Amadi et al. [76], *Fusarium oxysporum* was found to be the most prevalent species isolated from guava fruit rot-infected plants. However, Latiffah et al. [208] reported that the *Fusarium oxysporum* and *Fusarium semitectum* isolated from guava rot-infected plants are not pathogenic.

Other guava fruit rot pathogens include *Aspergillus awamori* [79], *Phytophthora nicotianae* [80], *Neoscytalidium dimidiatum* [81], and *Lasiodioplodia theobromae* [82]. Furthermore, other post-harvest fungi recovered from guava rot lesions are *Pestalotia psidii*, *Rhizopus stolonifer*, *Aspergillus niger*, *Penicillium expansum*, *Rhizoctonia solani*, *Fusarium* sp., *Colletotrichum gloeosporioides*, *Fusarium oxysporum*, *Mucor* sp., *Rhizopus stolonifer*, *Aspergillus fumigatus*, and *Aspergillus parasiticus* [75,77].

### *3.6. Canker*

The canker of guava affects the stems and fruits. The symptoms on the stem include longitudinal cracks and discoloration of the bark, which develop into large vertical cracks. The causal pathogen is *Diplodia natalensis* [83]. A common fruit canker is caused by *Pestalotia psidii*. The initial symptoms are small, brown, circular lesions. In severe infections, raised spots develop in large numbers, and the fruits may break, thereby exposing the seeds [83].

## 4. Fungal Diseases of Passion Fruit

Passion fruit (*Passiflora edulis*) is a vine belonging to the family Passifloraceae, which originated in southern Brazil through Paraguay to northern Argentina [182]. It is cultivated for commercial purposes in many tropical and subtropical regions. The local names of the fruit crops include buah susu (Malaysia), chum bap (Vietnam), linmangkon (Thailand), and lilikoi (Hawaii). In Spanish, passion fruit is called granadilla, parcha, parchita, parchita maracuyá, or ceibey, and in Portuguese, maracuja peroba [209].

The two major economically important varieties of passion fruit are the purple-type (*Passiflora edulis* Sims.) and yellow-type (*Passiflora edulis* f. *flavicarpa* O. Deg) [210]. Fruits of the purple type are often consumed fresh, while fruits of the yellow type are used in juice processing and preservation [182]. Passion fruits are categorized as minor tropical fruits as they are produced and traded at small amounts. Brazil is the major producer, followed by Peru, Colombia, Ecuador, Australia, New Zealand, Indonesia, and several African countries [2]. The major diseases of passion fruit caused by fungi are Fusarium wilt, root and collar rot, anthracnose, and scab (Table 1).

### *4.1. Vascular Wilt*

Vascular wilt is an important disease of passion fruit, which can cause substantial yield losses. The disease is caused by *Fusarium oxysporum* f. sp. *passiflorae* and was first detected in Australia in 1950. Subsequently, vascular wilt was reported in several countries, including Brazil, Colombia, Korea, New Zealand, Panama, South Africa, Uganda, Venezuela, and Zimbabwe [87–89,211].

Vascular wilt affects both purple- and yellow-type passion fruit plants as well *Passiflora cincinnata*, which bears blue or violet flowers [86] and *Passiflora mollissima* [212]. According to Melo et al. [86], the incidence, severity, and mortality of wilt are higher in *Passiflora edulis*, the purple-type passion fruit. *Fusarium oxysporum* infecting passion fruit is host-specific, and the pathogenic strain produces distinctive proteins or effectors known as Secreted in Xylem (*SIX*), which may confer host-specific virulence [87].

Initial symptoms of vascular wilt include slight wilt at the branch tips and, sometimes, partial wilt or wilting of one side of the plant can occur. Thereafter, the entire plant wilts, followed by sudden death within 4–14 days [213]. Vascular tissues of the roots and lower stem appear dark brown to discolored. Cracks can also develop at the stem base [85]. As the fungus is a soil-borne pathogen, wilt usually starts in localized areas and spreads throughout the field via conidial dispersal. Conidia are often produced at high humidity [213].

*Fusarium solani* has also been isolated from the vascular tissues of *Passiflora edulis* showing wilting symptoms. When *Fusarium solani* and *Phytophthora nicotianae* v. *parasitica* were co-inoculated on *Passiflora edulis*, wilt developed rapidly, indicating that the concomitant infections of these pathogens can lead to the development of severe wilt [89]. According to Hirooka et al. [214], vascular wilt disease manifests as sudden wilt, and the authors recovered reddish perithecia from lesions at the collar part of the plant. Two pathogens, namely *Haematonectria ipomoeae* (=*Fusarium solani* f. sp. *melongenae*) and *Fusarium striatum*, were isolated from the infected roots, flowers, stems, and fruits of *Passiflora edulis* in Colombia.

### *4.2. Collar Rot*

Collar rot caused by *Fusarium solani* is another severe disease of passion fruit. Bueno et al. [96] proposed *Fusarium solani* f. sp. *passiflorae* as the causative pathogen of collar rot; as in a phylogenetic tree based on the ITS region and EF-1$\alpha$ sequences, these isolates formed a distinct cluster from other formae speciales of *Fusarium solani*. Although there are fewer reports of collar rot than of wilt disease, the former can also cause significant yield losses and has been detected on passion fruit cultivated in Brazil, USA, China, Uganda [92–96,98].

Generally, collar rot affects passion fruit plants 1–2 years after planting, although infection may occur earlier in previously affected planting areas [215]. Initial symptoms include slight wilting, with leaf color turning pale green, followed by severe wilting and defoliation. Infected plants die when severe necrosis or necrotic girdling occurs in the infected areas. At high humidity, perithecia may emerge in infected collar tissues [96,216]. In addition to *Passiflora edulis* and *Passiflora edulis* f. *flavicarpa*, the disease affects several passion fruit species, including *Passiflora alata*, *Passiflora ligularis*, *Passiflora maliformis*, and *Passiflora quadrangularis* [95,96,216].

*Fusarium solani* can survive in the soil as chlamydospores for many years; thus, collar rot pathogen can spread through the transfer of infested soil or seedlings. Moreover, high temperature and humidity are conducive to the development of collar rot [96].

### *4.3. Canker*

Symptoms of passion fruit canker are similar to those of vascular wilt, in which the leaves wilt and become chlorotic. However, plants infected with this disease develop concave cankers on the stem. Typically, however, defoliation does not occur, and the fruits remain on the plant. Infected tissues at the base of the stem may often be girdled at the soil line, which may be associated with root rot, adventitious root growth, and stem swelling at the canker site. Canker can be observed at the soil line or where the plant is strapped to the trellis. In infected stem tissues, perithecia are formed, and the infected plants often die within 5 years [99,100].

Two major pathogens causing passion fruit canker are *Fusarium solani* and *Fusarium oxysporum* f. sp. *passiflorae* [101,217]. According to Ploetz [217], *Fusarium solani* is not aggressive, and the presence of wounds plays a critical role in disease development. Wounding accelerates symptom appearance and increases disease severity. Through molecular identification, *Fusarium oxysporum* and *Nectria haematococca*-type isolates were detected in diseased tissues [101].

Passion fruit canker, reported as Nectria canker, has been detected in Taiwan and Uganda [92,102]. Another disease similar to Nectria canker, reported as the base rot of passion fruit, has been reported in subtropical Australia, but the causal pathogen was *Fusarium solani* [218].

Detailed reports on passion fruit canker are available from Florida [93]. To date, however, there has been no report of canker from other producing countries, due perhaps to the resemblance of its symptoms to those of vascular wilt, which may lead to description of the disease as wilt or dieback and collar rot, which also present similar symptoms. However, in a pathogenicity test, canker symptoms take a longer time to develop, indicating the "subtle nature" of the disease [93,101].

### *4.4. Anthracnose*

Similar to other fruit crops, passion fruit is infected by anthracnose in the field or post-harvest during storage, transportation, and marketing. In addition to fruits, anthracnose affects leaves and twigs, causing defoliation and twig wilt [216]. Symptoms on leaves and twigs manifest as circular or irregular brown spots with dark edges [219]. On fruits, typical anthracnose symptoms are observed, starting as brownish-black spots, which coalesce to produce large sunken lesions with spore masses. Initially, most reports on passion fruit anthracnose indicated *Colletotrichum gloeosporioides* as the causal pathogen [217,220]. However, Tarnowski and Ploetz [108] reported four additional species, namely *Colletotrichum boninense*, *Colletotrichum truncatum*, *Colletotrichum gloeosporioides*, and *Glomerella* sp. as the pathogens of passion fruit anthracnose in Florida.

Based on molecular markers, several other species have been reported to be the causal pathogens of passion fruit anthracnose. For instance, *Colletotrichum boninense* has been identified as an anthracnose pathogen in Brazil [109], *Colletotrichum queenslandicum* in Northern Territory, Australia [110], *Colletotrichum brevisporum* in Fujian Province, China [111], *Colletotrichum capsici* (=*Colletotrichum truncatum*) in China and Taiwan [112,113], *Colletotrichum brasiliense* in China [114], and *Colletotrichum constrictum* in Yunnan, China [115].

### *4.5. Brown Spot and Septoria Spot*

Brown spot and Septoria spot are the two other common diseases that infect passion fruit leaves and fruits. Two *Alternaria* species, namely *Alternaria passiflorae* and *Alternaria alternata*, are the causal pathogens of brown spot. Brown spot lesions caused by *Alternaria passiflorae* are larger than those caused by *Alternaria alternata*. Severe infection of leaves causes defoliation and fruit infection, which in turn reduces the quality and commercial value of the fruits [215,216].

The causal pathogens of Septoria spot or blotch are *Septoria fructigena*, *Septoria passifloricola*, and *Septoria passiflorae*. Leaves are the most susceptible to *Septoria* spp., although the disease also infects young twigs, flowers, and fruits. The latest report of *Septoria* spot was in Taiwan, which infected 2–3-month-old grafted passion fruit seedlings, and the causal pathogen was *Septoria passifloricola* [221].

## **5. Fungal and Oomycete Diseases of Lychee**

Lychee or litchi (*Litchi chinensis* Sonn.) belongs to the family Sapindaceae, or the soapberry family. Presumably, lychee originated in Kwangtung and Fukien in southern China and has been cultivated for thousands of years in southern Guangdong [222]. From the 17th century onward, lychee cultivation spread to neighboring countries, particularly in Thailand, India, and Myanmar, and subsequently, in the 19th century, it expanded to the East Indies, Florida, and California [182].

In Asia, China is the leading producer of lychee, followed by India and Vietnam. Lychee production in China and India is mainly for the domestic market, particularly in China, as the fruit is very popular. Lychee produced in Vietnam is exported to China, the USA, Japan, and Australia. Following Asia, Africa is the most important region of lychee cultivation, with Madagascar being the leading producer of this fruit. Lychee cultivated in Madagascar is mainly exported to Europe, particularly France and the Netherlands [2].

Most of the published reports on the fungal diseases of lychee include anthracnose; pepper spot; and leaf, panicle, and fruit blight (Table 1). Other diseases include brown blight and tree decline [223]. Misra and Pandey [224] listed a number of fungal diseases of lychee in India, including leaf spot, root rot, and fruit rot, but the authors indicated that the diseases did not lead to a major economic impact on the yield.

The anthracnose of lychee infects not only fruits but also leaves, flowers, and flower stalk, leading to fruit rot, flower drop, and leaf spot. Infection is prevalent in warm and wet weather. The reported causal pathogen is *Colletotrichum gloeosporioides* and, sometimes, *Colletotrichum acutatum* [117]. Anthracnose of lychee fruits manifests as browning of the pericarp, but the fleshy part is typically unaffected [116]. Pericarp discoloration affects the appearance and quality of fruits. In Mexico, *Colletotrichum gloeosporioides* was isolated from immature fruits and asymptomatic flowers, indicating that the infection is a latent pathogen, and the pathogen may even be an endophyte [118]. In a recent study on lychee anthracnose, *Colletotrichum fioriniae* was found to be the causal pathogen of fruit anthracnose [119] and *Colletotrichum karstii* was found to be the causal pathogen of leaf anthracnose [119].

Another disease affecting lychee is pepper spot was reported in Australia, Taiwan, and China. Symptoms of pepper spots appear as slightly raised, dark small spots on leaves, petioles, and fruits. On fruits, small spots may merge and cover much of the fruit surface. Similar to anthracnose, pepper spots also affect the appearance and quality of lychee fruits [225]. According to Anderson et al. [122], lychee pepper spots may also occur in other producing countries, such as the USA, Taiwan, and China, as symptoms similar to those of pepper spot have been reported.

*Colletotrichum gloeosporioides* has been reported as the causal pathogen of pepper spots in Australia [121,122] and the same pathogen also causes lychee anthracnose. In Taiwan and China, *Colletotrichum siamense* is the causal pathogen of lychee pepper spots [123,124].

The occurrence of leaf, panicle, and fruit blight of lychee caused by *Alternaria alternata* has been reported in Bihar, India [125]. Leaf blight occurs on old senescent leaves in mature lychee orchards and is regarded as economically non-important. Panicles and fruit blight appear during flowering and fruit development. Infected panicles become shriveled and dried, leading to necrosis. Pedicel infection causes necrosis, further leading to fruit blight and drying of the developing fruit. In addition to anthracnose, fruit rot caused by *Alternaria* sp. is a common post-harvest disease of lychee in India [125].

*Colletotrichum* has been recently reported to affect ripe lychee fruit in Hainan, China. The disease was detected in a field in which brown-to-black lesions were observed on the inner pericarp [126].

In addition to fungal diseases, downy blight caused by the oomycete *Phytophthora litchi* is a major disease of lychee. Downy blight infects young leaves, flowers, fruits, panicles, and shoots. Infected tissues became brown and are covered with masses of sporangiophores and sporangia. Oomycetes also cause fruit rot, resulting in considerable post-harvest losses [127,128].

## 6. Fungal and Oomycete Diseases of Longan

Longan (*Dimocarpus longan* Lour.) belongs to the family Sapindaceae, the same family as lychee, and is also called eyeball or dragon's eye. The fruit crop originated in southern China, specifically in Fukien, Kwangsi, Kwangtung, and Schezwan provinces [182]. Longan is commercially cultivated in China, Thailand, Cambodia, India, and Vietnam, with China and Thailand being the largest producers. Other producing countries include Bangladesh, Australia, South Africa, Reunion, Brazil, and Israel [226]. Longan production has increased over the past few years due to rising demand in China and Thailand. Moreover, Thai longans are preferred in China because of their superior quality, and import by China increased to approximately 140% in 2017 [2].

Over the years, there have been a substantial number of reports and publications on the fungal and oomycete diseases of longan. Diseases in the field affect the yield, and diseases on the fruits affect the commercial value of the commodity. Diseases in the field include downy blight, dieback, inflorescence wilt, and blight. Regarding fruits, pericarp browning, brown rot, and fruit rot have been reported (Table 1).

Downy blight of longan is caused by *Phytophthora litchi* (formerly known as *Peronophythora litchi*). The disease affects young leaves, panicles, flowers, and fruits. Obvious signs and symptoms of downy blight include infected tissues that become brown and covered with masses of white sporangia and sporangiophores [227]. *Phytophthora litchi*-infected leaf and stem rot of longan seedlings has been reported in Taiwan. The infected young leaves appear as droopy, blighted leaves, which eventually wither and fall. Water-soaked lesions are formed on infected leaves [129].

Another species, *Phytophthora palmivora*, also infected young shoots, panicles, and fruits. Necrosis appears in young shoots and irregular lesions appear on fruits, causing fruit rot and premature fruit drop [117,228]. *Phytophthora palmivora* was reported to cause the brown rot of longan fruit in Thailand. Small brown spots appear on the skin, which develop into larger patches. Severe brown rot infection leads to fruit drop [131]. In addition to *Phytophthora litchi* and *Phytophthora palmivora*, which cause fruit rot, *Lasiodiplodia theobromae* and *Lasiodiplodia pseudotherobromae* have also been reported as the causal pathogens of longan fruit rot. *Lasiodiplodia theobromae* infected longan fruit in the field in Puerto Rico [132]. *Lasiodiplodia pseudotheobromae* was reported to cause longan fruit rot in Lamphun Province, Thailand, which developed post-harvest under high humidity and temperature [133].

Other fungi that infect longan fruit include *Phomopsis longanae* and *Lasiodiplodia theobromae*, causing pericarp browning, which affects the shelf life of fruits [134,135]. Pericarp browning is a major post-harvest disease of longan fruit in southern China [134].

Inflorescence and flower wilt and vascular necrosis of longan have been detected in Puerto Rico, and the causal pathogen was identified to be *Fusarium decemcellulare*. Inflorescence and flower wilt appeared in 50% plants and vascular necrosis on 70% plants [130]. Other diseases reported in Puerto Rico include dieback caused by four species of Botryosphaeriaceae, namely *Lasiodiplodia hormozganensis*, *Lasiodiplodia iraniensis*, *Lasiodiplodia pseudotheobromae*, and *Lasiodiplodia theobromae* [136]. *Lasiodiplodia theobromae* is also the pathogen of inflorescence blight of longan, which causes the rotting of flowers, rachis, and rachilla [132].

## 7. Fungal and Oomycete Diseases of Durian

Durian (*Durio zibethinus* L.) is a tropical fruit crop in the family Malvaceae, with the center of origin in Peninsular Malaysia, Indonesia, and Borneo [229]. From these countries of origin, durian was introduced to other Southeast Asian countries, including Thailand, Vietnam, the Philippines, and Myanmar. Durian is planted on a small scale in Hawaii, Costa Rica, Brazil, Ecuador, and Panama [230]. Thailand is the main exporter of durian, followed by Malaysia and Indonesia, and China is the leading importer of this fruit [2].

Durian is known as the king of tropical fruits because of its distinctive appearance, odor, and taste. Apart from the word durian from the Malay word "duri," meaning a thorn, other names or terms have been given to the fruits based on its smell, including stinkvrucht (stink fruit) in Dutch and civet fruit in India [182]. Durian is called tu-rien in Thailand, sau rieng in Vietnam, and liu-lian guo in Mandarin [230].

Economically important and the most severe diseases of durian are caused by the oomycete, *Phytophthora palmivora*, causing various types of diseases that infect durian in all growing countries. This oomycete is a soil-borne pathogen, and it can therefore infect the aerial parts of durian, leading to the infection of all plant parts and at all stages of plant growth. Moreover, hot and humid conditions as well as high rainfall are favorable for the pathogen growth and development [231].

The most severe diseases caused by *Phytophthora palmivora* are patch canker or stem canker, fruit rot, seedling dieback, foliar blight, and root rot [137–139]. The pathogen enters plant parts through natural openings or wounds [232]. *Phytophthora palmivora* is an effective pathogen, as the oomycete can reproduce rapidly under favorable conditions, and the zoospores are readily released from the sporangia in the presence of water [233]. Moreover, the pathogen produces several structures, including zoospores, sporangia, and chlamydospores for infection and spread [138].

The initial symptoms of patch canker caused by *Phytophthora palmivora* include distinct wet patches on the bark. When the patches on the stem or branch merge, the canker is formed, and reddish/brown substances ooze from the canker lesion. The lesion commonly spreads into the xylem, leading to leaf wilting and chlorosis and, ultimately, dieback [149]. Patch canker is regarded as the major disease of durian in Malaysia and was reported on many durian trees in Brunei, Darussalam [140]. Moreover, the incidence of patch canker was high in most durian orchards in Vietnam, and severe infection was noted on trees older than 20 years of age [141].

Symptoms of stem rot are rather similar to those of patch canker, in which the disease affects the trunk and bark and also causes yellowing and wilting of leaves. Stem rot is a severe disease of durians in Thailand. The causal pathogens are *Fusarium solani* and *Lasiodiplodia pseudotheobromae*, in addition to *Phytophthora* sp. [142].

In addition to *Phytophthora palmivora*, fungal pathogens cause durian leaf blight. In Vietnam and Peninsular Malaysia, *Rhizoctonia solani* is the causal pathogen of durian leaf blight [143,144]. Leaf blight occurs in nurseries and orchards, infecting individual leaves or the entire foliage. In orchards, when the symptoms are visible, the infection has spread to other parts of the tree [139,151], rendering control difficult. Leaf blight starts as small spots on leaves, which subsequently form larger lesions. The blighted lesions dry-up, turning dark brown, and the leaves appear necrotic and shriveled; the infected leaves easily fall, particularly when the disease is severe. Leaf blight reduces photosynthesis, which affects flower and fruit development.

Another fungal leaf disease is leaf spot caused by *Phomopsis durionis*, which infects durian seedlings and mature trees. Durian leaf spot is believed to be a latent infection in the field. Leaf spot begins as dark brown spots with a yellow halo, which are more obvious on mature leaves. The disease is more prevalent in poorly managed orchards, and the affected plants appear unhealthy due to reduced photosynthesis [145].

Symptoms of fruit rot caused by *Phytophthora palmivora* appear as small brown water-soaked patches on the outer skin, which later turn into dark brown or black lesions. Whitish mycelia and sporangia appear in the lesion. Infection can occur in both ripe and unripe fruits [234]. The rot lesion spreads to the pulp and seed, which affects the marketability of fruits as they are inedible [138]. Preharvest fruit rot of durian results in post-harvest rot, although the symptoms may not be obvious during or post-harvest. Infection can also occur when healthy fruits come in contact with infected fruits or orchard soil containing the pathogen inoculum. Infection of unwounded fruits can occur under prolonged (72 h) exposure to high humidity (minimum of 98%) [149]. Fruit rot can result in 10–25% loss [139].

Fungal pathogens can also cause durian fruit rot, causing symptoms similar to those caused by *Phytophthora palmivora*. *Sclerotium rolfsii* was found to be the pathogen of durian fruit rot that had come in contact with orchard soil [146]. Following harvest, several fungal pathogens were isolated from rot lesions of the infected fruit. *Colletotrichum gloeosporioides* and *Lasiodiplodia theobromae* are the most prevalent fruit rot pathogens [147]. Other pathogens including *Aspergillus* spp., *Penicillium* sp., and *Fusarium equiseti* are the secondary invaders or weak pathogens [148].

Durian tree decline has been reported in Queensland, Australia, and Indonesia. The disease was described to cause necrosis of the feeder root cortex tissues, rapid dieback, infrequent stem canker, and finally death. From infected durian trees in Queensland, Australia, two species of oomycetes, namely *Pythium vexans* and *Pythium palmivora*, were isolated, and the percentage of oomycetes isolated differed during dry and wet seasons. In both seasons, the percentage of *Pythium vexans* was higher than that of *Pythium palmivora*. A plant parasitic nematode, *Xiphenema* sp., was also isolated, suggesting a synergetic association between the oomycetes and nematode [149]. In Indonesia, diseases caused by *Phytophthora palmivora*, *Pythium cucurbitacearum*, and *Pythium vexans* led to durian tree decline [150].

In addition to *Phytophthora palmivora*, several species of *Phytophthora* and *Pythium* have been linked to durian diseases. *Phytophthora nicotianae* has been occasionally recovered from root rot and canker lesions [151]. Furthermore, *Phytophthora cinnamomi*, *Pythium* *cucurbitacearum*, *Pythium vexans*, and *Pythium deliense* have been reported as the causal pathogens of root and stem rot in durian trees [152,153].

*Phytophthora palmivora* remains a significant pathogen of durian and can infect a broad range of hosts, particularly wounded plants. Cross-infectivity studies have shown that *Phytophthora palmivora* isolates can infect other plant hosts. *Phytophthora palmivora* isolates from durian were found to be moderately pathogenic to papaya [235]. In addition, isolates from cocoa could infect durian, rubber, oil palm, and coconut [236–239]. These studies indicate the possibility of field infection by *Phytophthora palmivora* in susceptible plants. The ability of *Phytophthora palmivora* to infect a wide range of hosts might be due to the presence of multiple pathogenic strains of this oomycete [239]. Additional more virulent or aggressive strains of *Phytophthora palmivora* may emerge. Therefore, disease surveillance of susceptible crops is essential to avoid severe outbreaks. Moreover, quarantine measures should be implemented on susceptible crops and planting materials brought into the country.

## 8. Fungal Diseases of Rambutan

Rambutan (*Nephelium lappaceum* L.) belongs to the family Sapindaceae, the same family as longan and lychee. The fruit is native to Malaysia and cultivated throughout Southeast Asia, with Indonesia being the largest producer, followed by Thailand [2,182]. Rambutan is also cultivated on smaller scales in the American tropics, South Africa, Hawaii, Puerto Rico, Sri Lanka, the Philippines, Australia, and Madagascar [182].

Rambutans are primarily used for domestic consumption. In the international market, the fruit remains a niche for Asian ethnic consumers in Europe and the US; and is also in demand from specialty or premium stores. Previously, rambutans were not well-known to Western consumers, and high retail prices restricted fruit marketing. However, retail prices of rambutans have dropped, and the demand for specialty fruits has risen; thus, rambutans have the potential to grow and gain more prominence in the Western market [2,239].

Several fungal diseases of rambutans, either in the field or post-harvest, have been reported. The common diseases include fruit rot, corky bark, stem canker, dieback, and powdery mildew (Table 1). These diseases have been reported in several rambutan-producing countries worldwide.

### *8.1. Fruit Rot*

Fruit rot is one of the most severe diseases of rambutan, involving various fungal pathogens that infect fruits in the field and post-harvest. Infection in the field has the potential to affect fruits post-harvest, particularly if the fruits are not treated and stored under appropriate conditions [160], which ultimately affects their marketability.

Symptoms of fruit rot in mature and immature fruits are characterized by light to dark brown and sometimes black areas with water-soaked lesions on the surface of fruits. The lesions developed into the pericarp, causing blackening and drying of the infected parts (Figure 3A,B). The pericarp may crack, exposing the flesh [159,164].

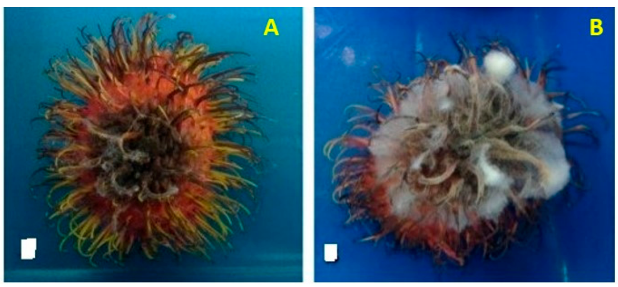


**Figure 3.** Rambutan fruit rot. (**A**) Fruit rot lesion. (**B**) Mycelia growth from the lesion.

Rambutan fruit rot has been reported in Hawaii, Puerto Rico, Malaysia, Thailand, and Sri Lanka. In previous reports of rambutan fruit rot in Thailand and Sri Lanka, various fungal pathogens or a complex of fungal pathogens were isolated from infected fruits, including *Botryodiplodia theobromae*, *Colletotrichum gloeosporioides*, *Gliocephalotrichum bulbilium*, *Pestalotiopsis* sp., *Phomopsis* sp., and *Glomerella* sp. [155,157]. In China, fruit rot of rambutan is referred to as a gray spot caused by *Pestalatiopsis* sp. [158].

In Hawaii, the causal pathogens of rambutan fruit rot include *Lasmenia* sp., *Gliocephalotrichum* spp., and *Pestalatiopsis virgatula* [159,160]. Several species of fungi have been recovered from fruit rot lesions, namely *Gliocephalotrichum bulbilium*, *Gliocephalotrichum simplex* [161]; *Calonectria hongkongensis* [162], *Colletotrichum fructicola*, and *Colletotrichum queenslandicum* [149]. In Malaysia, rambutan fruit rot is caused by *Gliocephalotrichum bacillisporum* [164].

### *8.2. Corky Bark, Stem Canker, and Dieback*

Corky bark is a severe disease of rambutan and is often associated with stem canker and dieback [45,47,136]. *Dolabra nepheliae* is the causal pathogen of corky bark on rambutan, which was first detected in Malaysia [45]. Years later, the pathogen was reported on diseased rambutans in Hawaii, Puerto Rico, and Honduras. Corky bark initially emerges as irregular patches on the main stem and lateral branches, which later develop into brown lumps. The pathogen spreads to young stems or twigs, and the lumps appear as corky and rough structures bulging from the bark. As the stem and branches develop, the lumps or corky structures became larger, and the bark cracks, forming canker on the stem and branches. The canker formed on the stem appears roughened with irregular to spherical shapes. Ascomata of the pathogen develop in the bark fissure [166]. In severe cases, dieback of the branches manifests, which reduces tree growth [167].

The stem canker of rambutan was reported in Hawaii, Puerto Rico, and Honduras, and the causal pathogen was *Dolabra nepheliae*. The disease is relatively common in Hawaii and Puerto Rico and has likely been introduced from infected germplasm. Symptoms of stem canker normally appear on rambutan trees that are approximately 3 years old. The pathogen also infects branches. The bark fissures of infected stems appear swollen, with dark brown to black discoloration. As the tree matures, the size of the canker increases and the branches weaken and break due to the weight of the fruits, causing substantial fruit loss and tree damage [168,169].

In Puerto Rico, corky bark and dieback of rambutan caused by Botryosphaeriaceae species, including *Lasiodiplodia brasiliensis*, *Lasiodiplodia hormozganensis*, *Lasiodiplodia iraniensis*, *Lasiodiplodia pseudotheobromae*, *Lasiodiplodia theobromae*, *Neofusicoccum batangarum*, and *Neofusicoccum parvum*, were reported. The symptoms begin with necrosis of vascular tissues and branches, followed by dieback, in which the infected branches turned dark brown. The disease later spreads to the leaves. Corky bark symptoms appear, with the development of pycnidia on branches and the main stems, which become discolored [130].

### *8.3. Powdery Mildew*

Powdery mildew of rambutan is caused by *Oidium nephelii*, an obligate parasite that is prevalent in Sri Lanka, the Philippines, Thailand, and Malaysia [170,172]. The fungus appears as mycelia on young leaves in white patches, and subsequently completely covers leaves, flowers, and fruits. Infected fruits become discolored, turn black, and may crack, affecting fruit quality [172,240].

### *8.4. Other Fungal Diseases*

*Pseudocercospora nephelii* was identified as the causal pathogen of leaf necrosis in rambutan seedlings, which can also lead to defoliation. Necrosis on leaves starts as small light brown spots that merge and become larger, turning 70–80% of the leaves necrotic. Severe infections can lead to defoliation and death of infected seedlings. The disease was reported in Brunei as well as in Sabah and Selangor in Malaysia [173]. Thus far, there has been no updated or latest report on the occurrence of this disease.

Inflorescence wilt and flower and vascular necrosis of rambutan were reported in Puerto Rico. The diseases affected 50% of rambutan inflorescences, and the causal pathogen was *Fusarium decemcellulare* [130], which also caused the same diseases on longan and mango in Puerto Rico.

## 9. Fungal Diseases of Mangosteen

Mangosteen (*Garcinia mangostana* L.) belongs to the family Guttiferae and is planted for fruits. The fruit crop is called the queen of fruits because of its sweet and sour taste, and it is mainly consumed fresh. Mangosteen is native to Southeast Asia, and the place of origin is believed to be the Sunda Islands and the Moluccas (Maluku Islands). In Kemaman, Malaysia, wild mangosteen trees are found in forests [182]. Southeast Asian countries, namely Thailand, Malaysia, Indonesia, and the Philippines, are the major mangosteen producers, with Thailand being the largest producer and exporter [2]. Mangosteens are also planted in South America, tropical Africa, and northern Australia [241].

Unlike other tropical fruit crops, pre- and post-harvest diseases of mangosteen are not a major problem. Several fungal diseases have been reported to infect mangosteen, including leaf disease, stem canker, fruit rot, and tree decline [179] (Table 1). The causal pathogens were similar to those reported for other fruit crops.

Leaf blight caused by *Pestalotiopsis flagisettula* has been reported in Thailand. Pestalotiopsis leaf blight has also been reported in Malaysia and North Queensland [152]. Brown leaf spots and blotches were detected in Hakalau, Hawaii, and the causal pathogen was identified to be *Pestalotiopsis* sp. [175].

Several fungal pathogens have been identified as the causal pathogens of mangosteen fruit rot, which occur mainly during post-harvest. Many of these fungal pathogens are secondary or weak pathogens that infect fruits through wounds in the field during storage and transportation [148]. *Diplodia* fruit rot affected mangosteen in Thailand, and the causal pathogen was reported to be *Diplodia theobromae* [174]. Several fungal pathogens are linked with mangosteen fruit rot in the field, with *Lasiodiplodia theobromae* being the causal pathogen of black aril rot, *Phomopsis* sp. of white aril rot, and *Pestalotiopsis* sp. of soft aril rot [179]. *Phomopsis* sp. and *Pestalotiopsis* sp. also cause mangosteen storage rot [177].

Imported mangosteen fruits in Guangzhou, China were infected by *Gliocephalotrichum bulbilium*, the pathogen causing discoloration of the pericarp and rotting of the edible flesh [176]. *Gliocephalotrichum bulbilium* and *Graphium* sp. are also associated with mangosteen storage rot [177]. Another fungal pathogen causing mangosteen fruit rot is *Mucor irregularis*, isolated from samples obtained from several markets and supermarkets in Wujing Town, Shanghai [178].

A decline in mangosteen trees was reported on the southern coast of Bahia, Brazil. Infection starts from the roots and spreads to the entire tree, with symptoms of wilting, yellowing, blighting, and defoliation, eventually causing tree death [180]. Two species of *Lasiodiplodia*, namely *Lasiodiplodia theobromae* and *Lasiodiplodia parva*, have been reported to be the causative pathogens of the disease. Other diseases of mangosteen include brown root rot caused by *Phellinus noxius*, stem canker and dieback caused by *Pestalotiopsis* sp. and thread blight caused by *Marasmiellus scandens* [174].

## 10. Management of Fungal and Oomycetes Diseases

Integrated disease management (IDM) is recommended to manage fungal and oomycete diseases of minor tropical fruit crops. Common methods in IDM are combinations of cultural, chemical, and biological methods which are applied to manage a wide range of diseases at the same time. Among the cultural methods commonly used are healthy seeds or propagating materials, field sanitation, and proper irrigation/drainage. These methods allow low or non-damaging levels of disease occurrence [242].

Some of the fruit crops are propagated through seed (rambutan, mangosteen, and durian), cutting (dragon fruits), budding, and grafting (passion fruit, longan and lychee).

The use of infected planting materials readily transmits and spreads the disease. Thus, the use of disease-free planting materials is important to avoid disease occurrence [243].

Proper irrigation and drainage are essential to manage wilt, root rot, crown rot, foot rot, stem rot, and die back, particularly caused by *Phytophthora*, *Pythium*, and *Fusarium*. The movement of water increases disease spreading to healthy plants which can be controlled by good and proper drainage. In the production area or nursery, accumulation of water should be avoided. To prevent infection, plants should be planted in raised beds which create drier conditions at the base. The pathogen or inoculum in irrigation and drainage water either in the nursery or in the field can infect the foliar part as well as the trunk and stem through water splashing, causing leaf blight, stem rot, gummosis, and canker [244].

Minor tropical fruit crops are perennial, of which several disease cycles occur and produce inoculum that can remain dormant. Pruning and removal of infected and dead plant parts including branches, leaves, twigs, and mummified fruits are the easiest methods to reduce the inoculum. Removal of canker should be followed by fungicide application such as Bordeaux mixture which allows faster wound healing and reduces dormant inoculum [243].

Sanitation in the nursery and in the field includes removing diseased or infected plant parts which can prevent spreading of pathogens to healthy plants. Diseased leaves, twigs, branches, stems, trunks, and fruits are sources of inoculum, and to eliminate the inoculum/pathogen, these plant parts are destroyed by burning. It is advisable to remove infected plant parts as soon as disease symptoms appear. Cleaning and disinfection of farming tools are part of sanitation methods of which this method can minimize disease spreading [243]. In addition to field sanitation, regular monitoring of healthy trees for signs and symptoms of diseases is essential to treat infected trees and to prevent widespread infections.

The application of fungicides has a large impact in fruit crops' disease management; thus, the use of fungicides should be within the scope of IDM strategy [245]. Important criteria to consider when using fungicides are the proper timing of application, the suitable fungicides to be used to manage the disease and the duration of protection by the fungicide. Triazoles are systemic and curative fungicides which are only effective during early infections. Most strobilurin fungicides provide protection of approximately 21–28 days after infection [246]. It is highly advisable to read the label carefully to ensure recommended fungicide for a particular disease is used and for efficient as well as safe use of the fungicide.

Biocontrol agents are alternatives to fungicides due to their perceived safety levels and minimal impact on the environment. Moreover, the current trend is switching towards reducing the use of agrochemicals to more eco-friendly methods of plant disease management. Several commercial products containing biocontrol agents are available to be used against fungal pathogens. Among the products are Primastop, containing *Clonostachys rosea* (*Gliocladium catenulatum*) to control wilt, seed rot, stem and root rot; Trichoderma Viride Trieco, containing *Trichoderma viridae* against soilborne fungal diseases; and RootShield®, containing *Trichoderma harzianum* to manage root rot diseases caused by *Pythium*, *Fusarium*, *Rhizoctonia*, and *Cylindrocladium* [247].

After harvest, the fruits can become infected by a number of fungal pathogens which affect the quality of the produce. Infection by fungi can occur in the field, during harvesting, handling, grading, storage, transportation and marketing [248]. The anthracnose pathogen becomes latent after infection and symptoms appear after harvest. Other fungal pathogens can directly penetrate the fruit's skin through wounds or mechanical injury, causing fruit rot.

Washing of fruits is carried out after harvest to remove dirt, latex and stains as well as to improve the appearance of the produce. The most common sanitation wash is chlorine which is considered inexpensive. Other than washing, other forms of physical methods for the treatment of fruit crops are hot water treatment, heat treatment and gamma radiation [249].

Several fungicides including dichloran, imazalil, sodium ortho-phenil phenate, and thiabendazole are used as post-harvest treatments against wide range of fruit rot pathogens.

Application of the fungicides are usually as drenches, high and low volume sprayers as well as dipping and flooder. However, due to issues related to fungicide residues and pathogen resistance, other alternative chemicals such as generally recognized as safe (GRAS) salts, namely sodium benzoate, sorbic acid, propionic acid, and acetic acid are used as postharvest treatment of fruit crops. These GRAS salts are applied as edible coating [250]. In addition to GRAS salts, chitosan, mineral oil, essential oil and cellulose are can also be used as edible coating [251].

There is a range of disease management methods and post-harvest technologies available that would enable smallholders and large plantation owners to improve the quality of the fruit crops. For smallholder farmers, they may face budget constraints to adopt new methods especially for postharvest practices and technologies.

## 11. Conclusions

Minor tropical fruits contribute to the economic growth and livelihood of smallholder farmers and promote local food security. However, several diseases affect production, which directly impacts the income of farmers. In most cases, common diseases of minor tropical fruits are wilt, stem diseases, anthracnose, and fruit rot. Diseases originating in the field such as anthracnose may express after harvest, particularly during storage. Fruit rot commonly occurs during storage due to improper handling and storage conditions. Thus, the knowledge of these diseases and their causal pathogens is paramount for planning and strengthening management in the field and during storage, transportation, and marketing post-harvest, as some of these fruit crops are grown for export markets.

However, there have been fewer studies on the diseases of minor tropical fruit crops compared to major tropical fruit crops, except for diseases on dragon fruits, as this fruit is cultivated commercially in many parts of the world, including several countries in Central and South America, Asia, and Australia. The great demand for dragon fruits in the international market has also contributed to many studies conducted on this fruit. However, the trend has now improved due to the rise in global demand for several minor fruit crops, such as passion fruit, guava, lychee, and longan. In addition to diseases, other research areas are also important, including post-harvest handling, storage conditions, and transportation, as minor tropical fruits have short shelf-lives and can easily perish.

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## ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

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| Management of phytophthora and phytopythium oomycete diseases in durian (Durio zibethinus) / Singh, A., Chow, C., Nathaniel, K., Vun, Y. L., Javad, S., & Jabeen, K. |
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Review

# Management of *Phytophthora* and *Phytopythium* oomycete diseases in durian (*Durio zibethinus*)

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ABSTRACT

Durian (*Durio zibethinus* L.) is a valuable fruit crop originating from Borneo and widely cultivated in Southeast Asia, including Malaysia, Thailand, and Indonesia. Increasing consumer demand, particularly from China, has boosted its trade and value. However, the durian industry faces significant challenges from the devastating pathogens *Phytophthora palmivora* and *Phytopythium vexans*, which cause various forms of rot and dieback, leading to economic losses. Current management strategies include cultural practices, synthetic fungicides, biological controls, and integrated management. While cultural practices and synthetic fungicides are commonly used, they have limitations such as health and environmental risks, labor intensity, and inconsistent effectiveness. Alternative approaches, such as gene silencing of Protein Phosphatase 2A to produce disease-resistant plants and the use of plant extracts with antimicrobial properties, show promise and warrant further exploration. This review aims to guide farmers and beginners in exploring alternative methods for managing durian diseases.

## 1. Introduction

Durian (*Durio zibethinus*) is a tropical fruit belonging to the Malvaceae family. It is widely cultivated in Southeast Asia, particularly in countries like Malaysia, Thailand, and Indonesia. The fruit is renowned for its large size, thorn-covered husk, creamy flesh, and strong, distinctive odor, which has led to its ban in many hotels and public places (Young, 2017). Despite its polarizing smell, durian is highly valued for its rich nutritional content, including essential vitamins, carbohydrates, dietary fibers, bioactive compounds, minerals, fats, and proteins (Leontowicz et al., 2011).

The global production of durian has seen significant growth, with approximately 3 million tons produced in 2023, primarily by Indonesia, Thailand, and Malaysia. The increasing international demand, especially from China, has further boosted its trade and economic value (FAO, 2023; Khoo, 2024). However, durian cultivation faces several challenges, including environmental factors such as unpredictable rainfall patterns, rising temperatures, and extreme weather events, which adversely affect productivity (Lilavanichakul and Pathak, 2024). Additionally, the spread of diseases in durian trees poses a significant threat to yield and quality, leading to increased production costs, loss of biodiversity, and economic losses (Kumar, 2014).

Among the various pathogens affecting durian, *Phytophthora palmivora* and *Phytopythium vexans* are the most devastating. These oomycete pathogens cause severe diseases such as root rot, patch canker, foliar blight, and fruit rot, leading to dieback in many durian orchards. *P. palmivora* is particularly notorious, having infected up to 30% of durian trees in some areas of Penang Island (Khew, 1990). Studies have reported root rot infection rates of 24% in the dry season and 35% in the wet season (Vawdrey et al., 2005a,b). In the southern Philippines, 40% of durian trees were affected by *Phytophthora* (Preciados et al., 2013), with overall disease losses in Southeast Asia estimated at 20–25%, translating to approximately US$2.3 billion (Drenth and Guest, 2004). In Davao City, a durian farm reported 13%–30% fruit loss due to *P. palmivora* infection over two years (Abad and Cruz, 2013). The incidence of the disease is also linked to orchard age and soil pH, with older orchards and acidic soils being more susceptible (Leng et al., 2024).

*Phytopythium vexans* is another significant pathogen causing root rot

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**Fig. 1.** Durian tree and the development of durian fruit.

in durian. Although less reported than *P. palmivora*, it is more infectious, affecting 68% of durians in the dry season and 45% in the wet season (Vawdrey et al., 2005a,b). In Indonesia, *P. vexans* affected 58.8% of durian trees across ten provinces (Santoso et al., 2015), and in Vietnam, it caused a 10% loss of durian trees in certain regions (Thao et al., 2020).

Current disease management practices for durian include traditional, chemical, and biological controls. Traditional methods, while effective, can be labor-intensive and may not provide complete disease control, leading to recurrent infections. Chemical fungicides, though more effective, pose risks to beneficial soil microorganisms and the environment, and there is a growing concern about resistance development. For instance, overuse of metalaxyl has led to resistance in some *P. palmivora* isolates (Kongtragoul, 2018). Biological control agents offer a more sustainable and environmentally friendly alternative but can be inconsistent and costly, with effectiveness varying based on pathogen strain, application method, and environmental conditions (Dar and Soytong, 2014).

Given these challenges, there is a need for alternative approaches to manage *P. palmivora* and *P. vexans* infections in durian trees. This review aims to explore the morphology, taxonomy, and life cycle of these pathogens and discuss various control methods, including potential solutions such as gene silencing of Protein Phosphatase 2A to produce disease-resistant plants and the use of plant extracts with antimicrobial activities. This review serves as a guide for farmers and researchers seeking effective strategies to manage durian diseases.

## 2. Methodology

To gather comprehensive information on the control of *Phytophthora* and *Phytopythium* diseases in durian trees, a thorough review of scientific literature from 1970 to 2024 was conducted. The following steps outline the methodology used in this review:

**Literature Search**: Various search engines and scientific databases were utilized to obtain relevant journal articles. These included Google, Google Scholar, NUSearch, ScienceDirect, ISHS, Agris (FAO), CAB Direct, Semantic Scholar, Springer, ResearchGate, Frontiers in Plant Science, Horticultural Reviews, and the International Journal of Agricultural Technology.

**Search Terms**: Specific search terms were selected to narrow down the related publications. These terms included "durian," "durian disease management," "Phytophthora palmivora durian symptoms," "Phytopythium vexans durian symptoms," "Phytophthora palmivora durian control," "Phytopythium vexans durian control," "antagonistic fungus of *P. palmivora* and *P. vexans*," "molecular markers for durian," and "Protein Phosphatase 2A."

**Scope of Review**: The review focused primarily on the pre-harvest stage of durian disease management, although a few controls for the post-harvest stage were also included.

**Screening and Selection**: Over 150 publication titles were initially screened for relevance. This screening process resulted in the selection of over 100 references that were deemed pertinent to the review. The articles were predominantly in English, with a few in Malay, Thai, and Indonesian languages.

**Data Extraction**: Information extracted from the selected articles included the methods and treatments used for disease control and the results of each treatment. This data was systematically organized to provide a comprehensive overview of the current strategies and potential solutions for managing *Phytophthora* and *Phytopythium* infections in durian trees.

By following this methodology, the review aims to present a detailed and well-rounded analysis of the existing literature on durian disease management, highlighting both traditional and innovative approaches to controlling these devastating pathogens.

## 3. Discussion

### 3.1. Durian crop

#### 3.1.1. Taxonomy and botany of the durian

Durian is believed to have originated from Borneo Island but is now a valuable tropical crop in Southeast Asia. It is an angiosperm under the order Malvales, family Malvaceae, and *Durio* genus (Siriphanich, 2011). *Durio zibethinus* is the most harvested and economically important plant among a total of 28 *Durio* species (Ketsa, 2018; Aziz and Jalil, 2019). The name '*Durio zibethinus*' is derived from the Malay word 'duri,' meaning thorn, and the species name '*zibethinus*' comes from the Italian word 'zibetto,' which refers to a civet (cat-like animal) known for its strong odor (Ketsa et al., 2019; Ketsa, 2018). Its shape, unique taste, and strong aroma, alongside the seasonal availability, have added value to the fruit itself. Thus, the title 'King of Fruits' is awarded to durian (Husin et al., 2018; Sawitri et al., 2019). In general, durian trees are dicotyledonous and have trunk diameters of 50–120 cm, and can grow up to 25–50 m, depending on the species (Fig. 1). The leaves are ellipse-ovoid with 15–20 cm length and 5–7.5 cm width. Durian flowers are perfect and ramiflorous, consisting of 1–45 flowers per cluster with three petals per flower. *D. zibethinus* is incapable of self-pollination because the timing of stigma receptivity and pollen shedding does not overlap. Therefore, cross-pollination is effective in increasing the successful pollination rate (Somsri et al., 2006). Durian fruit comes in different shapes, including ovoid, capsular, and round, and could weigh between 2 and 5 kg. Its outer skin could be green to brownish-yellow, and the flesh inside varies in color from yellow to red. The thorny husk usually contains five sections or locules. The seeds are light brown and vary in round, ovoid, ellipse, and oblong shapes (Lestari et al., 2011).

#### 3.1.2. Nutritional value and other utilization

Durian is known to have several health benefits attributed to its high level of minerals, bioactive compounds (carotenoids, polyphenols, ascorbic acid, flavonoids, flavanols, anthocyanins, and tannins), and vitamins (Table 1), which possess antioxidant and anti-inflammatory activities (Chingsuwanrote et al., 2016). It contains high carbohydrate (27%), a good amount of fat (5.33%), protein (1.47%), and is rich in dietary fibers (3.1%) (Leontowicz et al., 2011). Durian also contains various fatty acids, such as stearic acid (35.93%), palmitoleic acid (9.50%), myristic acid (2.52%), linoleic acid (2.20%), oleic acid (4.68%), palmitic acid (32.91%), and 10-octadecenoic acid (4.86%) (Husin et al., 2018). These fatty acids, particularly unsaturated ones such as omega-3 fatty acids, could help lower platelet aggregation, triglyceride levels, blood pressure, and inflammation (Rodriguez et al., 2022). Traditionally, the leaves, roots, fruits, and husks of durian plants are thought to have medicinal properties for treating various conditions, such as fever, jaundice, skin issues, colds, and enhancing sexual function (Ho and Bhat, 2015). Additionally, ***in vivo*** and ***in vitro*** studies have demonstrated that durian possesses medicinal properties that could prevent increases in plasma lipids and reductions in plasma antioxidant activity. It also provides protection against neuroinflammation and neurotoxicity, shows antidiabetic and anticancer effects, and supports cardiovascular health (Gorinstein et al., 2011; Khaksar et al., 2024; Tran et al., 2023; Yen Yee, 2020; Aziz and Jalil, 2019).

In addition to its health benefits, various studies have explored alternative uses of the different parts of durian fruit. Rahmawati et al. (2023) identified durian peel as an alternative fuel in the form of charcoal briquette due to its cellulose, starch, and lignin content, which are combustible materials. Cornelia et al. (2015) showed that gum derived from durian seeds has good emulsifying activity, making it an effective emulsifier for making vegan mayonnaise. The starch found in durian seeds could also be extracted to be used as a material to make an edible film for food packaging and preservation (Rahmawati et al., 2021). Moreover, durian peel contains flavonoids, alkaloids, and fatty acids that could potentially kill armyworm larvae, thus serving as an effective bioinsecticide for controlling armyworm spread in corn crops (Sumayyah et al., 2024). Aside from the abovementioned uses, durian

**Table 1**
Mineral, trace element, vitamin, and phytochemical content of durian pulp.

| Compounds | Amount | References |
|---|---|---|
| **Minerals (mg/100 g fresh weight)** | | Haruenkit et al. (2007) |
| Sodium | 2.1 ± 0.1 | |
| Potassium | 201.2 ± 13.7 | |
| Magnesium | 11.23 ± 1.1 | |
| Calcium | 18.32 ± 0.3 | |
| Trace elements (μg/100 g fresh weight) | | |
| Iron | 991.1 ± 18.5 | |
| Manganese | 145.2 ± 9.9 | |
| Zinc | 32.3 ± 2.9 | |
| Copper | 24.1 ± 1.8 | |
| **Vitamins (mg/100 g fresh weight)** | | Devalaraja et al. (2011) |
| Vitamin A | 44.0 | |
| Pantothenic acid | 0.23 | |
| Niacin | 1.07 | |
| Thiamin | 0.37 | |
| Vitamin C | 19.7 | |
| Riboflavin | 0.2 | |
| **Phytochemicals (fresh weight)** | | Ho and Bhat (2015) |
| Total carotenoids (μg/g) | 7.26 ± 0.40 | |
| Tannin (mg catechin/g) | 1.37 ± 0.10 | |
| Anthocyanins (mg cyanidin-3-glucoside/g) | 17.12 ± 1.10 | |
| Polyphenols (mg gallic acid/g) | 2.58 ± 0.10 | |
| Flavonoids (mg catechin/g) | 1.52 ± 0.17 | |
| Flavanols (μg catechin/g) | 67.05 ± 3.10 | |

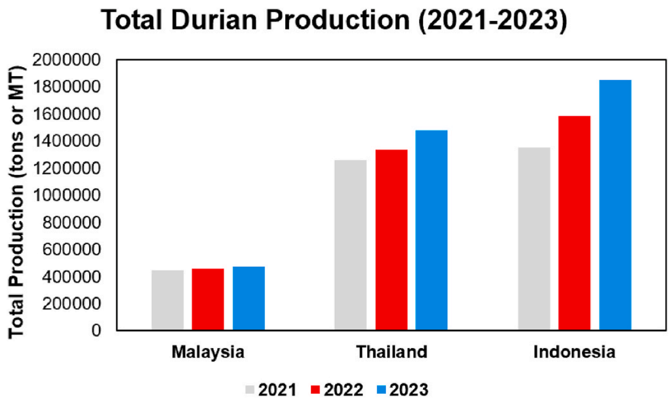


**Fig. 2.** Total durian production trends in Malaysia, Thailand, and Indonesia from the year 2021–2023. The production increased over time, and Indonesia produced more durian than Malaysia and Thailand. This may be due to the large number of areas in Indonesia that have suitable soil and beneficial geographic location for durian cultivation (Data source: DOA, 2023; BPS, 2024; OAE, 2024a).

seeds, and peels could also be used for making pectin, durian flour, bioethanol, adsorbents, and other products (Jong et al., 2023; Baraheng and Karrila, 2019; Chriswardana et al., 2021; Payus et al., 2021).

#### 3.1.3. Durian production and distribution

Durian cultivation is predominantly practiced in Thailand, Malaysia, and Indonesia, with the Philippines and Vietnam focusing on local consumption (O'Gara et al., 2004). According to DOA in 2023, Malaysia had approximately 87,365 ha dedicated to durian cultivation, yielding 471,672 tons of fruit (Fig. 2). However, the harvested area was only 63.16% of the total planted area, with an average yield of 8.26 MT/Ha, which is lower compared to other fruits like starfruit, guava, and pomelo (DOA, 2022). Factors influencing production density in Malaysia include flowering and fruiting seasons, climate patterns, environmental suitability, and urban development (Ahmad et al., 2020).

In Indonesia, durian production in 2023 involved 11,719,439 trees, resulting in 1,852,045 tons of fruit (BPS, 2024). Thailand, another major producer, utilized approximately 248,160 ha for durian cultivation, with a harvested area of around 168,160 ha, yielding 1,475,980 tons of fruit in 2023 (OAE, 2024a). Due to its seasonal availability, durian supply is often limited when demand is high, enhancing its market value.

Thailand is the leading global exporter of durian, accounting for 90% of the international market, followed by Malaysia and Indonesia. The primary importers are China, Hong Kong, and Singapore, with popular exported varieties including 'Monthong,' 'Kan Yao,' 'Chanee,' 'Musang King,' and 'D24' (Safari et al., 2018). Thailand's dominance in the market is attributed to improved agricultural practices, enhanced production quality, and efficient transportation routes. Table 2 illustrates the increasing export rates from these countries, with Thailand leading in both value and quantity.

In terms of export forms, Thai durians are predominantly exported fresh, frozen, dried, or as durian paste. Table 3 shows that fresh and frozen durian were the most exported forms from 2019 to 2023, indicating consumer preference for these products over dried durian and durian paste (OAE, 2024b). This trend underscores the importance of maintaining high standards in durian production and processing to meet international demand.

### 3.2. Durian pathogens

#### 3.2.1. Taxonomy, morphology and life cycle of the pathogens

Oomycetes, a diverse group of eukaryotic organisms, thrive in both aquatic and terrestrial habitats. Despite sharing physiological and morphological features with fungi, they are more closely related to diatoms and algae, classified within the Chromalveolata kingdom (Hardham, 2007; Panth et al., 2021a). Oomycetes possess unique characteristics, including mitochondria with tubular cristae, motile zoospores, cellulose hyphal walls, diploid thalli with gametangial meiosis, and non-septate hyphae (Ghimire et al., 2022). The genus *Phytophthora*, meaning 'plant destroyer,' includes over 200 pathogenic species, with *Phytophthora palmivora* being particularly harmful to durian (Perrine-Walker, 2020; Sarker et al., 2023). *Phytopythium*, genetically closer to *Phytophthora* than *Pythium*, includes over 20 species causing plant rots (Tkaczyk, 2020).

The life cycle of oomycete pathogens involves both sexual and asexual reproduction. They disperse through oospores (sexual reproduction), sporangia, or motile zoospores (asexual reproduction)

**Table 2**
Value and net weight of durian exported from Thailand, Malaysia, and Indonesia from 2019 to 2023.

| Year | Thailand | | Malaysia | | Indonesia | |
|---|---|---|---|---|---|---|
| | Value (USD) | Net weight (ton) | Value (USD) | Net weight (ton) | Value (USD) | Net weight (ton) |
| 2019 | $ 1,289,888,400 | 655,394.989 | $22,270,430 | 22,161.717 | $301,000 | 360 |
| 2020 | $ 1,861,345,033 | 620,892.579 | $17,645,508 | 16,967.741 | $232,000 | 102 |
| 2021 | $ 3,096,600,364 | 875,149.871 | $29,421,563 | 24,684.102 | $149,000 | 50 |
| 2022 | $ 3,123,828,991 | 827,219,268 | $34,468,846 | 24,558,901 | $181,000 | 227 |
| 2023 | $ 4,000,431,035 | 141,055,191.965 | $44,456,921 | 27,451,147 | $1,113,000 | 592 |

*Assuming 1 Thai Baht = 0.028 USD. Data source: OAE, 2024b; UN Comtrade (2024); BPS, 2024.

**Table 3**
Export quantity and value for Thai durian in the form of fresh, frozen, dried, and durian paste from 2019 to 2023.

| Export quantity (tons) | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|
| Fresh durian | 655,394,989 | 620,892,579 | 875,149,871 | 827,219,268 | 991,577,221 |
| Frozen durian | 25,985,837 | 31,133,585 | 50,113,786 | 88,813,523 | 100,926,206 |
| Durian paste | 1,210,935 | 1,187,476 | 351,130 | 141,250 | 60,849 |
| Dried durian | 214,996 | 261,930 | 359,112 | 676,529 | 2,394,092 |
| **Export Value (Million Baht)** | | | | | |
| Fresh durian | 45,481.462 | 65,631.022 | 109,186.123 | 110,146.205 | 141,055.191 |
| Frozen durian | 5370.487 | 6548.651 | 9579.402 | 15,261.971 | 23,167.032 |
| Durian paste | 131.750 | 156.613 | 46.952 | 27.603 | 13.460 |
| Dried durian | 197.716 | 229.679 | 335.866 | 382.728 | 570.229 |

*Data source: OAE, 2024b.

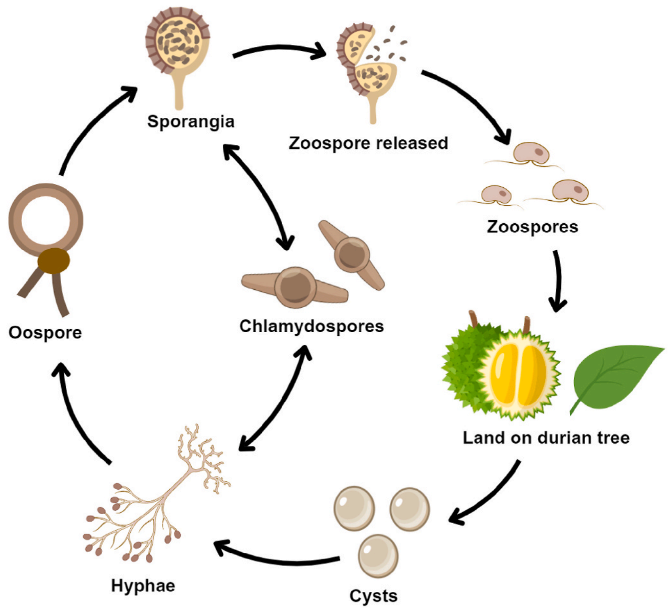


**Fig. 3.** Life cycle of oomycete pathogens.

**Table 4**
Symptoms of *P. palmivora* and *P. vexans* infection in durian.

| Causal agent | Symptoms in Durian | References |
|---|---|---|
| *Phytophthora palmivora* | • **Fruit rot**: dark brown to black lesion with whitish mycelia and sporangia on the lesion.<br>• **Root rot**: root turns brown and soft.<br>• **Leaf blight**: at first, small flecks, then expand to large lesions. Infected tissue is water-soaked that will become necrotic (brown/black). Spores were observed as white velvet in the leaf abaxial.<br>• **Patch canker**: often in the main trunk near the base and on lower branches, reddish brown discoloration on bark and sapwood, bark necrosis, defoliation, and dieback of twigs. | (Lim and Chan, 1986; Drenth and Guest, 2004; Sivapalan et al., 1997) |
| *Phytopythium vexans* | • **Root rot**: root necrosis, root change into brown color, dark brown color in inner cortex, reddish color on bark, decaying of tap root downwards.<br>• **Dieback** of branches<br>• **Yellowing of leaves and wilting**: cause leaves to drop, eventually leading to dead trees. | (Suksiri et al., 2018; Myagro, 2018; Jabiri et al., 2021) |

(Perrine-Walker, 2020). Both *P. palmivora* and *P. vexans* are heterothallic, requiring two compatible partners for sexual reproduction (Ghimire et al., 2022; Hendrix, Jr. and Campbell, 1970). Under stress, they produce long-term survival spores called chlamydospores, which germinate to form sporangia in favorable conditions (McCarren et al., 2005). These propagules disperse through farming activities, wind, animals, rain, and warm temperatures (Boevink et al., 2020). Zoospores, released from sporangia, swim in water and attach to host plants, forming cysts that germinate into appressoria, penetrating the plant surface (Fawke et al., 2015). The pathogen then undergoes sporulation, repeating its life cycle (Putaporntip et al., 2023). Fig. 3 illustrates the life cycle of oomycete pathogens.

*Phytophthora* species are hemibiotrophs, initially feeding on living cells before switching to dead cells, while *Phytopythium* species are necrotrophs, feeding on dead cells throughout their life cycle (Fawke et al., 2015). Optimal growth temperatures for *Phytophthora* range from 16 °C to 32 °C, while *Phytopythium* species thrive between 10 °C and 35 °C, depending on the specific species (Jung and Burgess, 2009; Nzungize et al., 2012; Cantrell and Dowler, 1971). These pathogens can infect all parts of a durian tree, including stems, roots, leaves, branches, and fruits, causing significant agricultural losses.

#### 3.2.2. Symptoms of the disease and infection

*Phytophthora palmivora* and *Phytopythium vexans* are soilborne pathogens that infect various parts of durian trees, including stems, roots, leaves, branches, and fruits. Poor drainage, excessive watering, and heavy clay soil exacerbate their spread (Mohamed et al., 2019). *P. palmivora* zoospores adhere to durian leaves, germinate under favorable conditions, and complete their life cycle within 8 h, penetrating through the leaf epidermis, cuticle, fruit spines, or stomata (Misman et al., 2022; Torres et al., 2016). Symptoms of *P. palmivora* infection include root necrosis, fruit rot with dark lesions, leaf blight with water-soaked necrotic lesions, and patch canker causing bark discoloration and twig dieback (Lim and Chan, 1986; Drenth and Guest, 2004; Sivapalan et al., 1997).

*P. vexans* primarily causes root rot, leading to root necrosis, dark brown discoloration in the inner cortex, and tap root decay. It also results in branch dieback, leaf yellowing, wilting, and eventual leaf drop, which can kill the tree (Suksiri et al., 2018; Myagro, 2018; Jabiri et al., 2021). Table 4 summarizes the symptoms of *P. palmivora* and *P. vexans* infections in durian. Early detection and appropriate control measures are crucial to prevent significant damage to durian orchards. Understanding these symptoms and infection mechanisms is essential for developing effective disease management strategies.

### 3.3. Control of the disease

#### 3.3.1. Traditional control

Traditional control methods are essential in minimizing the risk of infection by creating unfavorable conditions for pathogen growth and spread. These practices include host eradication, where infected plants are completely removed or pruned to eliminate sources of inoculum. Pruning not only removes infected parts but also enhances air circulation and sunlight penetration, which can improve fruit production and reduce disease incidence (Walters, 2009). Maintaining good orchard hygiene is crucial and can be achieved by minimizing the movement of people and vehicles within the orchard to prevent the spread of pathogens (Drenth and Guest, 2004).

Healthy planting materials, resistant tree varieties, and steam-treated potting mixes can significantly reduce pathogen inoculum. Mulching is another effective practice, as it helps maintain soil moisture and organic matter content, thereby reducing soil temperature and inhibiting pathogen development (Walters, 2009; Drenth and Guest, 2004). The use of organic amendments, such as green compost, rice husk, and chicken manure, can also reduce disease incidence and plant mortality by enhancing populations of beneficial endospore-forming bacteria that support plant health (Muryati et al., 2009).

Proper water management is critical in disease control. Good drainage, prevention of waterlogging and flooding, appropriate fertilizer application, and proper irrigation water treatment can all help mitigate disease risks. Excessive irrigation can promote the proliferation of pathogen propagules, as oomycete zoospores tend to travel with water flow (Martínez-Arias et al., 2022). Soil suppressiveness, determined by microbial properties such as rhizosphere, endophytes, soil microfauna, and arbuscular mycorrhizal fungi, can inhibit pathogens through mechanisms like antibiotic production, siderophore formation, and nutrient competition (Yadav et al., 2015). Additionally, plants can release root exudates to encourage the development of beneficial

**Table 5**
More biocontrol agent options for durian *P. palmivora* and *P. vexans* control.

| Causal agent | Biocontrol agent | Mixture concentration/application | Effect | References |
|---|---|---|---|---|
| ***P. palmivora*** | *Chaetomium brasilense* | - Dual culture assay<br>– 1000 μg/ml crude ethyl acetate extract<br>– 15 μg/ml nanoparticle extracts (Nano-CBH, Nano-CBM, Nano-CBE) | – 58.33% growth & 88.82% spore inhibition<br>– 82.75% growth & 97.72% spore inhibition<br>– 90% growth & 100% spore inhibition | Tongon et al. (2018) |
| ***P. palmivora*** | *Chaetomium cupreum* | 15 μg/ml nanoparticle of methanol extract (Nano-CCM) | 86% growth & 99.55% sporangia inhibition | Thongkham et al. (2017) |
| ***P. palmivora*** | *Trichoderma harzianum* | - 1 L spore suspension/tree<br>- Dual culture assay | - Lesions healed after 1 month of all treated trees<br>– 84.69% growth inhibition | (Soguilon and Yebes, 2005; Saikeur, 2013) |
| ***P. palmivora*** | *Chaetomium goblosum* | Mixture of C. goblosum & C. cupreum:<br>- Greenhouse test: 5g/plant<br>- Field test: 40g/plant | – 85.56% disease reduction in greenhouse test<br>– 81.04% disease reduction in field test after 3 years | Soytong (2010) |
| ***P. palmivora*** | *Trichoderma virens* | Dual culture assay | 100% growth inhibition after 5 days of incubation | Sunarwati and Yoza (2010) |
| ***P. palmivora*** | *Paenibacillus polymyxa* | Roots liquid assay | 99.7% reduction of zoospores | Timmusk et al. (2009) |
| ***P. palmivora*** | *Papiliotrema laurentii* | Dual culture assay | 53.2–59.5% growth inhibition after 7 days of incubation | Satianpakiranakorn et al. (2020) |
| ***P. palmivora*** | *Coniochaeta ligniaria* | Crude ethyl acetate extract at 100 μg/ml | 100% mycelial inhibition after 24 h | Kokaew et al. (2011) |
| ***P. vexans*** | *Streptomyces* spp. | Dual culture assay: non-volatile compounds & volatile compounds | – 52.25%–79.95% and 22.58%–59.84% inhibition of radial mycelia growth, respectively | Corral et al. (2020) |
| ***P. vexans*** | *Pythium oligandrum* | Dual culture assay | - No oospores after 9 days & 100% growth inhibition after 14 days | (Berry et al., 1993) |

microbes, which help camouflage the plants against pathogens by blending with microbial populations and restricting excessive proliferation of root microbial communities (Yadav et al., 2015). It is important to note that the use of fungicides, particularly phosphonates, should be avoided in nurseries as they can mask disease symptoms without eliminating the pathogens (Walters, 2009; Drenth and Guest, 2004).

#### 3.3.2. Chemical control

Chemical fungicides are widely used to manage diseases caused by *Phytophthora* and *Phytopythium*. Effective fungicides include metalaxyl (Ridomil), captafol (Difolatan), and etridiazole (Terrazole), which inhibit mycelial growth, germ tube length, and sporangium and chlamydospore production (Chan and Kwee, 1986). Captafol is particularly effective against zoospore germination, followed by fosetyl-Al (Aliette), where the application of 0.1 μg/ml captafol resulted in a 50% reduction in germ tube length. However, metalaxyl is less effective against zoospores compared to sporangium and chlamydospores. Other fungicides, such as azoxystrobin, copper hydroxide, and propamocarb, also inhibit mycelium growth of both *Phytophthora* spp. and *Phytopythium* spp. (Mabbett, 2014). Copper hydroxide is highly toxic and may inhibit zoospore germination at concentrations greater than 100 μg/ml, whereas azoxystrobin and propamocarb are less effective against zoospores (Kuhajek et al., 2003). The use of traditional Bordeaux mixture, mancozeb, and phosphorus acid has also been reported to be effective (Drenth and Guest, 2004; Bannaphoomi et al., 1994).

Phosphonate, derived from fosetyl-Al, is extensively used to control oomycete diseases in perennial trees, including durian. The phosphonate itself is derived from a soluble form of fosetyl-Al marketed under the brand name Aliette, which contains aluminum salt of phosphonate (Kromann et al., 2012). Initially used as a foliar spray and soil drench, it was later found to be more effective when injected into the trunk. Trunk injection of phosphonate has proven effective in reducing lesions and patch canker caused by *P. palmivora* (Pegg et al., 1995; Myint et al., 2002; Montiel et al., 2013). An experiment by Myint et al. (2002) using 20% phosphonate for trunk injection in a durian orchard in Myanmar inhibited lesion development after the second injection (11 months). Similarly, Montiel et al. (2013) reported that 10%–20% phosphonate trunk injection significantly reduced patch canker after one year, with only 1–3 lesions recorded per tree. Although trunk injection is cost-effective and requires a small proportion of phosphonate, the process is labor-intensive as it involves drilling the trunk for injector insertion.

#### 3.3.3. Biological control

Biological control involves using living organisms antagonistic to pathogens to manage diseases. These biocontrol agents can interact directly with pathogens by parasitizing their cells or indirectly by enhancing plant resistance and competing for nutrients (Köhl et al., 2019; Narayanasamy, 2013). *Chaetomium brasilense* has shown significant growth inhibition and spore suppression of *P. palmivora*. Tongon et al. (2018) reported 58.53% growth inhibition and 88.82% spore suppression by *C. brasilense*. Additionally, nanoparticles derived from *C. brasilense* inhibited 90% of *P. palmivora* colony growth and completely halted spore production, demonstrating their effectiveness. Similarly, nanoparticle extracts from *C. cupreum* have demonstrated high inhibitory effects on *Phytophthora* spp., with 86% growth inhibition and 99.55% sporangia inhibition (Thongkham et al., 2017).

*Streptomyces* strains have been effective against *P. vexans*, reducing mycelium growth through volatile and non-volatile antimicrobial compounds. Corral et al. (2020) reported that non-volatile compounds from *S. kanamyceticus* (CIAD-CA48) significantly reduced mycelium growth by 52.25%–79.95%, while volatile compounds were also effective, reducing growth by 22.58%–59.84%. Several non-volatile and volatile compounds of *Streptomyces* have been identified to suppress pathogens, such as reveromycin A and B, valinomycin, ketones, alcohols, alkenes, alkanes, and esters.

Other biocontrol agents, such as *Trichoderma* spp., have shown success in controlling pathogens due to their production of secondary metabolites with fungicidal, bactericidal, and growth-regulating properties (Raut et al., 2014; Salwan et al., 2019). Lim and Sangchote (2003) suggested using a sterile potting mix combined with *Trichoderma* spp. to control *P. vexans* growth. Panth et al. (2021a) tested the bio fungicide Stargus containing *Bacillus amyloliquefaciens* and RootShield PLUS + containing *T. harzianum* for controlling *P. vexans* on ginkgo and red maple trees, finding significant reductions in disease severity. Patil et al. (2012) also found that volatile metabolites of *Trichoderma* spp. had a significant inhibitory effect on *P. vexans* in tomatoes. However, this contrasts with other studies on *Trichoderma*'s secondary metabolites, which suggest that non-volatile metabolites are more effective than volatile ones (Bunker and Mathur, 2001; Raut et al., 2014). Further research is needed to evaluate the effectiveness of these agents specifically in durian trees.

Table 5 provides more details on potential biocontrol agents, their preparation, and their effects on controlling *Phytophthora* and *Phytopythium* diseases in durian.

### 3.4. Potential approaches

#### 3.4.1. Resistant cultivar screening

Screening for pathogen-resistant durian cultivars is crucial for managing diseases caused by *Phytophthora* and *Phytopythium*. Traditionally, breeding for resistance involved phenotyping, where desirable traits were identified through measurable characteristics. Sangchote (2002) assessed disease incidence in durian cultivars (Chanee, Kanyao, Monthong, and Kadoom) by inoculating them with pathogen sporangial suspension. The Chanee cultivar showed higher resistance, with disease incidence ranging from 20% to 47% on all inoculated parts and only 10% root infection. However, phenotyping is slow, costly, and requires strict monitoring and observation of disease development.

To address these limitations, Vawdrey et al. (2005a,b) developed a more reliable, rapid, and non-destructive technique using detached leaf bioassay to evaluate durian germplasm susceptibility to pathogens. They evaluated five durian cultivars (Chanee, D10, Monthong, Gob, and Hew 3) by inoculating durian leaves with *P. palmivora* isolates. The Gob cultivar was found to be tolerant to *P. palmivora*, with significantly smaller lesions compared to other cultivars, while Monthong and Chanee were the most susceptible. This method proved effective for screening resistant cultivars, which can be used as rootstocks for propagation (Emilda, 2007).

Recent advancements include the use of molecular markers for marker-assisted selection (MAS). Molecular markers track polymorphisms in genome regions associated with disease resistance genes. Camellia et al. (2019) developed SCAR markers 886-2 from inter simple sequence repeats (ISSR) polymorphisms to identify resistant and susceptible *Durio* species to *Phytophthora*. Another approach by Santoso et al. (2020) used 77 simple sequence repeat (SSR) markers to identify loci associated with resistance to *P. palmivora* and *P. vexans*. They used Bulked pseudo-Segregant Analysis (BpSA) to compare polymorphisms in germplasms from detached leaf bioassay, identifying three loci (mDz03F10, mDz3B1, and mDz4B2) associated with resistance. These molecular markers provide a rapid and reliable method for screening resistant durian cultivars, facilitating the development of disease-resistant plants.

Protein Phosphatase 2A (PP2A) is crucial in determining host defense response against pathogens. It is a complex consisting of scaffold subunit A, regulatory subunit B, and catalytic subunit C. PP2A is under the serine/threonine (Ser/Thr) phosphatases group that is highly conserved, and it functions to regulate stress signaling in eukaryotes (Bheri and Pandey, 2019). In *Arabidopsis thaliana*, PP2A is mainly located in the cytoplasm and nucleus. It functions to regulate cellular signaling pathways (e.g., ABA, JA, auxin, and brassinosteroid signaling pathways), control receptors for pathogen-associated molecular pattern (PAMP) triggered immunity, reactive oxygen species (ROS) homeostasis, and control negative regulation of apoptosis (Durian et al., 2016). This negative regulation response of PP2A was proven by Zhu et al. (2018) in PP2Ac proteins of wheat (*Triticum aestivum*), namely TaPP2Ac-4D. Knockdown of both TAPP2Ac-4D and TAPP2Ac-4B using virus-induced gene silencing (VIGS) method resulted in the significant increase of wheat resistance to Rhizoctonia cerealis, where the particular pathogenesis-related (PR) proteins and ROS level significantly increase in TAPP2Ac- silenced wheat plants. The authors suggested that both the TAPP2Ac genes alter the expression of PR proteins and ROS, which resulted in the negative regulation of wheat plants' defense against the pathogen.

Another study was done by Chen et al. (2019) for Phytophthora species, specifically *P. capsici*. It was known that the cytoplasmic effector proteins encoded by Phytophthora, which contain a highly conserved N-terminal RXLR motif (PcAvh1), play a significant role in pathogenesis. This study discovered that PcAvh1 expression is very low during P. capsici development without a host but rapidly surged during infection. Moreover, the CRISPR/Cas9 knockout of PcAvh1 of P. capsici severely affected its virulence, demonstrating its importance. They also revealed the interaction of the PPA2 subunit and PcAvh1 in plant cells using yeast-two hybrid screening.

Furthermore, gene silencing of PP2Aa in Nicotiana benthamiana (NbPP2Aa-1 and NbPP2Aa-2) resulted in dwarfism, and it significantly increased *N. benthamiana*'s susceptibility to P. capsici infection. This indicates that there is a positive regulation between PP2Aa and plant growth and immunity, which contradicts the result from the study by Zhu et al. (2018). Therefore, it could be concluded that the PP2A regulation depends on the pathogen effectors and plant species itself.

On the other hand, the authors also stated that phylogenetic analysis of PcAvh1 from P. capsici indicated it has a homolog with PHPALM28136 of *P. palmivora* with 76% similarity, thus making it the closest relative. This could serve as fundamental evidence that the RXLR effector of *P. palmivora* or other effectors may interact with PP2Aa of durian tree, which could be further studied to develop resistant plants.

#### 3.4.2. Plant extracts

Using plant extracts is a promising strategy for controlling durian tree diseases due to their antimicrobial properties, non-toxicity, and affordability (Upadhyay et al., 2014). A study led by USEP Professor Belly Dionio found that garden balsam (*Impatiens balsamina*) extract effectively controls durian patch canker by inhibiting *Phytophthora* growth and reducing defoliation. Spraying *I. balsamina* extract 1 h before inoculation reduced lesion numbers by 86% and defoliation by 13.4%, showing comparable effectiveness to fosetyl-Al fungicide (Gerida and Dionio, unpublished results). The seeds of *I. balsamina* contain antimicrobial peptides (Ib-AMPs), with Ib-AMP4 exhibiting the highest antifungal activity (Vásquez et al., 2009; Thevissen et al., 2005).

Jagtap et al. (2012) reported that extracts from ginger, turmeric, garlic, neem, tulasi, and red onion effectively inhibit *P. palmivora* mycelial growth in citrus. Garlic extract showed the highest inhibition (mean 50.64%), while turmeric had the least (mean 27.12%). Neem, onion, and ginger exhibited moderate inhibition (mean 33.51%, 29.58%, and 27.72%, respectively). Widmer and Laurent (2006) found that rosemary extracts at 10% and 25% concentrations completely inhibited *Phytophthora* mycelial growth in cacao leaves, while lavender and lavender hybrid extracts significantly reduced mycelial growth at 25% concentration.

Studies on natural extracts against *P. vexans* are limited. Panth et al. (2021b) recommended using cover crops as secondary hosts for sustainable management. They tested nine cover crops, finding that buckwheat had the highest disease severity and recovery, while Austrian winter pea had the lowest. Tillage radish and crimson clover showed high severity and moderate recovery. Lower severity was observed in annual ryegrass, triticale, Japanese millet, and cowpea, with low recovery percentages. Legumes like cowpea and Austrian winter pea, and grass cover crops like triticale, annual ryegrass, and Japanese millet were least susceptible to *P. vexans*. Further research is needed to explore the potential of botanicals against these pathogens in durian.

#### 3.4.3. Integrated approach

Integrated disease management combines multiple strategies to effectively control durian diseases caused by *Phytophthora palmivora* and *Phytopythium vexans*. This approach includes using disease-free planting materials, appropriate fungicides, biological controls, resistant seeds, and cultural practices such as pruning, maintaining orchard cleanliness, and removing infected trees (Guest, 2000). Incorporating green manure and chicken manure mixed with Effective Microorganisms (EM) can enhance soil health by promoting beneficial microorganisms and suppressing pathogens through anaerobic fermentation (Drenth and Guest, 2004). A survey by Daniel et al. (2014) demonstrated the efficacy of this treatment, resulting in less than 25% branch dieback and no visible symptoms or lesions in treated durian trees.

Proper irrigation, mulching, and the application of organic fertilizers like chicken manure and potash fertilizer help retain soil moisture, reduce rot incidence, and improve fruit quality (Drenth and Guest, 2004;

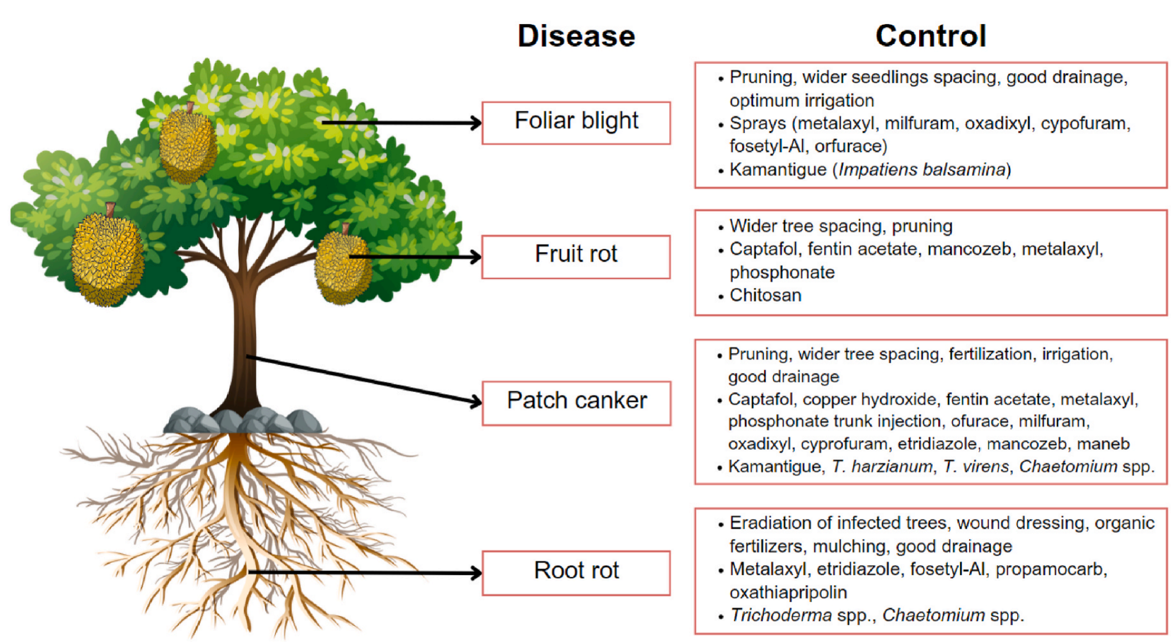


**Fig. 4.** Summarized controls for durian disease caused by *P. palmivora* and *P. vexans.*

Jaafar, 1998; Cheychom et al., 2019). Chuebandit et al. (2017) evaluated integrated management in the field using five treatment combinations. They found that combining metalaxyl, chitosan, and Microbial Activator Super LDD3 (containing *Trichoderma* spp.) was the most cost-effective and efficient, resulting in no lesions and a high recovery rate. The use of chitosan has also been proven effective, with Kongtragoul (2018) reporting complete inhibition of mycelial growth at 2000 ppm.

Fig. 4 summarizes the integrated disease control strategies for durian trees. By combining these methods, farmers can achieve sustainable and effective management of durian diseases, ensuring better crop health and yield.

## 4. Conclusions

The management of *Phytophthora palmivora* and *Phytopythium vexans* diseases in durian (*Durio zibethinus*) is critical for sustaining the health and productivity of durian orchards. This review has highlighted the significant impact of these pathogens on durian cultivation, causing severe economic losses and affecting fruit quality. Traditional control methods, while effective to some extent, are labor-intensive and do not completely eradicate the disease. Chemical fungicides, although more effective, pose environmental risks and can lead to resistance development. Biological control agents offer a more sustainable alternative but can be inconsistent and costly.

Advancements in resistant cultivar screening, including phenotyping and molecular marker-assisted selection (MAS), have shown promise in identifying and developing disease-resistant durian varieties. Techniques such as detached leaf bioassay and the use of SCAR and SSR markers have improved the efficiency and reliability of screening processes. Additionally, the potential of Protein Phosphatase 2A (PP2A) in enhancing plant defense mechanisms against pathogens opens new avenues for breeding resistant plants.

The use of plant extracts, such as those from garden balsam, garlic, and rosemary, has demonstrated significant antimicrobial activity against *Phytophthora* and *Phytopythium* species. These natural extracts are non-toxic, affordable, and environmentally friendly, making them a viable option for disease management. Furthermore, integrated disease management approaches, combining cultural practices, chemical and biological controls, and the use of resistant cultivars, have proven to be effective in controlling durian diseases.

Overall, this review underscores the importance of a multifaceted approach to managing durian diseases. By integrating traditional, chemical, biological, and innovative methods, farmers can achieve sustainable and effective disease control, ensuring the long-term health and productivity of durian orchards. Continued research and development in these areas are essential to address the evolving challenges posed by these devastating pathogens.

## CRediT authorship contribution statement

**Ajit Singh:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Caryn Chow:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Kevin Nathaniel:** Writing – review & editing, Investigation, Visualization. **Yap Lip Vun:** Writing – review & editing, Visualization, Project administration, Formal analysis, Conceptualization. **Sumera Javad:** Writing – review & editing, Validation, Investigation. **Khajista Jabeen:** Writing – review & editing, Validation, Investigation.

## 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.

## Data availability

No data was used for the research described in the article.

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## ARTICLES FOR FACULTY MEMBERS

# DEVELOPMENT OF TRANSDISCIPLINARY APPROACH ON CROP HEALTH MANAGEMENT PROGRAM FOR DURIAN FARMING IN MALAYSIA

**Reinforcement learning algorithm for optimising durian irrigation systems: Maximising growth and water efficiency / Ramli, M. S. A., Abidin, M. S. Z., Hasan, N. S., Reba, M. N. M., Kolawole, K. K., Ardiansyah, R. A., & Mpuhus, S. L.**

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# Reinforcement Learning Algorithm for Optimising Durian Irrigation Systems: Maximising Growth and Water Efficiency

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## ABSTRACT

This study presents a Reinforcement Learning-based algorithm designed to optimise irrigation for Durio Zibethinus (i.e., durian) trees, aiming to maximise tree growth and reduce water usage. Traditional irrigation methods, as well as current machine learning models, often focus only on soil moisture and weather data, neglecting critical factors like actual tree growth. This study proposed a reinforcement learning irrigation (RL-Irr) algorithm incorporating tree growth stages, soil moisture, and weather conditions to determine precise irrigation needs. The algorithm was developed by calibrating the AQUACROP model using data from actual durian plantations where rain-fed irrigation (rain-fed) was practised. Daily irrigation volumes were calculated based on real-time soil moisture, weather forecasts, and weekly tree growth measurements. The reinforcement learning method was used to optimise irrigation schedules, with rewards based on soil moisture, tree growth, rainfall, and weather conditions. The algorithm was tested using AQUACROP simulations and compared against soil moisture balance irrigation (SMB-Irr) and rain-fed. The results showed that the RL-Irr reduced water use by up to 75 percent while maintaining tree growth. These findings suggest the algorithm could significantly improve water efficiency in durian farming, though real-world applications should consider potential model limitations.

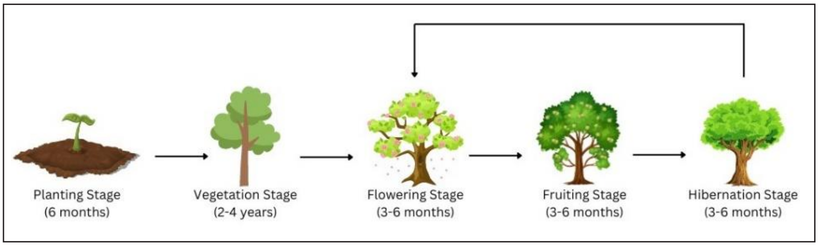
**Keywords**: Durian Farming, Durio Zibethinus, Machine Learning, Reinforcement Learning, Smart Irrigation.

## INTRODUCTION

Durio Zibethinus, commonly known as durian and often referred to as the "king of fruits," is a well-known tropical fruit from Southeast Asia, celebrated for its intense aroma and uniquely rich flavour. This fruit is harvested bi-annually and is of significant economic value, enjoying widespread local and global demand. In Malaysia, a significant number of smallholder farmers cultivate durian, contributing to its commercial significance. In fact, durian has the largest cultivation area in Malaysia compared to all other fruits (Syafiqah et al., 2019). The maturation period of durian trees varies based on the variety, generally taking between two to six years (Chung, 2020). As illustrated in Figure 1, the cultivation of the durian tree involves five key stages: planting, vegetative growth, flowering, fruiting/harvesting and hibernation.

**Figure 1**

*Durian Planting Stage from Seedling to Vegetation Stage*




When cultivating durian trees, seedlings are first grown in polybags inside a shaded greenhouse. They are frequently provided with nutrient feedings and receive daily irrigation to ensure they stay properly hydrated. This controlled environment is essential for promoting healthy growth. Before being transferred to the open field, the trees undergo a hardening process, which includes exposing them to sunlight for at least a week to help them adapt to outdoor conditions. Once transplanted into open areas, the trees enter the vegetative stage, which is the longest and most critical phase, lasting up to four years, depending on the variety. If the trees fail to meet growth standards, farmers replace them and restart the vegetative process. Durian cultivation requires significant time, cost, resources and careful monitoring (Zakaria, 2020). Farmers watch for indicators such as leaf colour and quality, trunk diameter and overall height. Consistent irrigation and regular fertilisation are crucial during this stage. Water is more important than fertiliser for durian trees (Ketsa et al., 2020). Over-irrigation can saturate the soil, harming root growth, with excess water running off to lower areas. Under-irrigation can leave trees without enough water to survive. This emphasises the importance of precise water management in durian cultivation. Ensuring that each tree receives the right amount of water is crucial for optimal growth and hydration.

## RELATED WORK

Adequate irrigation is essential for sustainable agriculture to meet the increasing food demands of the global population. Managing soil moisture is crucial for efficient water usage and boosting crop productivity. Soil moisture balance refers to the equilibrium between water added to the soil through rainfall or irrigation and water lost through evaporation and plant absorption (Ritchie, 1998). This equilibrium is vital for maintaining healthy soil and ensuring sufficient water for crops. Advancements in technology and a better understanding of the interactions of soil, water and plants have led to modern irrigation systems that utilise soil moisture data. These systems aim to align irrigation with the actual water needs of crops, conserving water and improving crop yields (Abioye et al., 2022). The use of soil moisture sensors and computerised controls demonstrates how modern technology has reformed traditional irrigation methods (Kumar et al., 2016). While soil moisture balance is vital for irrigation, challenges in its use include high costs, the need for specialised knowledge and various environmental factors affecting soil moisture (Pereira et al., 2020). This study explores the development, current technologies, benefits, challenges and valuable applications of irrigation systems based on soil moisture balance, drawing information from numerous academic and practical sources.

Integrating soil moisture balance into irrigation systems can bring about significant benefits and challenges for sustainable agriculture. One major advantage is the efficient use of water. Accurate measurement of soil moisture levels enables farmers to water crops effectively, ensuring responsible water usage, especially in areas with varying climates and soil types. Research in Nebraska shows that soil moisture and Vapour Pressure Deficit (VPD) affect plant water use, highlighting the importance of soil moisture in water management (Zhang et al., 2021). Proper irrigation reduces plant stress, promoting better growth and potentially higher crop yields. However, there are challenges involved. These include the time, labour and cost of installing and maintaining soil moisture sensors. Probes, particularly the advanced versions that collect data from multiple soil layers, are generally easier to install than point sensors but can be more expensive (Soothar et al., 2021). The precision of soil moisture sensors presents an additional challenge. Sensor accuracy can vary based on soil characteristics, such as clay content or salinity (Shakya et al., 2021). Electromagnetic sensors, for example, may be less accurate in soils with high clay or salinity. Therefore, choosing the correct sensor for the specific field conditions is crucial.

Moreover, the data from these sensors require careful analysis. Understanding all aspects of soil moisture levels is essential for accurate irrigation decisions. Some sensors provide easy-to-read graphical data, while others offer information in less intuitive formats, complicating the decision-making process for farmers (Jabro et al., 2020). Soil moisture balance-based irrigation (SBM-Irr) systems offer significant benefits, like optimised water use and potential yield increases. However, challenges include sensor accuracy, data analysis and costs. Addressing these issues is essential to fully realise the potential of these systems for sustainable farming. When cultivating durian trees, seedlings are first grown in polybags inside a shaded greenhouse. They are frequently provided with nutrient feedings and receive daily irrigation to ensure they stay properly hydrated. This controlled environment is essential for promoting healthy growth. Before being transferred to the open field, the trees undergo a hardening process, which includes exposing them to sunlight for at least a week to help them adapt to outdoor conditions. Once transplanted into open areas, the trees enter the vegetative stage, which is the longest and most critical phase, lasting up to four years depending on the variety. If the trees fail to meet growth standards, farmers replace them and restart the vegetative process. Durian cultivation requires significant time, cost, resources and careful monitoring (Zakaria, 2020). Farmers watch for indicators such as leaf colour and quality, trunk diameter and overall height. Consistent irrigation and regular fertilisation are crucial during this stage. For durian trees, water is more important than fertiliser (Ketsa et al., 2020). Over-irrigation can saturate the soil, harming root growth, with excess water running off to lower areas. Under-irrigation can leave trees without enough water to survive. This emphasises the importance of precise water management in durian cultivation. Ensuring that each tree receives the right amount of water is crucial for optimal growth and hydration.

The integration of Artificial Intelligence (AI) and machine learning (ML) into irrigation systems has transformed agriculture by optimising water usage, enhancing crop productivity, and reducing environmental impacts. These technologies have become vital in the face of global water shortages and increasing food demand due to population growth. AI-driven irrigation employs precision agriculture techniques, where irrigation schedules are tailored based on real-time data inputs, such as soil moisture levels, weather forecasts, and satellite imagery. By analysing these data streams, AI systems recommend precise irrigation schedules and automating water distribution to increase efficiency and reduce the need for manual labour.

ML algorithms, including Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Convolutional Neural Networks (CNN), are integral to this process, analysing complex data patterns to predict ideal watering schedules, as well as potential disease and pest outbreaks. These algorithms also enable adaptive irrigation strategies to respond dynamically to climate shifts. Recent advancements in IoT and cloud computing have further strengthened data collection and processing capabilities, creating highly responsive irrigation systems. Despite these advancements, challenges such as high initial setup costs, data reliability issues, and the learning curve for new technologies still pose barriers to widespread adoption. However, AI-driven irrigation remains essential for fostering sustainability and efficiency in agriculture (Talaviya et al., 2020). AI has significantly impacted agricultural irrigation systems. The MIT GEAR Lab has proposed an Automatic Scheduling-Manual Operation (AS-MO) irrigation tool to bring precision irrigation benefits to farmers in resource-limited regions. This tool integrates automatic scheduling to optimise water usage with manual operation of irrigation valves, allowing farmers to maintain control while benefiting from precision irrigation's efficiency. Designed specifically for East Africa and MENA regions, the AS-MO tool uses cloud-based algorithms to generate optimal irrigation schedules without the need for costly and complex soil moisture sensors. Instead, it uses soil water balance calculations based on affordable sensors for weather, solar power, and crop details. This design addresses the high cost and complexity of fully automated systems, which are often prohibitive for small and medium-sized farms. The AS-MO tool sends schedule updates via SMS to farmers' mobile phones, guiding them on when to manually open or close irrigation valves. This approach bridges the gap between existing expensive systems and traditional manual methods, making efficient irrigation more accessible to cost-constrained farms while minimising water and energy use (Van de Zande et al., 2023).

AI also plays a vital role in agricultural management. ML algorithms such as Random Forest (RF), SVM, ANN and CNN are used to analyse soil and crop health, helping to detect and predict crop diseases. These algorithms optimise irrigation by calculating the best watering schedules and timings (Awais et al., 2023). Combining the Internet of Things (IoT) and ML in smart agriculture is a major advancement. These systems are designed to reduce human involvement and improve water management efficiency. Unmanned Aerial Vehicles (UAVs) equipped with AI technology are increasingly used in agriculture. These UAVs help identify and monitor crops, providing vital data for improving irrigation techniques through detailed analysis of crop health and soil conditions. ML algorithms such as object-based image analysis (OBIA) were applied to process the images and identify areas of crops that required attention, such as herbicide spray for diseased crops (Yousaf et al., 2023).

Irrigation using real-time environment data is required to integrate various sensors, controllers, and communication networks to monitor and manage water delivery to crops based on real-time data such as soil moisture, weather conditions, and crop water requirements. AI techniques like ML and deep learning (DL) are used to analyse large datasets, including soil, water content, and environmental factors, enabling precise irrigation schedules. The system's ability to adapt to changing conditions helps improve water efficiency, reduce waste, and maintain crop health. Furthermore, the AI model leverages predictive tools to forecast future irrigation needs and adjusts the irrigation schedule dynamically, optimising water use while ensuring crop growth. This approach is particularly valuable for addressing challenges such as water scarcity and the unpredictable nature of climate change in agriculture (Obaideen et al., 2022). ML predicts irrigation needs, enabling proactive water management strategies that reduce consumption and increase productivity. Technologies such as ANN, fuzzy logic and expert systems enable adaptive decision-making and real-time monitoring, leading to higher yields and optimised water use. ANN-based controllers are particularly effective due to their learning and adaptability, making irrigation more efficient and sustainable (Bwambale et al., 2022). The algorithm can analyse large amounts of data to identify patterns and predict future water needs, helping farmers in planning and managing their irrigation systems more effectively. Other than that, in-situ AI sensors monitor soil moisture levels and provide alerts when irrigation is needed, reducing manual labour and improving overall efficiency (Tomar et al., 2023).

Smart irrigation systems offer numerous benefits for both urban and rural agriculture. These systems enhance agricultural productivity by minimising water waste and ensuring crops receive the precise amount of water needed for optimal growth and yield. Additionally, they contribute to reducing agriculture's environmental impact by promoting efficient water use, decreasing runoff, and supporting sustainable farming practices. These systems can be tailored to various agricultural environments, including urban areas with varying access to space, water, and electricity, although they may involve higher costs or operational limitations in some cases. Overall, AI-driven smart irrigation systems offer improved sustainability, efficiency and adaptability in various farming environments (Vallejo-Gómez et al., 2023).

However, implementing AI-based irrigation systems faces several key challenges. First, data availability is a significant issue as ML algorithms require large volumes of data to construct accurate predictions. In many regions, there is limited reliable data on soil moisture, weather patterns and crop growth, which impacts the accuracy of data predictions. Second, sensor reliability is a concern due to the high cost of installation and maintenance, as well as susceptibility to environmental factors such as temperature, humidity and electromagnetic interference, which can affect their accuracy. Third, a stable and reliable power supply is required in areas with limited electricity, especially in remote agricultural areas. The high cost of implementing intelligent irrigation systems is another significant obstacle, particularly for small-scale farmers (Ghareeb et al., 2023). Finally, farmers may lack the technical expertise to operate and maintain these systems, which hinders widespread adoption (Mohan et al., 2021). Apart from that, the concerns about privacy and security related to storing, processing and sharing sensitive data collected by the system, alongside the potential for cyber-attacks, further complicate the implementation of AI in irrigation (Tzachor et al., 2022).

Integrating AI into irrigation systems has revolutionised agriculture by optimising water use, boosting crop productivity and reducing environmental impacts. This is especially important given global water shortages and the rising demand for food due to population growth. AI in irrigation uses ML algorithms to provide precise agriculture techniques, tailoring irrigation based on data inputs like soil moisture, weather forecasts and satellite images. The ML algorithms analyse this data to recommend optimal irrigation schedules. Apart from that, the systems can also automate watering, improving efficiency and reducing the need for manual labour.

Reinforcement learning (RL) irrigation is considered a superior approach compared to conventional irrigation techniques and other AI irrigation models due to its adaptive decision-making ability (Saikai et al., 2023). While traditional methods rely on fixed schedules or basic rules, RL-based irrigation systems continuously learn and evolve by interacting with the environment. This allows them to optimise water use based on real-time conditions and weather forecasts. The flexibility of RL irrigation enables it to effectively manage water resources, minimise wastage and maintain crop productivity, even in the face of uncertain weather patterns. Moreover, RL irrigation has the potential to surpass other AI-driven methods by refining its strategies over time, balancing both immediate and future considerations for water efficiency and crop yield. Consequently, RL irrigation offers a more robust, efficient and viable solution for sustainable agricultural practices, especially in areas where water is a limiting factor. The Deep Reinforcement Learning for Irrigation Control (DRLIC) system is practical for irrigation because it seamlessly integrates with existing agricultural infrastructure, such as micro-sprinklers and soil moisture sensors and leverages real-time data to optimise water use efficiently. By employing a data-driven approach, DRLIC dynamically adapts to varying soil and weather conditions, reducing the need for manual adjustments and ensuring optimal irrigation levels to maintain crop health. The inclusion of a safety mechanism further enhances its practicality by preventing potential crop damage from unforeseen conditions, while its training methodology using a soil-water simulator accelerates deployment without lengthy field trials.

Moreover, the system has demonstrated significant water savings in real-world tests, making it a cost-effective and sustainable solution for irrigation in water-scarce regions. Overall, DRLIC's adaptability, compatibility, safety, and efficiency make it a highly practical choice for modern irrigation management (Ding & Du, 2024). The Deep Q-Learning Network Reinforcement Learning Irrigation (DQN RL-Irr) strategy leverages short-term weather forecasts to make optimal irrigation decisions, conserving water by reducing unnecessary irrigation and improving rainfall utilisation. This strategy effectively balances the risks of water waste and potential yield loss due to uncertainties in weather forecasts, making it a practical and efficient solution for managing irrigation in paddy rice cultivation (Chen et al., 2021). The proposed Semi-centralised Multi-agent Reinforcement Learning (SCMARL) framework combines both centralised and decentralised RL agents to handle spatial variability in large-scale agricultural fields, optimising water use across different management zones. The SCMARL approach achieved better water savings and improvement in Irrigation Water Use Efficiency (IWUE) compared to a learning-based multi-agent model predictive control (MPC) approach (Agyeman et al., 2024). This demonstrates RL's ability to efficiently coordinate irrigation decisions while addressing non-stationarity and scalability issues, making it a robust solution for precise irrigation management.

This work aims to propose an irrigation algorithm that minimises water usage while maintaining tree growth based on typical irrigation practices at the farm. Reinforcement Learning Irrigation (RL-Irr), an approach that relies heavily on weather conditions, current tree growth, and soil conditions, was introduced to attain this objective. RL-Irr is a non-model AI approach that adapts and learns dynamically as it uses real-time data and continuous interaction with the environment to optimise water usage efficiently and does not require any pre-built models to plan irrigation. In this study, the irrigation performance was compared with the rain-fed irrigation (rain-fed) and SMB-Irr models, and the results were evaluated based on the amount of water used and the simulated tree growth by AQUACROP. The Related Work section explains that SMB-Irr is the farmers' most used tool to identify the best daily irrigation volume. Therefore, it is crucial to recognise that the results obtained from the simulation rely on replicating real-world processes, interactivity, models, algorithms, and randomness, and thus, the findings provide insights for further empirical investigations to imitate real-world processes of durian farming and adaptive irrigations over time.

## METHODOLOGY

### Research Design

This work approach consists of four distinct steps, each with an intended output.

1) Soil sensor and weather station installation at the site and data collection
   Soil sensors were installed at specific locations to collect daily soil moisture readings. A weather station was positioned at the site's highest point to record daily weather data. Data from

both the soil sensors and the weather station were utilised to calculate rewards in the proposed algorithm.

2) AQUACROP parameters calibration
Rain-fed was the system practised on the farm, where irrigation was carried out based on rainfall data. The growth of selected durian trees was measured weekly, and the irrigation volume was measured daily, starting in November 2020. In this study, a custom crop was created in the AQUACROP model, as durian or biologically similar species (e.g., apple) were not available in the AQUACROP library. The model parameters were calibrated using the tree growth data collected on-site as the target output, with adjustments made to reflect the rain-fed model applied on the farm.

3) Development of Irrigation Model
Soil moisture and weather data will be incorporated into the proposed irrigation model. This model will analyse all relevant factors for initiating the irrigation system, including current and forecasted weather conditions, soil characteristics, and historical irrigation records. The model's performance will be evaluated by comparing the irrigation volume used, ensuring that water efficiency is achieved without compromising tree growth.

4) Testing and evaluation for the proposed irrigation model
The proposed model aims to reduce irrigation volume without compromising tree growth. The model was validated using independent tree growth data from the farm, which was not used during the tuning the AQUACROP parameters. The irrigation model's performance was evaluated by comparing the total irrigation volume with other existing irrigation models.

## Farm Irrigation Setup

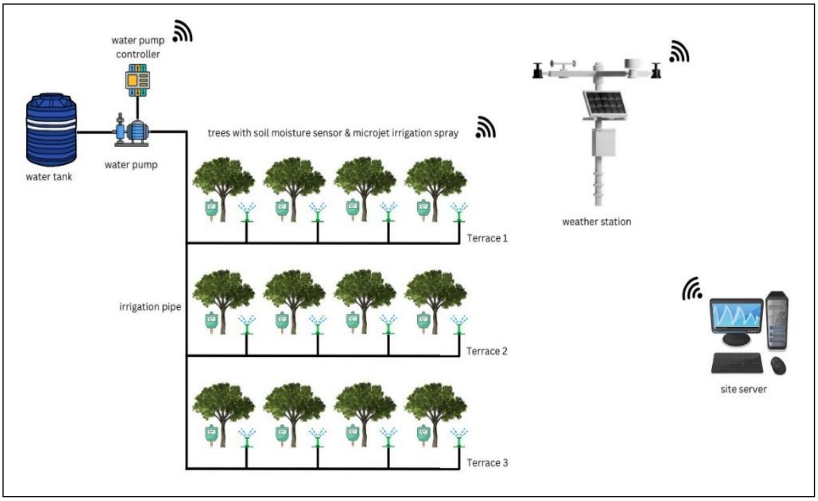
The work was conducted at MIE Agro Durian Farm in Selangor, Malaysia, located at coordinates 1°33'30.3336" N 103°37'33.4596" E. Each sub-block of the farm has a 2200-litre water reservoir with a pump for irrigation. Water was applied to each tree using a 180-microjet spray, which dispersed water at a flow rate of 0.5 litres per minute. Water was sprayed within the tree's canopy during irrigation to ensure optimal root absorption (Zakaria, 2020), as shown in Figure 2. The microjet spray flow rate was 0.5 litres per minute. Figure 3 shows the setup overview of the system implemented at the site.

**Figure 2**

*Microjet Irrigation Spray*

**Figure 3**

*Setup Overview of the System at MIE Agro Farm*




On the farm, 5,000 durian trees were planted in four blocks, each containing multiple sub-blocks. The trees in each sub-durian block are planted on terraces. The number of terraces varies between subblocks, and each terrace's slope gradient depends on the subblock's characteristics. Each sub-block is equipped with a 2200-litre water tank for irrigation purposes. In this work, sub- block D13, A1 and A3 were selected where the trees were planted between five and eight trees on each terrace. Each tree had a soil moisture sensor and a microjet irrigation sprinkler. A controller was connected to the water pump to control its operation, such as turning it on and off. A weather station was installed at the site's highest point, and a server was located in the site control room. The sensors, weather station and water pump controller were powered by batteries and solar panels and connected to the site server using wireless connectivity to facilitate future implementation scaling. The data were transmitted by the soil sensors and weather station to the server at the frequency of 5-minute intervals and were processed daily by the server using the proposed algorithm to control the irrigation system.

## AQUACROP Simulation Software

AQUACROP is a simulation software that models how crop yield responds to water. It models based on user input data, considering factors like soil type, climate, crop type and management practices to predict how changes in water availability affect crop yield. It simulates water movement within the soil-plant-atmosphere system and the impact of different irrigation strategies on crop yield. This helps optimise water use in agriculture and promotes sustainable water management.

In the present work, the AQUACROP model is utilised to simulate the efficacy of the suggested irrigation strategy. AQUACROP employs above-ground biomass as an indicator of tree growth, which is determined through calculations involving the height of the trees for the forest-type trees, as shown in Equation 1.

$$Y = 10 + 6.4\, x\ tree\ height \quad (1)$$

where Y is the above-ground tree biomass in kilogram (kg), and the tree height is in metres (m). Data about the trees were systematically gathered weekly at the farm, and information from the trees exhibiting optimal growth was aggregated and established as the growth benchmark for this research. Consequently, the recommended irrigation strategy was modified daily to align with the attainment of this growth objective.

Standard parameters were configured in a custom crop setup in AQUACROP. As shown in Table 1, some parameters are standard for the trees, which refer to the crop-dependent parameters based on the crop's biological characteristics, while others are site-dependent parameters, which are based on the site setup and conditions that significantly affect tree growth.

**Table 1**

*AQUACROP Custom Crop Input Parameters*

| Parameters | Definition | Remarks |
|---|---|---|
| Maximum temperature (°C) | Maximum temperature at site | Site dependent |
| Minimum temperature (°C) | Minimum temperature at the site | Site dependent |
| Canopy growth coefficient, CGC | Rate canopy cover (CC) increase at the initial planting state | Crop dependent |
| Canopy decline coefficient, CDC | Rate canopy cover (CC) decreases due to ageing or dying | Crop dependent |
| Crop coefficient, $K_{ct}$ | Ratio crop evapo-transpiration over site evapotranspiration | Crop & site dependent |
| Maximum canopy cover, $CC_x$ (%) | Maximum coverage of the canopy | Crop & site dependent |
| Maximum rooting depth, $Z_x$ (m) | Maximum depth of the tree root | Crop & site dependent |
| Initial root depth, $Z_o$ (m) | Initial depth of the tree root after transplant | Crop & site dependent |
| Irrigation efficiency (%) | Percentage efficiency of the irrigation setup | Site dependent |
| Soil surface wetted | Percentage of wetted area during irrigation | Site dependent |
| Tree spacing ($m^2$) | Distance between trees | Site dependent |
| Reference harvest index ($HI_o$) | Standard ratio of total biomass in ideal condition | Crop dependent |

## Rain-fed Irrigation (Rain-fed)

This work focused on three (3) sub-blocks on the farm: D13, A1 and A3. The sub-blocks used rain-fed irrigation, an agricultural irrigation technique that relies solely on rainfall as the water source. This method is the primary way of farming, though its success depends greatly on the amount and distribution of rainfall. A weather station was set up on-site to measure daily rainfall and help decide when to irrigate. The irrigation was done manually, providing each tree with 30 litres of water for one (1) hour. The pseudo-code of the rain-fed irrigation practised on the farm is shown in Algorithm 1.

**Algorithm 1: Algorithm for Irrigation Control Based on Rain-fed**

**Input:** Rain volume: rain volume measured from 10:00 AM the previous day until 7:00 AM on the current day.
**Output:** Irrigation control decision.

**Procedure:**

1. Check rain status at 8:00 AM daily:
2. **If** rain occurred between 10:00 AM the previous day and 7:00 AM today:
3. **If** rain volume < 5 mm
4. Irrigate 30 litres.
5. **Else If** rain volume > 10 mm
6. No irrigation for the next 2 days.
7. **Else**
8. No irrigation for the current day.
9. **Else (If No Rain Occurred):**
10. Irrigate 30 litres.

**End Procedure**

## Soil Moisture Balance Irrigation (SMB- Irr)

The SMB-Irr system determines the optimal timing and the optimal amount of crop irrigation by considering soil moisture levels. It balances water inputs such as rain and irrigation with outputs, such as evapotranspiration, drainage and runoff relative to the soil's water-holding capacity. The SMB-Irr system used in this work was based on the Field Capacity (θfc) and Wilting Point (θwp) of the soil, the variables which are specific to the soil type and were chosen according to the Malaysia Soil Standard (Ashraf, 2017) and the USDA Soil Standard (Jabro et al., 2008). The following steps outline how to calculate irrigation volume using SMB-Irr:

Step 1: Calculate the soil threshold value, $\theta_x$, by using the formulation in Equation 2.

$$\theta_x = \theta_{fc} - (ASMD\ x\ (\theta_{fc} - \theta_{wp}) \qquad (2)$$

where ASMD stands for Available Soil Moisture Deficit, which represents the allowable deficit for the trees before they experience a deficit state of a moisture shortage, assuming the ASMD durian tree is 0.2, which is 20%.

Step 2: Calculate the weighted average soil moisture, $\theta_a$ at the root zone level by using Equation 3.

$$\theta_a = (\theta_{SM} \ x \ D_s)/RZD \tag{3}$$

where $\theta_{SM}$ is the soil moisture value from the sensor, $D_s$ is the Sensor Depth and RZD is the Root Zone Depth, where RZD is 0.1-metre for the trees between one (1) to three (3) years of age.

Step 3: Compare $\theta_x$ and $\theta_a$ values. If $\theta_a$ is lower than $\theta_x$, calculate the irrigation volume as in Step 4. If higher, no irrigation is required.

Step 4: Calculate the irrigation volume, $V_{irr}$ by using Equation 4.

$$V_{irr} = (\theta_{fc} - \theta_a) \times RZD \times 1000 \tag{4}$$

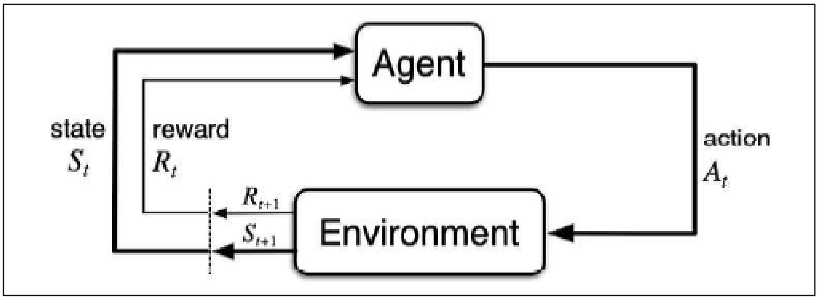
where the $V_{irr}$ is in litre

**Reinforcement Learning Irrigation (RL- Irr)**

RL is a non-model type of AI that involves an agent learning to make decisions by interacting with its environment. In reinforcement learning (RL), the agent is not given explicit instructions on which actions to take. Instead, it must autonomously explore and experiment with different actions to determine which ones yield the highest rewards. This approach is inspired by behavioural psychology and is particularly effective in complex contexts where explicit programming is impractical. The agent tries different actions to see which ones produce the best rewards (Devraj et al., 2021). The process involves an agent, a set of states representing the environment and the actions taken by the agent. The agent receives feedback in the form of rewards or penalties and develops a policy, which is a systematic approach for selecting actions based on the current state of the environment. RL uses this feedback to reinforce effective strategies and diminish ineffective ones. The fundamentals of RL are shown in Figure 4.

**Figure 4**

*Fundamental Architecture of RL (Sutton & Barto, 1999)*




In RL, it is crucial to strike a balance between exploring and attempting new approaches and exploitations by using familiar knowledge (Ladosz et al., 2022). The agent interacts with the environment in discrete time steps. At each time step, t, the agent receives some representation of the state of the environment S(t) and selects an action A(t) based on that state to perform in the environment. The action then changes the state of the environment, and the agent receives a reward R(t+1) and a new state S(t+1) as feedback from the environment. If the action leads to an undesired outcome, the agent receives a penalty (a negative reward) instead of a reward. This process continues, and the agent's objective is to learn a policy by mapping from states to actions in order to maximise the cumulative reward over time. RL is utilised in various fields, including robotics, transportation, energy and computer systems (Aradi, 2022; Jayaramireddy et al., 2023; Polydoros & Nalpantidis, 2017; Yu et al., 2021).

The implementation of RL in this work is as follows:

1) Agent (*i*) is the entity that performs actions in the problem. In this work, the agent represents the system's core elements that interact with the environment, formulate decisions based on information and acquire knowledge from the consequences of those decisions.
2) Environment (ε) is the space in which the agent performs actions. In this work, the environment encompasses all the elements that influence the actions, which are soil conditions, weather conditions and tree growth.
3) Action (*A*) is the potential moves that can be performed by the agent. In this context, the action refers to the absolute irrigation

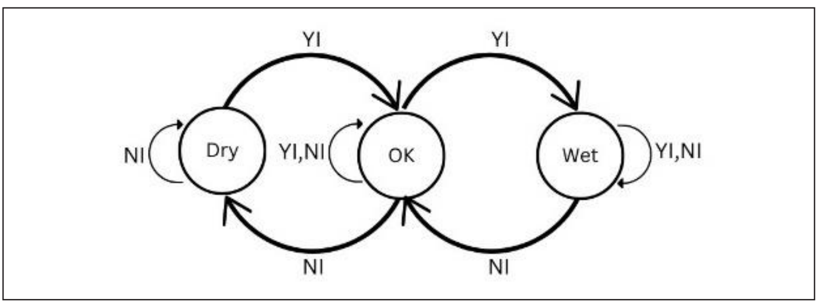
volume set in the system. These volumes ranged from 0 to 30 litres, with increments of 2 litres.

4) State (*S*) is the specific condition of the environment at a specific time. In this work, state refers to the specific condition of the soil at a given time. The soil condition is categorised as dry (soil moisture is less than 25%), good (soil moisture is between 25% to 35%) or wet (soil moisture is more than 35%).
5) Policy (π) is the guideline employed by the agent to determine the next step of action to take based on the current state. In this work, Policy refers to the sequence of irrigation actions that the agent takes to solve the problem.
6) Rewards and Penalties (*R*) are the outcomes the agent receives after taking an action. They are result-oriented and can be either positive (Reward) or negative (Penalty). The calculation of Rewards and Penalties must be in line with the environment to ensure that the agent receives them accurately. In this work, the Reward depends on soil tension, tree growth and water balance. A Penalty is incurred if the irrigation action causes the soil to become either Dry or Wet.

Figure 5 presents the RL states employed for tree irrigation in this study. YI and NI represent Yes Irrigation and No Irrigation, respectively.

**Figure 5**

*RL State for RL-Irr*




The diagram above illustrates the actions taken by the agent in response to varying soil conditions. In scenarios without irrigation, the soil retains its ‘Dry’ state. Its transition to an ‘OK’ state occurs only upon the commencement of irrigation. The soil maintains its condition without further irrigation in this ‘OK’ state. However, prolonged periods without irrigation will lead the soil back to a 'Dry' state. Conversely, initiating irrigation while the soil is in an 'OK' state causes it to become 'Wet'. Typically, irrigation is withheld in the 'Wet' state to prevent soil saturation. Nonetheless, rainfall might occur when the soil is already 'Wet', thereby maintaining its 'Wet' state. The soil eventually reverts to the 'OK' state after a certain period without irrigation and gradually becomes drier. This dynamic reflects the agent's adaptive responses to the evolving moisture levels in the soil, corresponding to the root water uptake from the trees.

This work has several target goals, such as enhancing water efficiency, conserving soil fertility and maximising crop vitality. An effectively designed reward function can skilfully balance these objectives by providing suitable incentives for actions that contribute to each goal. Moreover, the reward function can account for the inherent trade-offs within the application. For instance, in irrigation management, higher water consumption may initially promote crop growth but could negatively impact long-term water conservation. The reward function is crucial in reconciling these conflicting requirements. It will ensure that the RL agent's learning path is theoretically rigorous and practically applicable, bridging the gap between mathematical modelling and the complexity of real-world implementation. Equation 5 shows the Rewards function used in this work.

$$R_{total} = (w_{soil\ tension} \times R_{soil\ tension}) + (w_{tree\ growth} \times R_{tree\ growth}) + (w_{rain} \times R_{rain}) + (w_{Et} \times R_{Et}) \quad (5)$$

The variable $w$ represents the weight assigned to different elements, determined by the proportion of each element relative to the overall weight distribution. These weights were set according to the specific objectives of irrigation and the prevailing conditions during that period. For example, $w_{soil\_tension}$ was assigned a higher value in instances of arid soil and a lower value in other cases. Conversely, $w_{tree\_growth}$ was high when irrigation occurred on the first day of the week, as per the standard operating procedure of the farm, which involved collecting data on tree growth exclusively on this day. This approach ensures that the weighting aligns with the immediate environmental needs and the operational procedures of the farm. Similarly, the variables $w_{rain}$ and $w_{Et}$ were assigned high values, respectively, if the actual value was lower than the calculated value, and a lower value if it was higher.

In Equation 6, the term 'Rewards' ($R$) encapsulates the rewards attributed to each critical element: soil tension, tree growth and water efficiency. These rewards are intricately linked to the prevailing conditions of the respective period, ensuring that the rewards allocated to the agent are optimised based on the actual environmental and operational circumstances. Equations 6 to 9 outline the formulas for calculating the rewards for the elements.

$$R_{soil\ tension} = -\left(soil\ tension_{target} - soil\ tension_{actual}\right) \tag{6}$$

$$R_{tree\ growth} = -\left(tree\ growth_{target} - tree\ growth_{actual}\right) \tag{7}$$

$$R_{Et} = -\left(Et_{forecast} - Et_{actual}\right) \tag{8}$$

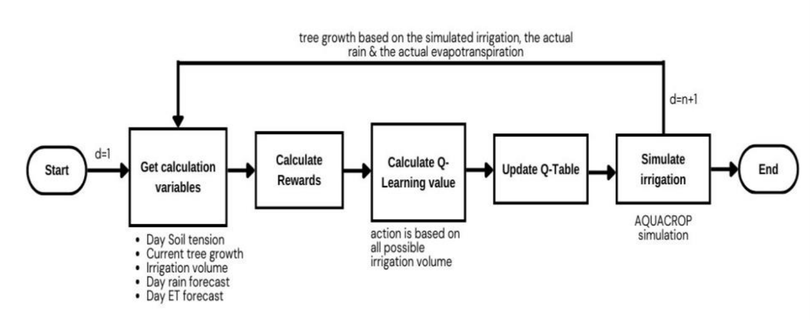
$$R_{rain} = -\left(Rain_{forecast} - Rain_{actual}\right) \tag{9}$$

The target for tree growth was calculated using a model crafted and simulated with the AQUACROP software. The study suggests that using a deseasonalised fuzzy time series model for rainfall forecasting yields higher accuracy than traditional methods, as shown by lower MSE and RMSE values (Othman & Azhari, 2016). However, the use of actual rainfall data at a specific location is preferred for real-time predictions since it reflects the real-world environmental conditions and variability. Rainfall predictions are based on forecasts from the Malaysian Meteorological Department (MET). Additionally, the forecast for evapotranspiration (Et) is computed utilising the Penman-Monteith (PM) Equation, which incorporates meteorological forecast data from the MET. This integrated approach ensures a comprehensive and accurate assessment of precipitation and evapotranspiration, which is crucial for effective irrigation planning and management.

The flowchart in Figure 6 above illustrates the proposed RL-Irr system. On the first day *(d=1)*, the system assessed the soil tension using the current soil moisture value, tree growth, previous irrigation volume, rain prediction from the MET website and calculated evapotranspiration based on forecasted weather data from the MET website. The system then calculated the Rewards using the formula from Equations 6 to 9. Q-Learning for all possible actions (irrigation volume) was calculated and updated in the Q-table. Then, the system simulated irrigation using AQUACROP and observed the simulated tree growth from the simulation output. The variance between the simulated and expected tree growth, based on actual growth data collected at the site, was calculated and input into the system for the next day's irrigation *(d=n+1)*.

**Figure 6**

*System Flow for the Proposed RL-Irr*




## RESULTS AND DISCUSSION

This section compares the irrigation volume between SMB-Irr, rain-fed, and RL-Irr. In this study, the actual tree growth data were gathered on-site using the SMB technique for irrigation. The soil type was sandy clay loam, and the soil moisture threshold for the SMB was set to 35 percent based on the soil field capacity standard for sandy clay loam soil (RainMachine, 2018). If the current soil moisture fell below the threshold value, irrigation would be initiated for a few minutes until the moisture reaches the set threshold.

### Tree Growth

AQUACROP evaluates irrigation efficiency using biomass values proportional to tree height, as shown in Equation (1). Weekly tree growth data were collected for trees at D13, A1 and A3. The AQUACROP model was calibrated to match tree growth using the rain-fed irrigation method practiced on-site. Since the AQUACROP model is unavailable for durian, calibration was necessary to ensure the model accurately reflected tree growth (Ismail et al., 2015). The study then simulated the suggested irrigation methods using the calibrated AQUACROP model to assess their effectiveness. Figures 6 to 9 show the tree growth pattern from November 2020 to December

2023. Weekly measurements were taken at three farm sub-blocks: D13, A3, and A1. Sub-blocks D13 and A3 consisted of five terraces of different elevations, each with 10 to 20 trees, totalling 100 trees per sub-block. Sub-block A1 consisted of one terrace with 10 trees. Since tree growth was nearly identical on each terrace, the average growth per terrace was used in this study instead of individual tree measurements.

**Figure 7**

*Tree Height from Week 1 (November 2020) to Week 113 (March 2023)*

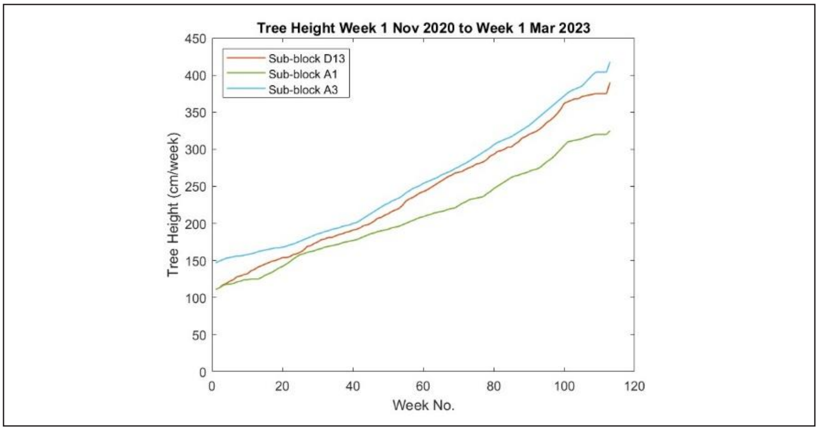



**Figure 8**

*Tree Girth from Week 1 (November 2020) to Week 113 (March 2023)*

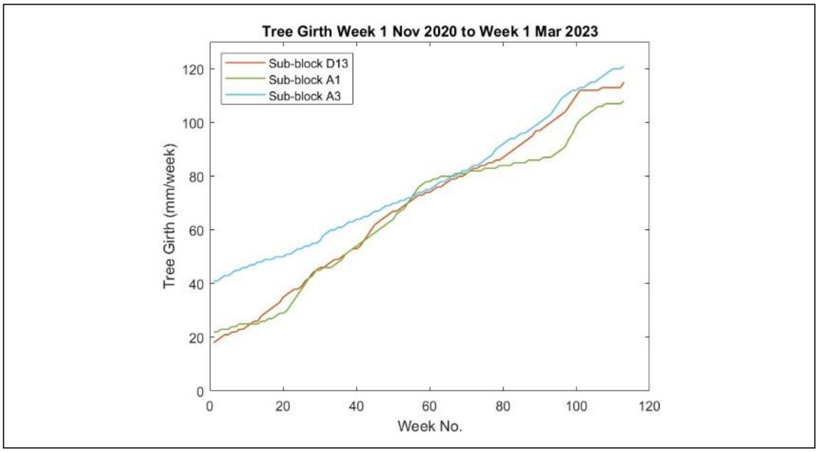


**Figure 9**

*Tree Height Growth Rate from Week 1 (November 2020) to Week 113 (March 2023)*

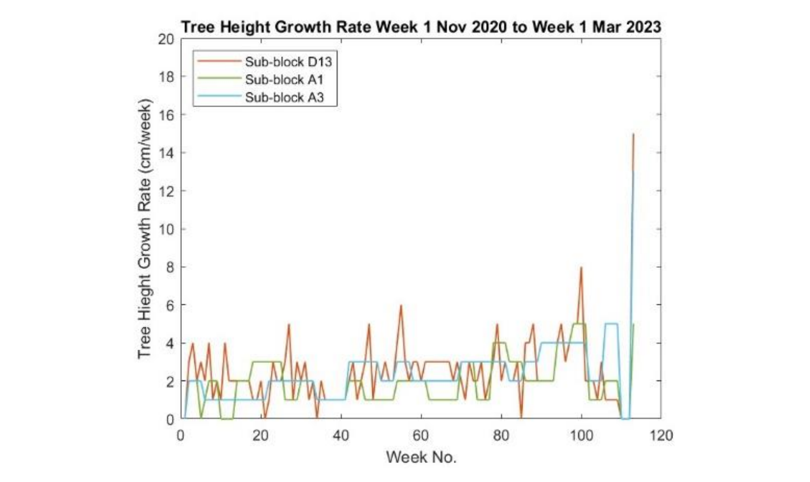
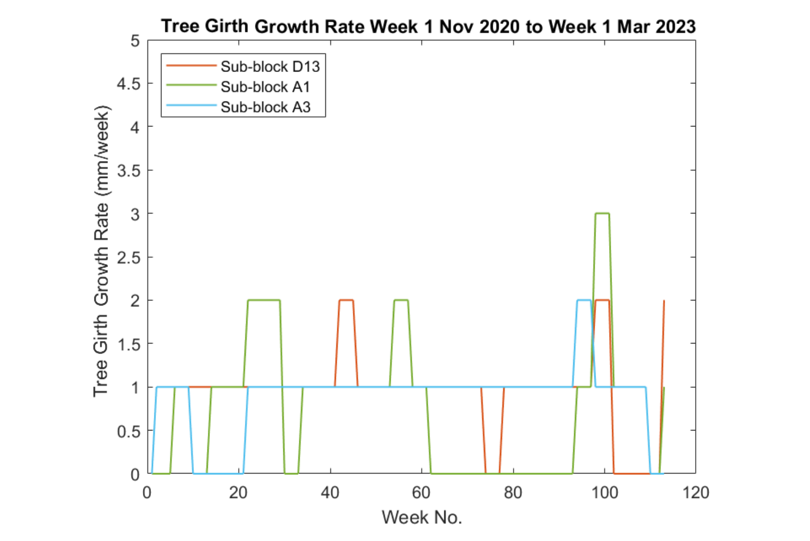



**Figure 10**

*Tree Girth Growth Rate from Week 1 (November 2020) to Week 113 (March 2023)*



The trees were transplanted at heights of 1 to 1.5 meters in Week 1. Figures 7 and 8 display the growth metrics, specifically tree height and girth, for three sub-blocks (D13, A1, and A3) from Week 1 (November 2020) to Week 113 (March 2023). Figure 7 illustrates tree height in centimetres on the y-axis and the week number on the x-axis. The trees exhibited a steady increase in height from the beginning, with the growth rate represented by the slope of the curve. The curve follows a sigmoidal pattern, typical of biological growth, with an initial slow phase, rapid growth and a slowdown as the trees matured. Sub-block D13 consistently exhibited the highest growth throughout the period, followed closely by A1, while A3 exhibited significantly lower growth. Figure 8 shows the trunk girth of the trees in millimetres (mm) on the y-axis, plotted against the week number on the x-axis. As tree height increased, the trunk girth also grew over time. All sub-blocks showed an increase in trunk size, with sub-block D13 exhibiting the most significant increase, followed by A1 and A3, similar to the height growth trend. These results suggest that soil conditions at D13 positively impacted tree growth. The consistent growth across all blocks indicates that the care provided was effective, adhering to the farm's standard operating procedures, including proper irrigation and nutrient supply (Zakaria, 2020).

Figures 9 and 10 illustrate tree height and girth growth rates for D13, A1, and A3 from Week 1 (November 2020) to Week 113 (March 2023). Figure 6 displays the weekly growth rate of tree height in centimetres. The height growth rates for all sub-blocks vary significantly each week, showing spikes and drops. This variability is likely due to environmental and biological factors, such as inconsistent weather and nutrient and water uptake variations. The growth rates for each sub-block were inconsistent throughout the monitoring period, which is typical for open-field farming, where environmental factors affect tree growth (Cocozza et al., 2021).

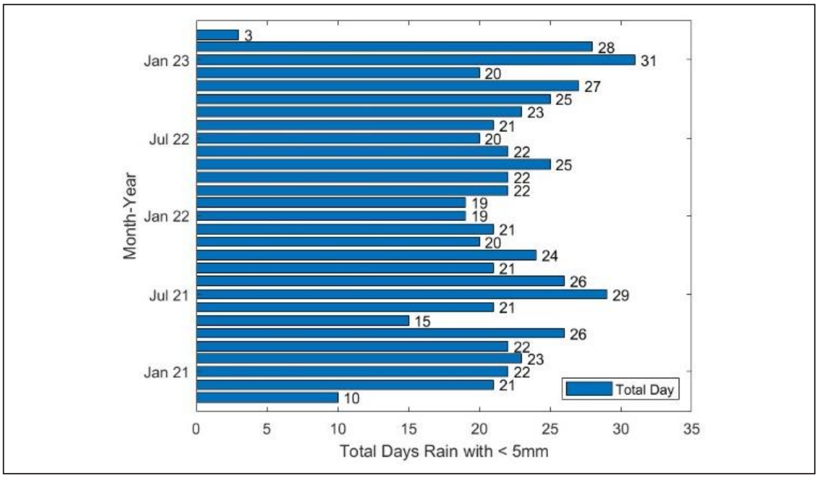
Additionally, Figure 10 indicates the weekly increase in tree girth, measured in millimetres (mm). The girth growth rates were generally lower than the height growth rates, which is typical of biological growth patterns. The girth growth rates were more consistent, with less fluctuation than height growth. Both height and girth growth were affected by weather, environmental changes, resource availability, and the trees' natural biological cycles. Trees in sub-block D13 showed higher growth peaks in both height and girth compared to those in A1 and A3. Despite using the same procedures for all trees, the trees in D13 responded better, indicating more favourable growth conditions.

## Irrigation Volume

The farm utilised a rain-fed irrigation method, supplying 30 litres of water to the trees on days with no rain or less than 5 mm of rainfall. The growth of the trees based on this irrigation method is depicted in Figures 7 and 8. Additionally, Figure 11 displays the monthly total of days with less than 5 mm of rain, indicating when 30 litres of water were applied, using data from the farm's weather station.

**Figure 11**

*Total Days of Rain with Less Than 5mm on the Farm*




Based on the analysis of rainfall frequency, the farm required irrigation almost every day. In March 2023, there was the highest amount of rainfall, with only three days out of 30 receiving less than 5mm of rain. On the other hand, January 2023 experienced the least amount of rain, with all 31 days having less than 5mm of rain daily. A single weather station represented the entire farm area. When the rainfall was less than 5mm, each sub-block received 30 litres of irrigation, effectively tripling the total irrigation volume for D13, A1, and A3 combined.

Figures 12 to 14 illustrate the daily irrigation volume using SMB-Irr and RL-Irr for all terraces. Despite each sub-block having five terraces, the irrigation volume applied to the trees was consistent across all terraces within each sub-block.

**Figure 12**

*Irrigation Volume Using SMB-Irr and RL-Irr for D13*

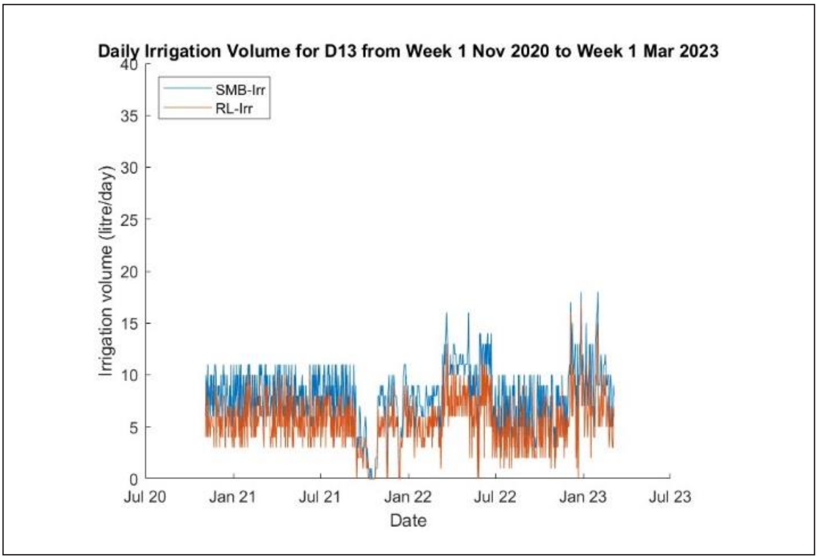



**Figure 13**

*Irrigation Volume Using SMB-Irr and RL-Irr for A1*

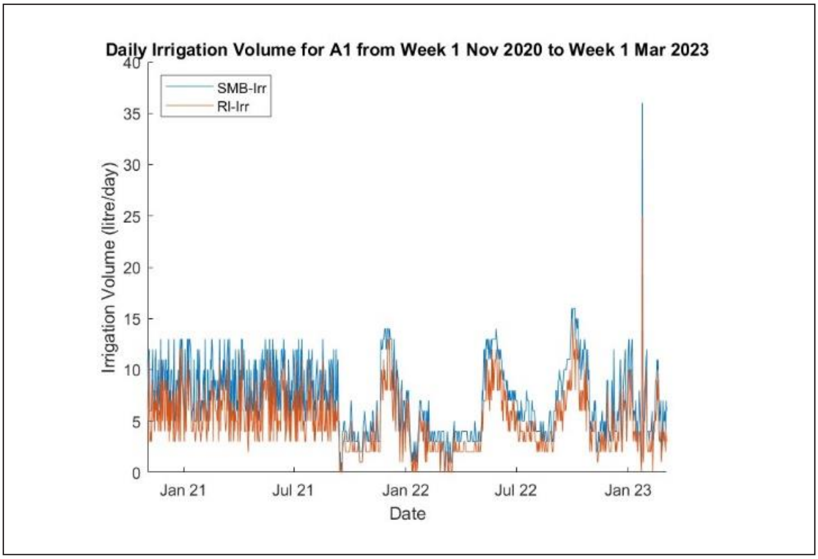
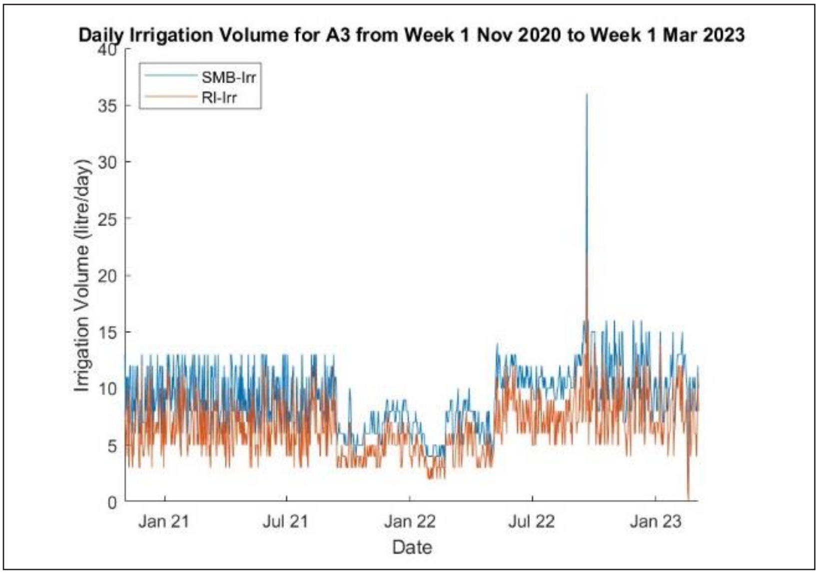


**Figure 14**

*Irrigation Volume Using SMB-Irr and RL-Irr for A3*




Figures 12 to 14 display the daily water usage for irrigation in litres for three sub-blocks (D13, A1 and A3) from November 2020 to March 2023. The data compares two irrigation methods: SMB-Irr (based on soil moisture) and RL-Irr. Both methods exhibited daily variations influenced by rainfall, temperature, evapotranspiration and the needs of the trees over the three years. Water usage fluctuated, with some days requiring significantly more water, indicating the necessity for adaptive irrigation strategies. RL-Irr used less water overall compared to SMB-Irr across all sub-blocks. RL-Irr did not perform irrigation on several days, such as November 3, 2020, September 15, 2021, and various days in October 2021, November 2021, December 2021, May 2022 and December 2022. On the other hand, SMB-Irr showed sudden increases in irrigation when soil moisture was low, but such occurrences were rare in RL-Irr. RL-Irr accounted for additional factors to determine the specific amount of water needed each day. Figures 15 to 17 illustrate the cumulative weekly irrigation volume for each terrace, and Table 2 compares the total irrigation volumes of SMB-Irr and RL-Irr with the measured rain-fed method.

**Figure 15**

*Cumulative Irrigation Volume for Trees at D13*

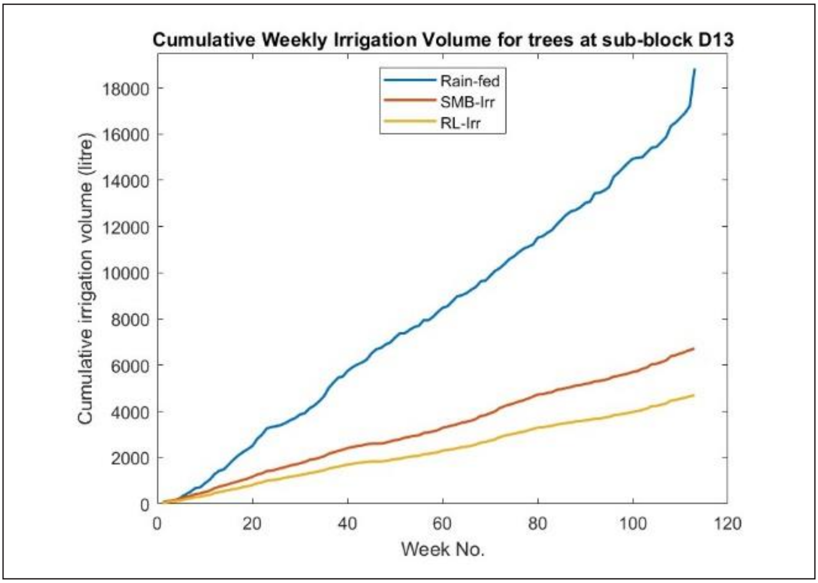



**Figure 16**

*Cumulative Irrigation Volume for Trees at A1*

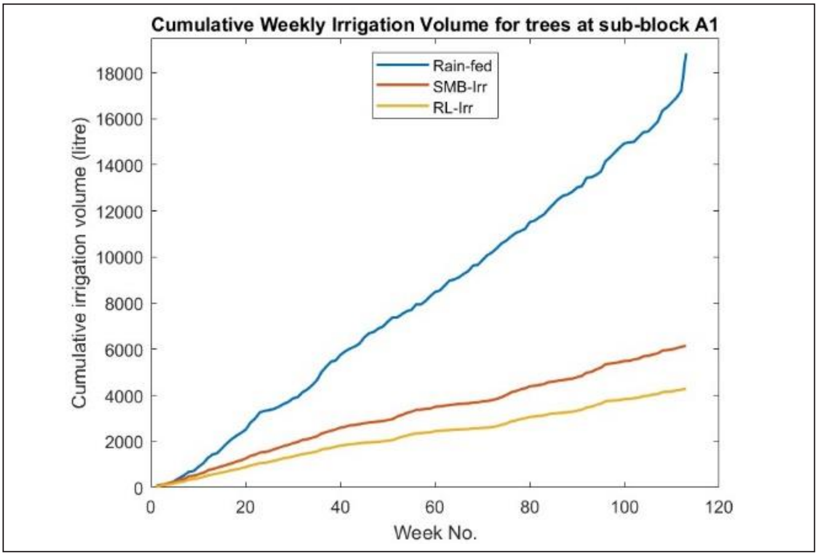


**Figure 17**

*Cumulative Irrigation Volume for Trees at A3*

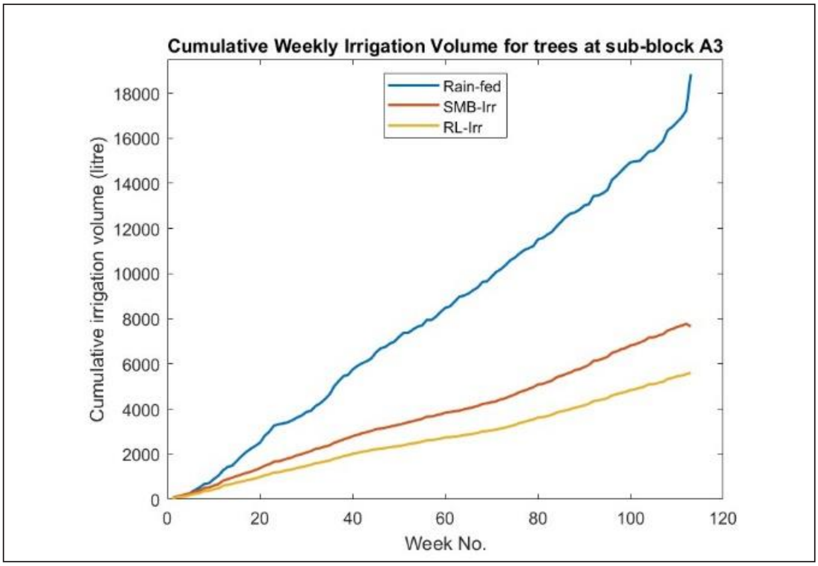



**Table 2**

*Total Irrigation Volume for All Sub-blocks Calculated Using Different Irrigation Strategies*

| Irrigation Method | Irrigation Volume (litres) | | | |
|---|---|---|---|---|
| | D13 | A1 | A3 | Total |
| Rain-fed | 18840 | 18840 | 18840 | 56520 |
| SMB-Irr | 6731 | 6161 | 7862 | 20754 |
| RL-Irr | 4704 | 4290 | 5606 | 14600 |

The graphs illustrate the cumulative weekly irrigation volume for trees at sub-blocks D13, A1 and A3 over a period of 113 weeks. Each graph compares three irrigation methods: rain-fed, SMB-Irr and RL-Irr. The X-axis represents the number of weeks, while the Y-axis shows the cumulative volume of irrigation water in litres.

The rain-fed method indicated the highest cumulative irrigation volume across all three sub-blocks, with a consistent increase in water usage over time. The SMB-Irr method used a moderate amount of water, with its cumulative volume steadily rising but remaining below the rain-fed method throughout the period. Notably, the RL-Irr method demonstrated the lowest cumulative irrigation volume for all sub-blocks, increasing much slower than the other two methods. The RL-Irr method consistently used the least water over the 113 weeks for all sub-blocks, indicating that RL-Irr is the most water-efficient method among the three, offering substantial water savings while maintaining adequate irrigation.

Based on Table 1, the RL-Irr method uses approximately 75.03 percent, 77.23 percent and 70.24 percent less water than the rain-fed method for sub-blocks D13, A1 and A3, respectively, with a total percentage difference of about 74.16 percent. Similarly, RL-Irr uses approximately 30.13 percent, 30.39 percent and 28.72 percent less water than the SMB-Irr method for sub-blocks D13, A1 and A3, respectively, with a total percentage difference of about 29.68 percent. This indicates that RL-Irr is significantly more water-efficient than the other two methods across all sub-blocks.

The RL-Irr system is highly effective and uses less water consistently in all sub-blocks. If RL-Irr can meet the trees' water needs while maintaining their growth, it could be a more sustainable irrigation method that conserves water, especially in water-scarce regions or during droughts. Using RL-Irr instead of SMB-Irr could significantly reduce water usage, lower irrigation costs and lessen the strain on water supplies, particularly in large-scale agriculture.

## Tree Height Comparison with Rain-fed, SMB- Irr and RL- Irr Strategies

Tree growth section demonstrates that measuring tree girth may be less significant due to the minimal changes observed. Consequently, comparisons are made based on the tree heights of sub-blocks D13, A1 and A3 to validate the outcomes of the irrigation strategies.

**Figure 18**

*Simulated Tree Height for Trees Sub-block D13 Using the AQUACROP Model with Different Irrigation Strategies*

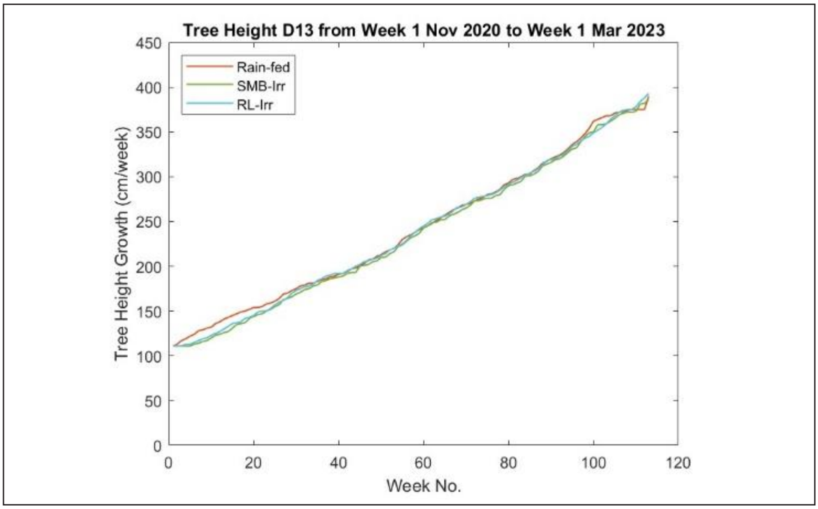



**Figure 19**

*Simulated Tree Height for Trees Sub-block A1 Using the AQUACROP Model with Different Irrigation Strategies*

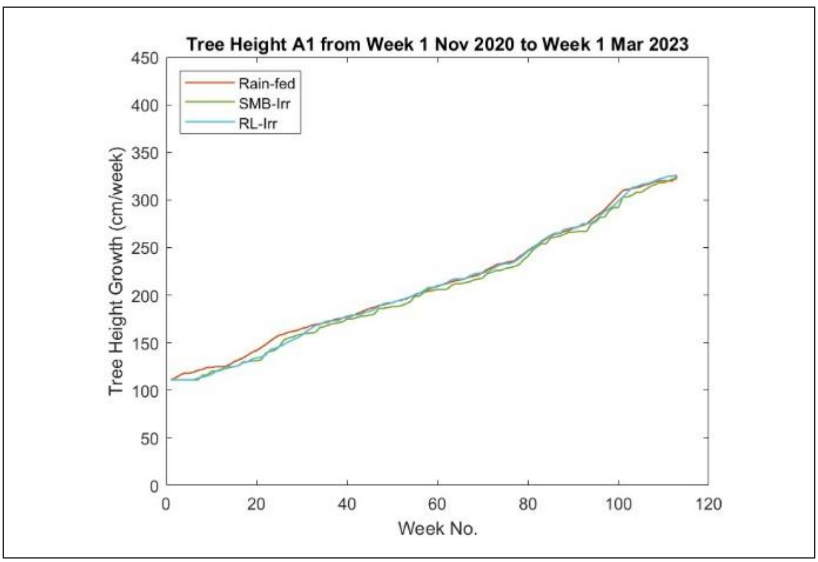
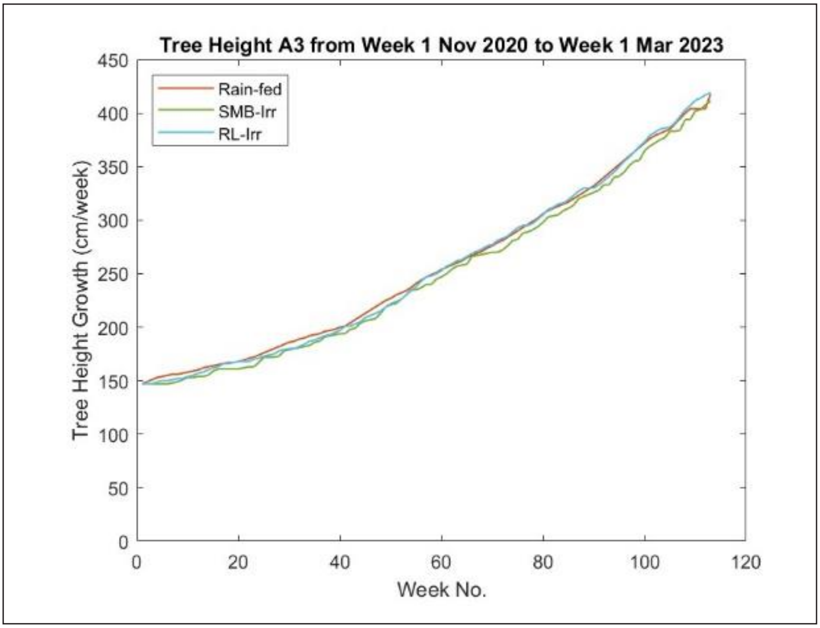


**Figure 20**

*Simulated Tree Height for Trees Sub-block A3 Using the AQUACROP Model with Different Irrigation Strategies*




Figures 18 to 20 illustrate the impact of different irrigation techniques on tree growth over a period of 113 weeks. The growth from rain-fed irrigation was used as a benchmark. The AQUACROP model was adjusted to match the growth of rain-fed trees. The data indicates that the tree growth AQUACROP simulated closely matched the rain-fed growth. The trees showed a progressive increase in height over time. The figures demonstrate that different irrigation methods and rain-fed conditions resulted in similar growth patterns, with the lines closely overlapping. The rain-fed trees exhibited steady growth that closely mirrored the growth of trees using SMB-Irr and RL-Irr methods. The proximity of the lines in each figure suggests that various irrigation methods and rain-fed conditions led to similar tree heights after the monitoring period. The growth curves illustrate that irrigation technologies and natural rainfall contributed similarly to the trees' growth. This is further illustrated in Figures 21 to 23.

**Figure 21**

*Simulated Tree Height Growth Rate for Tree Sub-block D13 Using the AQUACROP Model with Different Irrigation Strategies*

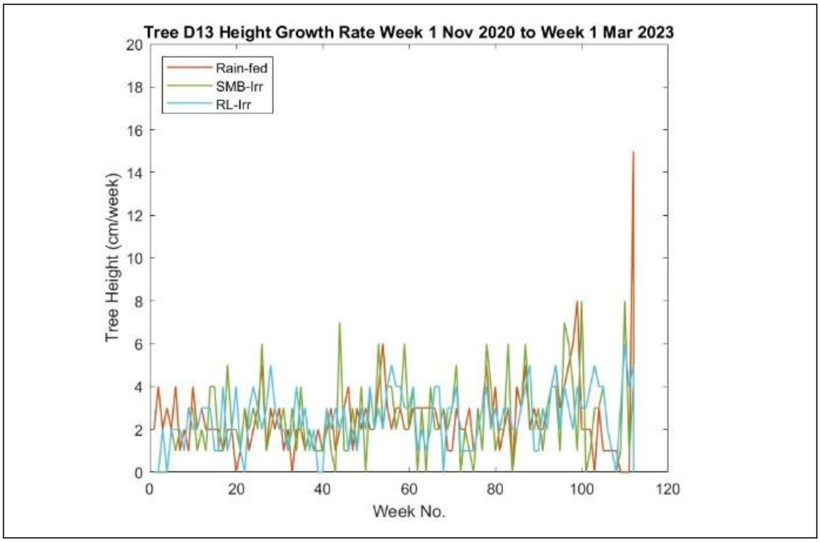



**Figure 22**

*Simulated Tree Height Growth Rate for Tree Sub-block A1 Using the AQUACROP Model With Different Irrigation Strategies*

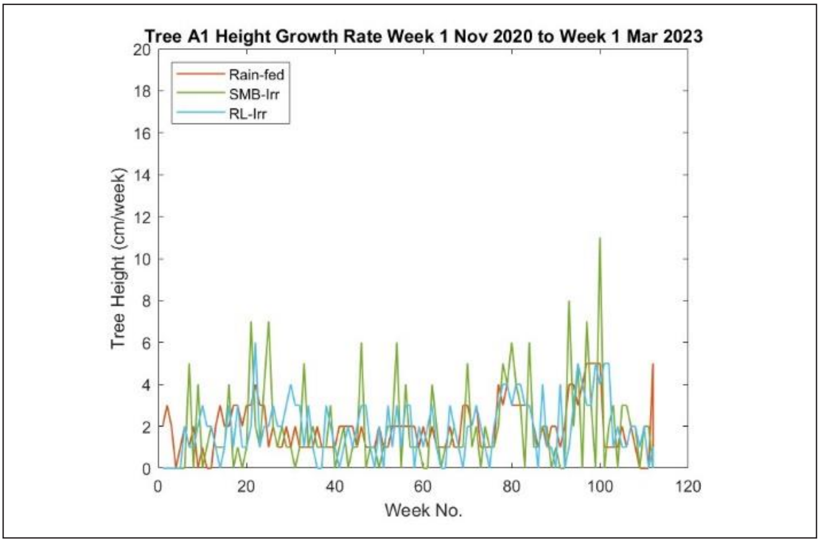
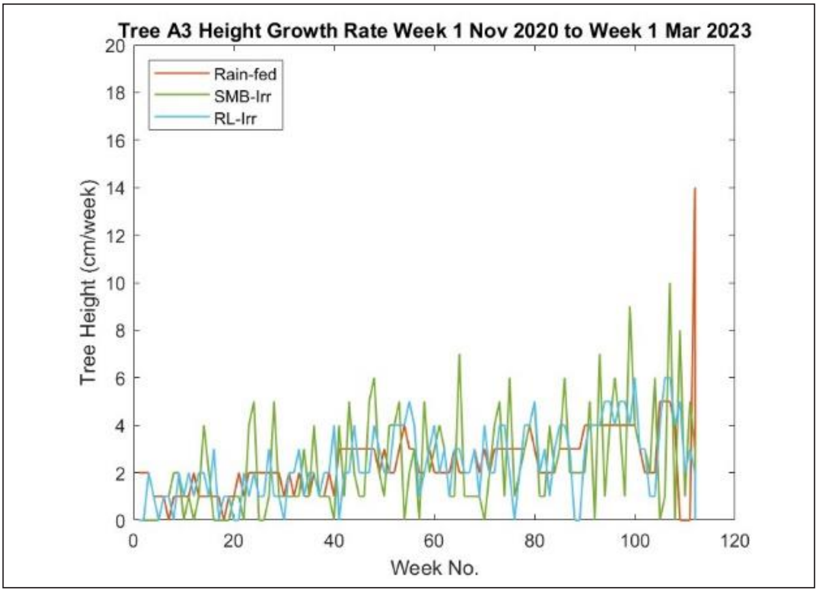


**Figure 23**

*Simulated Tree Height Growth Rate for Tree Sub-block A3 Using the AQUACROP Model With Different Irrigation Strategies*




The figures compare the growth rates of tree heights in sub-blocks D13, A1 and A3 using three different irrigation methods: rain-fed, SMB-Irr, and RL-Irr. Rain-fed serves as the baseline, SMB-Irr supplies water when soil moisture falls below 25%, and RL-Irr uses a Reinforcement Learning algorithm to optimise water usage. In sub-block D13, there is a significant increase in growth under RL-Irr towards the end of the observed period. Similarly, sub-blocks A1 and A3 also show fluctuations with peaks in growth under both SMB-Irr and RL-Irr. Overall, the RL-Irr method generally resulted in higher growth rates than rain-fed and SMB-Irr, indicating better optimisation of water usage for improved growth. However, the effectiveness of RL-Irr varied across different trees, likely due to individual tree health and conditions. In sub-block A3, RL-Irr occasionally showed the highest growth rate peaks, especially towards the end of the observed period. Across all sub-blocks, RL-Irr sometimes optimised water amounts to significantly boost growth by leveraging past and current data to predict and apply the most beneficial irrigation schedule, thus avoiding over- and under-irrigation.

**Table 3**

*Statistical Analysis for Rain-fed, SMB-Irr and RL-Irr for Tree Growth (mm)*

| | Mean (m) (mm) | | | Standard Deviation (s) (mm) | | |
|---|---|---|---|---|---|---|
| Sub-block | D13 | A1 | A3 | D13 | A1 | A3 |
| Rain-fed | 2.47 | 2.46 | 2.51 | 1.84 | 1.87 | 1.35 |
| SMB-Irr | 1.89 | 1.88 | 1.92 | 1.20 | 2.10 | 1.41 |
| RL-Irr | 2.41 | 2.36 | 2.46 | 1.60 | 2.19 | 1.54 |

Table 3 shows a statistical comparison of tree growth under three different irrigation methods: rain-fed, SMB-Irr, and RL-Irr. The analysis revealed noticeable differences in the performance of tree growth. The rain-fed shows relatively consistent growth across all sub-blocks, with mean values of 2.47 mm, 2.46 mm and 2.51 mm, respectively, and standard deviations ranging from 1.35 mm to 1.87 mm. SMB-Irr exhibits lower mean growth values of 1.89 mm, 1.88 mm and 1.92 mm, with varying levels of consistency, with the lowest standard deviation in sub-block D13, which is 1.20 mm and higher variability in sub-block A1, which is 2.10 mm. RL-Irr demonstrates higher mean growth values closer to rain-fed, which is at 2.41 mm, 2.36 mm, and 2.46 mm, but with slightly higher standard deviations than SMB-Irr, indicating moderate consistency. Overall, RL-Irr combines near-optimal growth performance identical to rain-fed with a moderate level of variability, suggesting that it offers a balanced approach to achieving high growth and maintaining consistent results across different sub-blocks.

This study's results demonstrate the RL-Irr system's efficiency in optimising water usage for durian trees while maintaining growth performance. RL-Irr consistently reduced water consumption compared to traditional rain-fed and SMB-Irr methods. Specifically, RL-Irr achieved a water savings of up to 74.16 percent compared to rain-fed irrigation and approximately 29.68 percent compared to SMB-Irr across all sub-blocks. These findings highlight the potential of RL-Irr for water conservation and saving.

In addition, the simulation results indicate that tree growth under RL-Irr was comparable to that under rain-fed and SMB-Irr methods. Figures 18 to 23 show that tree height and girth growth patterns were similar across all sub-blocks, despite the reduced irrigation volume in the RL-Irr system. This suggests that RL-Irr can maintain optimal tree growth while using less water, providing a balanced solution for sustainable irrigation.

The implications of these results are notable for agriculture, particularly in durian cultivation, where efficient water management is critical. The RL-Irr system could be widely adopted to improve irrigation efficiency, reduce water costs, and promote sustainable farming practices. Since the RL-Irr parameters were calibrated using site-specific data, replicating the system in diverse locations with varying soil types and climates is recommended to enhance its robustness. Future studies should also consider including a larger sample of trees and different terrains to further refine the algorithm's sensitivity and overall effectiveness.

## CONCLUSION

This study applied Reinforcement Learning Irrigation (RL-Irr) to irrigate durian trees grown in an open area. The amount of water given to the trees was adjusted daily based on the trees' current growth rate, soil tension, previous irrigation volume, rain forecast, and evapotranspiration forecast. This approach differs from traditional irrigation methods, as irrigation was fine-tuned daily by adjusting the RL-Irr rewards to ensure a precise water supply to the trees. The AQUACROP model was used to simulate tree growth under various irrigation volumes, and its feedback was utilised to adjust the reward system in the RL-Irr algorithm for subsequent irrigation schedules.

When comparing RL-Irr with rain-fed (practised on the farm) and SMB-Irr, RL-Irr proved to be more efficient, effectively hydrating the trees while reducing water consumption. This suggests that RL-Irr can maintain optimal tree growth while conserving water, making it an ideal solution for sustainable agriculture. Adaptive irrigation systems like RL-Irr offer a way to address water wastage, particularly in regions facing water scarcity, and help combat the challenges posed by climate change.

The study was conducted in Malaysia, where 120 trees (2.5% of the total 4,800 trees on the farm) were used. As RL-Irr parameters, such as weather data, are site-specific, replicating this system in different regions with varying weather and soil conditions is recommended to improve its robustness. Future studies should consider testing the algorithm with more trees across varying terrains to enhance sensitivity. While the results provide valuable insights into adaptive irrigation, they are based on model assumptions and should be further validated through real-world applications.

## ACKNOWLEDGMENT

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