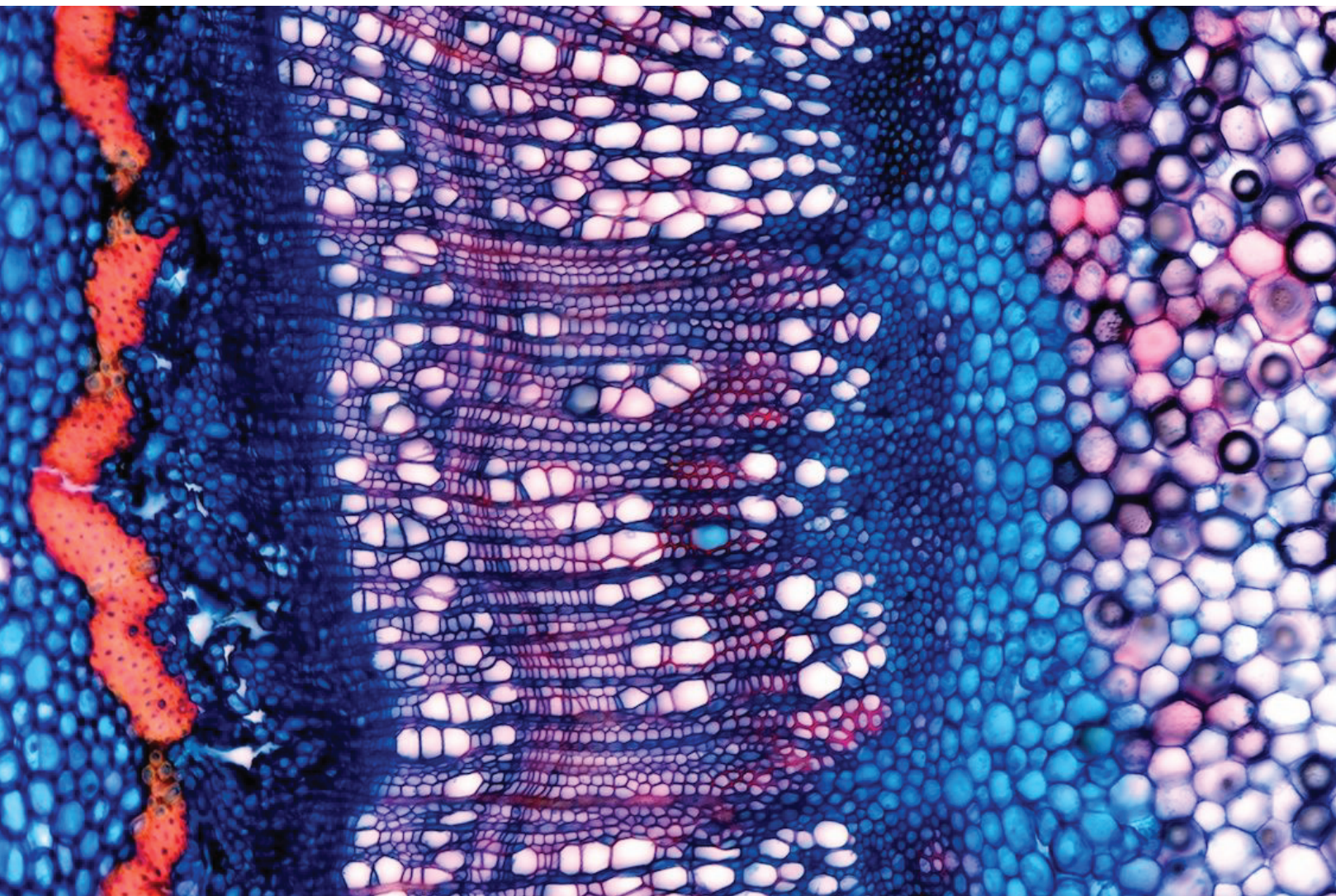


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TABLE OF CONTENTS

Results of Implementing the Online Reporting System for Oxygen Enrichment in Aquaculture Using Solar-Powered Energy for Cage Fish Farming	e264281
Prasert Nonthakarn and Sulaiman Madyod	
Effects of Flour Type and Longan Addition on the Quality of Longan-Fortified Baked Crackers	e266064
Natcha Laokuldilok, Rattanapath Monochai, Jeeraporn Pongpanpattana, Apiwat Sripuman and Paithun Intakhan	
The First Record of <i>Elysia</i> Species from the Mangrove Ecosystem of the Kamphuan Canal, Ranong Province, Thailand	e266568
Nantapong Kimpai and Worawit Pannak	
Comparative Analysis of Activated Carbon Derived from Coconut Shell and Oil Palm Biomass at Various Carbonization Temperatures	e267364
Narisa Binhayeeding, Maisoon Akhunsada, Nivaris Yapa, Trairat Srisuwan, Kitiya Thawarorit and Supojjanee Sansook	
Design and Development of Work Chairs Using Quality Function Deployment, Analytic Hierarchy Process, and Ergonomic Techniques	e267366
Watchanachai Joompha, Thitipon Wasstara, Nantawat Youraksa and Somsak Kaewploy	
Influence of Garlic Marinade on Maillard Reaction and Polycyclic Aromatic Hydrocarbon Formation in Grilled Chicken	e267708
Madeena Noitubtim, Charuwan Dangrod and Chuthipa Sringaokham	
Integrated Analysis of Climatic, Topographic and Geospatial Factors Affecting Durian Yield in Chanthaburi Province, Thailand	e267872
Kasidid Promproh, Narinjong Wongaud, Wachirathorn Janchomphu and Bhornchai Harakotr	
Effects of Protein- and Carbohydrate-Based Foaming Agents on Foam Stability and Microstructure in Freeze-Dried Coffee	e268030
Sureewan Rajchasom, Janyawat T Vuthijumnonk, Penwarat Panpatarachai and Maneerat Muangjai	

Effects of Avocado Puree as a Fat Replacer on the Quality Characteristics of Gluten-Free Brownies Achara Dholvitayakhun, Chisanupong Pukchinda, Thanatchaporn Tam-iam and Kiattisak Manasa	e268994
An Integrated Lean-Visual-Green (LVG) Model for Warehouse Layout Optimization and Carbon Footprint Reduction: A Case Study in the Food Products Industry Somkuan Sanguanpang, Peerawat Luesak and Aouypron Thawan	e269081
Land Use Changes after the Construction of the Xesalalong Reservoir: A Case Study of Three Villages in Thapangthong District, Savannakhet Province, Lao PDR Manolom Vongsenekeo, Inta Chanthavong and Sipasert Lathsabout	e269143
A Solar Powered Ultrasonic Water Level Monitoring System with IoT Type for Small-Scale Agricultural Water Management Attapol Kunlerd, Boonlueo Nabumroong, Narasuk Vongvas, Thongmee Lakonpol, Ruttanachira Ruttanaprasert and Kunlachat Burana	e269459
Performance Enhancement of PVT-Porous Dryer under Humid Tropical Conditions Eakpoom Boonthum, Apinunt Namkhat, Praphanpong Somsila, Kan Komanee and Umphisak Teeboonma	e269757
Effects of Azolla microphylla and Effective Microorganisms on Rice Production in Cement Pots for Small-Scale Farming Chutinan Jaroenchai	e267716
Production and Quality Evaluation of Dried Banana Stem Flavored with Miang-Kham Sauce Pakamart Purinthrapibal, Supasit Chooklin and Suwijak Hansriwijit	e266092

Research Article

Results of Implementing the Online Reporting System for Oxygen Enrichment in Aquaculture Using Solar-Powered Energy for Cage Fish Farming

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ABSTRACT

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Fish farming in ponds is popular due to its effective environmental control, whereas cage farming in rivers and canals faces challenges due to unregulated flowing water. Despite this, many farmers prefer cage farming due to lower costs and the absence of pond space expenses. A major issue in cage farming is low oxygen levels at night, which can lead to oxygen deprivation, reduced growth, or even mortality. However, oxygen parameters are not the only factors influencing fish health and growth. Other elements, such as fish density, feed quality, disease management, and water temperature, also significantly impact fish performance. To address the issue of oxygen deficiency, an advanced oxygen enrichment system was developed, utilizing solar-powered electricity to maintain optimal oxygen levels. The system automatically activates when oxygen levels drop, releasing pressurized air to maintain stability. It is equipped with sensors for real-time monitoring and uses stored solar energy to operate continuously, reducing operational costs and ensuring sustainability. The system's main features include solar panels for energy generation, battery storage for nighttime operation, and automated oxygen release when levels fall below a set threshold. After one year of operation, the system maintained an average oxygen level of 8.2 ppm and proved reliable, average power output of 300 W. These results showed that the system provides a stable environment for fish growth, thereby improving efficiency and reducing the risk of oxygen deprivation. This approach offers a cost-effective, sustainable solution for river cage farming, enhancing fish health and overall productivity. Nonetheless, optimizing other factors like fish stocking density, nutritional input, and disease management practices are also essential for achieving the best outcomes in cage aquaculture.

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1. Introduction

Cage fish farming, whether in natural ponds or other bodies of water, is a widely popular method due to its numerous advantages. A primary benefit of cage farming is the ease of controlling water quality and food supply, which enhances fish growth and health (Opiyo *et al.*, 2018). Additionally, cage farming is space-efficient, as it requires less area compared to pond or natural water body farming, allowing fish to be raised in more confined spaces. Cages also facilitate fish management tasks, such as feeding and health monitoring. They also provide protection against predators and diseases that could otherwise

harm or infect the fish. Furthermore, during harvest, cage farming simplifies and accelerates the fish collection process, thereby enhancing overall operational efficiency.

However, the growth of fish in cage culture systems is influenced by several critical factors beyond water quality, including fish density, food weight, and disease management. Research indicates that high fish density can lead to overcrowding, which may stress the fish and decrease growth rates (Mengistu *et al.*, 2019). The type and amount of food provided are also crucial, as inadequate nutrition can hinder growth and overall fish health (Liu *et al.*, 2017). Furthermore, disease management plays a significant role in preventing

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outbreaks, which could severely affect productivity. Effective disease control and proper feeding practices, along with optimized fish density, are essential for maximizing the efficiency and sustainability of cage fish farming systems (Tacon and Metian, 2008).

The emphasis on oxygen levels by researchers in controlling water quality in fish farming is due to the fundamental importance of dissolved oxygen for fish health and growth. Oxygen is a critical component of fish metabolism, directly influencing their ability to respire, metabolize food, and grow. Without sufficient oxygen, fish may experience stress, reduced feeding efficiency, and even mortality. Oxygen also plays a key role in maintaining the balance of other water quality parameters, such as pH, temperature, and nutrient levels. Although factors such as fish density, feed quality, and disease management are also important, oxygen is often prioritized because it is a limiting factor in many aquaculture systems. For example, oxygen levels can fluctuate significantly, particularly at night, and may become severely depleted under high stocking densities or after feeding. This can lead to hypoxia, which directly impacts fish health. By maintaining optimal oxygen levels, researchers aim to prevent such conditions and create a more stable and productive environment for fish. In summary, oxygen is a vital factor, as its concentration can significantly affect fish health and growth, and effective oxygen management is essential for improving the efficiency and sustainability of aquaculture systems.

In addition to these factors, oxygen supplementation is a critical method to improve fish health and growth. Traditional oxygenation techniques, such as mechanical aerators and diffusion systems, have been widely used in aquaculture (Beveridge, 2004). However, these methods often rely on high energy consumption and may not be as effective in maintaining stable oxygen levels throughout the day and night. The developed oxygen enrichment system, which uses solar energy, offers a more sustainable and cost-effective solution by automatically adjusting oxygen levels based on real-time data. Research by Hargreaves (2013) highlights the importance of maintaining stable oxygen levels in aquaculture, stating that optimal oxygen levels can significantly improve feed conversion ratios, fish growth rates, and survival. Additionally, studies have shown that solar-powered systems not only reduce operational costs but also enhance the sustainability of fish farming (Jalil *et al.*, 2020).

By comparing the developed oxygen supplementation system with traditional methods, it is evident that integrating renewable energy sources and automated oxygen monitoring can lead to more efficient and environmentally friendly fish farming practices. This system provides a more stable and sustainable environment for fish, enhancing overall productivity and reducing operational costs, making it a promising solution for cage aquaculture. The growth of fish in cage farming is

influenced by several critical factors, including water quality, food supply, fish density, and disease management (Mengistu *et al.*, 2019). This research focuses on improving water quality in cage fish farming, with particular emphasis on dissolved oxygen levels. Studies indicate that dissolved oxygen is a critical factor influencing fish growth, with most fish requiring levels of 5-7 ppm for optimal growth (Kramer, 1987). However, in cage systems, oxygen levels can be highly variable, sometimes dropping significantly during certain periods, such as at night, during dry seasons, and during floods. Each year, significant fish mortality is reported due to these fluctuating oxygen levels. Regular monitoring of dissolved oxygen and improvements in water quality are essential for the success of cage fish farming. Effective water quality management ensures that fish remain healthy, grow efficiently, and enhance overall productivity. Oxygen plays a vital role in aquatic ecosystems, not only for aquatic organisms but also for the entire food chain. In these systems, oxygen is essential for cellular respiration, the process by which fish and other organisms convert food into energy. Dissolved oxygen (DO) in water is the form utilized by aquatic organisms. Low oxygen levels can cause hypoxia, leading to stress, increased susceptibility to disease, and reduced growth rates in fish. Oxygen is particularly important during periods of rapid growth, reproduction, and environmental fluctuations, such as temperature changes or high stocking densities.

In cage farming, where water conditions are more confined and less controlled than in open water systems, maintaining sufficient oxygen levels becomes even more critical. Oxygen deprivation in these systems can reduce growth rates and lead to increased fish mortality, particularly when levels fall below 3 ppm, which is considered stressful for most species. Proper oxygenation ensures optimal conditions for fish growth, supports overall health, and helps prevent stress-related diseases. Moreover, a stable oxygen environment can improve feed conversion ratios and maximize the productivity of fish farming operations, making oxygen supplementation systems an integral component of modern aquaculture.

To address the issue of fluctuating oxygen levels in cage fish farming, an oxygen enrichment system has been developed (Nguyen *et al.*, 2023). This system aims to maintain optimal dissolved oxygen levels in the water, which is crucial for promoting healthy and vigorous fish growth. Such improvements positively impact both the quality and quantity of fish production. The system utilizes solar panels, providing a clean energy source. All components of the system are mounted on a floating platform, facilitating easy relocation to various positions as needed. Additionally, the system features an online reporting capability that monitors both dissolved oxygen levels and electricity production, ensuring efficient management and oversight (Cordova-Rozas *et al.*, 2019).

2. Materials and Methods

The experiment was conducted in a controlled river cage farming environment over a period of one year to assess the effectiveness of the developed oxygen supplementation system. The study was carried out at a medium-sized fish farm with a total of six cages, each measuring 10 meters by 10 meters, representing typical river cage farming conditions. Three cages were equipped with the developed oxygen supplementation system, while the remaining three served as control cages without the system for comparative analysis.

The primary focus of the experiment was to monitor and compare dissolved oxygen (DO) levels, fish growth rates, and fish health parameters between the experimental and control groups. Water temperature, pH, salinity, and turbidity were also monitored as potential variables that could affect oxygen levels and overall fish health. These factors were regulated to minimize their impact on the results by maintaining stable water quality conditions across both the experimental and control groups.

The oxygen supplementation system, powered by solar panels, was designed to automatically activate when dissolved oxygen (DO) levels dropped below a preset threshold of 5 ppm. Real-time monitoring sensors were installed in both the experimental and control cages to continuously measure oxygen concentrations in the water. The system's performance was evaluated based on its ability to maintain optimal oxygen levels and its impact on fish growth, feed conversion ratios, and survival rates.

To ensure the accuracy and reliability of the data, fish density was kept consistent across both the experimental and control cages, with each cage holding 500 fish of similar size and species. The fish were fed the same type and quantity of feed, and disease management protocols were standardized to minimize the potential influence of pathogens on fish growth and health.

The study also measured operational costs, focusing on electricity consumption and overall system efficiency. In addition, the effectiveness of the solar-powered oxygenation system was evaluated in terms of its sustainability and cost-effectiveness compared to traditional aeration methods.

The results of the study demonstrated a significant improvement in dissolved oxygen levels and fish growth rates in the cages equipped with the oxygen supplementation system. Fish in these cages exhibited higher survival rates, faster growth, and better overall health compared to those in the control cages, which experienced periodic oxygen deficiencies.

Oxygen Measurement Methods: Dissolved oxygen (DO) levels in the water were measured using a portable DO meter equipped with electrochemical sensors, providing real-time data on oxygen concentration in parts per million (ppm). Oxygen levels were measured at various depths within each cage to ensure accurate readings across different water layers. Data

were collected at regular intervals (every 4 hours) to monitor fluctuations in oxygen levels, particularly during nighttime when oxygen depletion was most likely to occur. Data quality was maintained through regular calibration of the instrument against known oxygen standards to ensure accuracy and consistency throughout the study.

The materials used in the design of this system can be categorized into two main components:

1) **Oxygen Enrichment System:** This component uses electrical energy generated from solar panels to enrich the water with oxygen.

2) **Online Reporting System:** This component monitors and reports both the dissolved oxygen levels in the water and the amount of electricity produced by the solar panels.

Each component is designed to work synergistically to maintain optimal water quality and provide real-time data for effective management of the fish farming system.

The electrical system comprises solar panels, a control unit, a battery, an inverter, and an electricity distribution network, as illustrated in Figure 1. The system operates as follows: Solar panels generate electrical power and transmit it to the control unit for quality regulation. The electrical power is subsequently stored in the battery. When required, the inverter converts the direct current (DC) from the battery into alternating current (AC) for use in various systems.

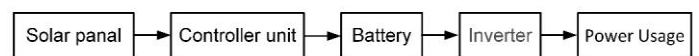


Figure 1 The electrical system.

The reporting system comprises three sensors: one for measuring dissolved oxygen levels in the water, one for measuring electrical power, and one for assessing other necessary parameters. Data from these sensors is transmitted to a microcontroller for processing, which then activates the oxygen pump to enrich the water with oxygen. Additionally, the system uses Wi-Fi to transmit data, informing users of the dissolved oxygen levels and electrical power status, as depicted in Figure 2.

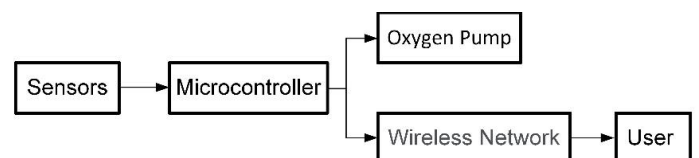


Figure 2 The reporting system.

An overview of the online reporting system and the solar-powered oxygen enrichment system for fish farming is presented in Figure 3. The figure should provide detailed information about the size of the prototype structure, including the dimensions of the system components. It should also illustrate the specific locations of key equipment, such as the oxygenation unit, solar panels, sensors, and storage batteries.

Additionally, the installation angle of the solar panels should be included to optimize solar energy absorption. The figure should emphasize how each part contributes to the overall efficiency and sustainability of the fish farming operation, with clear labels and annotations to guide the reader. All equipment is installed on a floating platform structure, facilitating convenient and efficient movement and management.

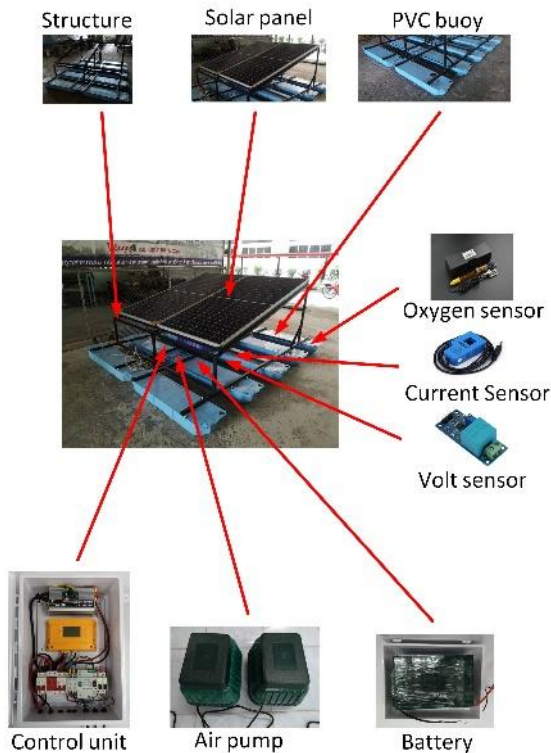


Figure 3 An overview of system.

3. Results and Discussion

Before deployment, the system will undergo testing to measure dissolved oxygen levels and compare them with readings from a standard instrument to ensure accuracy. This phase involves measuring the dissolved oxygen levels both before and after the use of the oxygen enrichment system. The data obtained from this test will be presented in Figure 4. To ensure reliability, one hundred tests will be conducted in each area of the cage, with each test performed 100 times. This extensive testing process will provide a comprehensive understanding of the system's performance across different conditions. The results will be used to verify the system's effectiveness in maintaining optimal oxygen levels, demonstrating its ability to improve water quality for fish farming. Each figure will clearly explain the measurement step or process, ensuring that the methodology is transparent and reproducible, which illustrates the comparison of dissolved oxygen levels before and after the use of the oxygen enrichment system, thereby confirming the system's effectiveness in increasing oxygen levels to meet the requirements of fish farming. Opiyo *et al.* (2018) discussed fish health management

in aquaculture systems, which can be compared to the advantages and limitations of the developed oxygen enrichment system. The experiment shows that increased oxygen levels positively impact fish growth. Mengistu *et al.* (2019) studied key factors affecting the growth rate and feed conversion ratio of Nile tilapia. This research helps analyze whether increased oxygen levels improve fish growth. Data collected over four months confirm that higher oxygen levels positively impact fish growth, aligning with their findings. A comparison with the study by Cordova-Rozas *et al.* (2019), which developed an IoT-based water quality monitoring system, shows that both systems share advantages in convenience, speed, and accuracy in oxygen level monitoring.

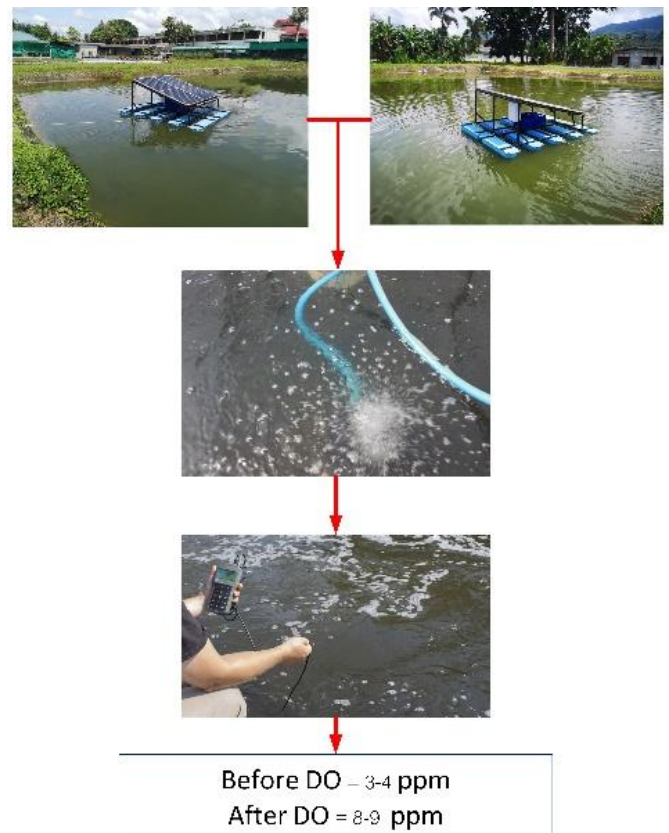


Figure 4 The data obtained.

In practical application, the system will be deployed for fish farming in cages situated in a river, as illustrated in Figure 5. This system will enhance oxygen levels in the water to meet the fish's needs by utilizing electrical power from solar panels, which provide a clean and sustainable energy source. Additionally, mounting the system on a floating platform will enable easy relocation and adjustment in response to the river's environmental conditions. This approach enhances efficiency in fish farming and contributes to sustainable production.

The recorded dissolved oxygen levels, observed during both the use and non-use of the oxygen enrichment system over a one-month period, clearly demonstrate the system's effectiveness. In the section where the oxygen enrichment system was utilized, the dissolved oxygen levels ranged from

6.0 to 8.3 ppm, with an average of 8.1 ppm for the month. In contrast, in the section without the oxygen enrichment system, the dissolved oxygen levels ranged from 4.0 to 5.3 ppm, with an average of 4.2 ppm for the month, as shown in Figure 6. This data indicates that the use of the oxygen enrichment system helps maintain optimal oxygen levels in the water, creating a better environment for fish growth and enhancing productivity efficiently.



Figure 5 Practical application.

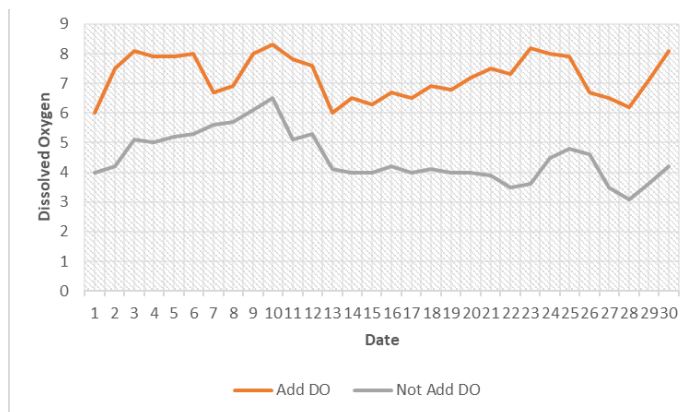


Figure 6 The recorded dissolved oxygen.

3.1 Statistical analysis of dissolved oxygen levels

To scientifically validate the effectiveness of the developed oxygen enrichment system, statistical analysis was conducted to compare the dissolved oxygen (DO) levels between the experimental and control cages. The mean DO levels in cages equipped with the oxygen supplementation system were recorded at 8.1 ± 0.35 ppm, whereas the control cages exhibited significantly lower DO levels at 4.2 ± 0.41 ppm over the one-month observation period.

An independent sample t-test was performed to determine whether the observed differences in DO levels between the two groups were statistically significant. The results indicated that the DO levels in the experimental cages were significantly higher than those in the control cages ($p < 0.05$). This finding confirms that the solar-powered oxygen enrichment system effectively improves oxygen availability in cage aquaculture environments.

Furthermore, the improved DO levels in the experimental cages were associated with enhanced fish growth performance

and survival rates compared to the control group. The statistical significance of these results demonstrates that the implementation of the developed system has a measurable impact on maintaining optimal environmental conditions necessary for fish health and productivity.

3.2 Analysis of variance and regression analysis

To further examine the effectiveness of the developed oxygen enrichment system, a one-way Analysis of Variance (ANOVA) was conducted to compare the dissolved oxygen (DO) levels between the experimental and control groups over the study period. The analysis revealed a statistically significant difference in DO levels between cages equipped with the oxygen supplementation system and those without the system ($F = 26.47$, $p < 0.05$). This result indicates that the implementation of the solar-powered oxygen enrichment system significantly improved oxygen availability in the cage farming environment.

In addition, regression analysis was performed to investigate the relationship between dissolved oxygen levels and fish growth performance. The results showed a positive correlation between DO concentration and fish growth rate ($R^2 = 0.81$), suggesting that higher oxygen levels contributed to improved metabolic activity and feed utilization efficiency. This finding supports the hypothesis that maintaining stable DO levels through automated oxygen supplementation has a measurable impact on fish productivity.

Furthermore, survival rates in the experimental cages were significantly higher compared to the control group, reinforcing the importance of oxygen stability in reducing physiological stress and mortality. These statistical outcomes confirm that the developed solar-powered oxygen enrichment system effectively enhances environmental conditions necessary for optimal fish growth and health in cage aquaculture systems.

The recorded data on energy production from the solar panels over a one-month period shows that the system generated between 265 and 329 watts, with an average of 300.5 watts for the month, as illustrated in Figure 7. This data reflects the system's capability to produce electricity consistently, providing adequate power for the oxygen enrichment system and other related operations in the fish farming process within the cages.

The recorded data indicates that the use of the oxygen enrichment system significantly increases the dissolved oxygen levels in the water. This increase in dissolved oxygen greatly improves water quality and has a significant positive impact on the overall quality of fish farming. The fish exhibit better growth, improved health, and higher survival rates, which, in turn, enhance both the quantity and quality of production. Comparison with water quality values is better than the work of Nguyen *et al.* (2023).

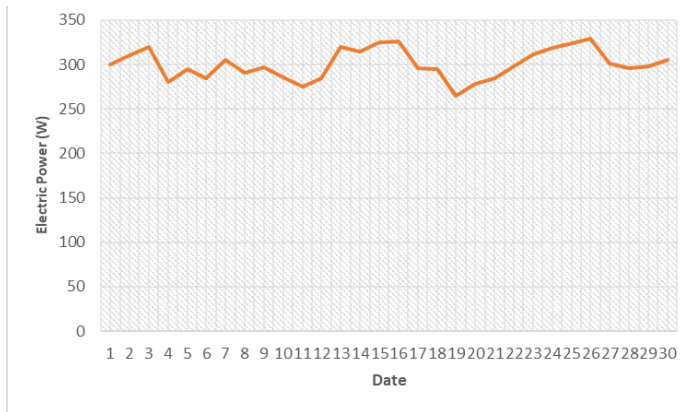


Figure 7 The recorded data on energy

The data obtained demonstrates that the solar panel system is capable of generating sufficient electrical power to support the system's operations throughout the entire day. The electricity generated by the solar panels and stored in the battery can be used continuously, both during the day and at night. This ensures that the oxygen enrichment system operates seamlessly and efficiently without concerns about power shortages, facilitating smooth and effective water quality management 24 hours a day. Comparing with the stability of the value transmission is better than the work of Cordova-Rozas *et al.* (2019) that sends values with less frequency

The use of Wi-Fi may have limitations in terms of the distance between the controller and the gateway. This constraint can lead to connectivity issues, particularly in large-scale fish farming operations where cages are distributed over a wide area. Signal interference from water, weather conditions, or nearby structures may further affect the system's reliability. Alternative communication technologies, such as long-range radio frequency (RF) transmission or cellular-based networks, could be explored to enhance connectivity and ensure uninterrupted data transmission for remote monitoring and automation.

4. Conclusion

Fish farming in ponds is popular due to its effective environmental control. However, farming fish in river or canal cages offers the advantages of lower costs and eliminates the need for pond space. Although water quality cannot be controlled as effectively as in ponds, the primary issue with cage farming is oxygen deficiency during the night, which can lead to slow fish growth or even mortality. To address this problem, an automatic oxygen enrichment system has been developed. This system utilizes electrical power from solar panels to generate and store electricity in batteries, ensuring operation throughout both day and night. The system continuously monitors dissolved oxygen levels in the water and activates when these levels fall below a set threshold, releasing pressurized air into the water.

After one year of operation, the system's average electrical output was found to be 30 volts and 10 amps (300 watts), with

a dissolved oxygen level of 8.2 ppm. These conditions are optimal for fish farming, leading to increased efficiency and reduced oxygen deficiency issues in cage aquaculture. Empirical studies have demonstrated that maintaining dissolved oxygen levels above 5 ppm significantly improves fish metabolism, reduces stress, and enhances growth rates. Additionally, research by supports the importance of adequate oxygen levels in promoting fish health and growth performance. confirmed that fish raised in environments with stable oxygen levels above 8 ppm exhibited higher survival rates and greater feed conversion efficiency compared to those in fluctuating oxygen conditions. These findings support the conclusion that consistent oxygen enrichment leads to improved aquaculture productivity. While the developed oxygen enrichment system offers promising benefits for cage aquaculture, several potential issues and limitations must be considered. One limitation is its reliance on solar energy. The system's performance may decrease on cloudy days or during the rainy season when sunlight is insufficient to adequately charge the solar panels. In such cases, the system's ability to maintain optimal oxygen levels may be compromised, particularly if the battery storage is not fully charged. Additionally, the system's performance may be affected by external factors such as water turbidity, temperature fluctuations, or irregular fish behavior, which can interfere with sensor accuracy or oxygen distribution. It is important to ensure that the system's sensors are regularly calibrated and kept clean to prevent inaccurate readings or malfunction.

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Research Article

Effects of Flour Type and Longan Addition on the Quality of Longan-Fortified Baked Crackers

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ABSTRACT

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 Snack

Khao Griab, a popular fried snack in Thailand, is typically made from deep-fried crackers. However, deep-fried foods are known for their high oil content, which is linked to metabolic disorders. This research aimed to develop a baked version of '*Khao Griab*' as a healthier alternative by modifying the traditional production process, substituting baking for frying. Three types of commercial flour/starch were compared: tapioca starch (TS), glutinous rice flour (GRF), and non-glutinous rice flour (NGRF). The moisture content of the crackers ranged from 0.80% to 2.36%, with water activity values between 0.133 and 0.287. The expansion ratios of the three cracker samples ranged from 21.67% to 56.67%, with NGRF-based crackers showing the lowest expansion, followed by GRF and TS. Crackers made from NGRF were the least hard, while those made from TS were slightly harder, and GRF-based crackers exhibited the highest hardness. The TS-based crackers had the highest L^* value and the lowest b^* value, whereas NGRF-based crackers had the lowest L^* value and the highest redness ($+a^*$) and yellowness ($+b^*$). Sensory evaluation indicated that TS-based crackers achieved higher scores across all attributes, establishing TS as the preferred base for fortification with 5–15% longan. Hardness increased with higher longan levels, and the 10% longan-fortified TS cracker was identified as the optimal formulation based on both sensory acceptance and nutritional improvement. A 30 g serving of longan-fortified baked crackers provides 120 kcal, with percent Daily Values (%DV) of 1% for fat and 2% for sodium—both lower than those of commercial products.

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1. Introduction

Snacks are enjoyed worldwide and play an important role in providing sustenance between main meals, helping to influence feelings of satiety. In Thailand, the snack retail sector was valued at 105,200.7 million baht in 2023, with savory snacks accounting for the largest share over 47,206.8 million baht, or 44.9% of total snack consumption, according to the Trade Policy and Strategy Office, Ministry of Commerce. However, like other energy-dense foods such as cakes, biscuits, and sugary drinks, many snacks are high in calories. Unhealthy snacks, often high

in sugar, fat, and salt, contribute to poor oral health, hypertension, obesity, and diabetes (Almoraie *et al.*, 2021).

Various technologies are used in snack production, including extrusion, frying, roasting, and baking. In Thailand, the traditional frying method, where food is cooked in hot oil, remains the most popular due to its low cost and quick preparation time, making it more accessible to consumers. Frying also imparts a distinctive flavor, taste, color, and crispness that consumers enjoy. However, a key concern with deep-fried foods is their high oil content, which is linked to metabolic disorders such as heart disease, obesity, and high

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cholesterol (Rani *et al.*, 2023). To address these concerns, healthier alternatives such as drying and baking are gaining popularity, as these methods do not require added fats and can result in lower calorie content (Chobot, 2024).

Local fried crackers, known as *Khao Griab* in Thailand, are a beloved snack, and their production process is relatively simple. It begins with mixing flour, ingredients like pepper, garlic, and coriander root, along with hot water in the right proportions. The dough is then molded, steamed, cooled, cut into thin pieces, and dried either through air drying or sun drying before being fried until fluffy. This straightforward process, using readily available materials and equipment, allows manufacturers to create a variety of products with distinct characteristics. However, shifting consumer preferences are pushing producers to innovate, seeking products that are not only ready for immediate consumption but also healthier.

The growing demand for healthier snacks, driven by consumer trends and government initiatives to reduce sugar, fat, and salt intake, has led manufacturers to develop alternatives such as gluten-free, sugar-free, vegan, high-fiber, and low-fat snacks. This trend is evident in the expanding healthy snack market, valued at over 28,314.8 million baht, representing 26.9% of the total snack market and growing at a rate of 11.3% (Trade Policy and Strategy Office, 2024). This shift presents an opportunity for local producers to tap into the health-conscious food market.

In response to these changing demands, this research aimed to develop a healthier version of the local cracker by using a baking method instead of frying, while keeping the other production steps the same. Deep fat frying, with its high rate of heat transfer from hot oil, is more efficient than baking, producing expanded, crispy textures, whereas the lower heat transfer rate in baking results in slower cooking and longer processing times (Tuta and Palazoglu, 2017). In this study, three types of flour were selected for comparison based on their potential to improve product quality in the baking process: tapioca starch (TS), the traditional flour for fried crackers (Akonor *et al.*, 2016); glutinous rice flour (GRF); and non-glutinous rice flour (NGRF). The choice of flour is a key determinant of both the physicochemical and sensory characteristics of crackers. TS, which is low in protein and lipids, is particularly suitable for fried cracker production (Noranizan *et al.*, 2010), as it promotes greater porosity through complete starch granule expansion, resulting in lower product density (Cheow *et al.*, 2004). In contrast, GRF and NGRF are commonly used in roasted rice snacks such as *arare* and *senbei* (Kim and Koh, 2019). During production, the chilling step facilitates slicing but also induces hardening, which varies with the rice cultivar and ripening stage. GRF, characterized by very low amylose and high amylopectin content, produces a sticky and elastic texture, whereas NGRF generally yields crackers with a harder, rougher texture (Pichetnawin, 2004). These flours were selected

for their potential to enhance product quality and consumer acceptance, thereby providing guidance for the development of healthier cracker alternatives.

Longan (*Dimocarpus longan* Lour.), widely cultivated in Northern Thailand, is prized for its sweet flavor and bioactive compounds, with total phenolic content (22.09–132.47 mg GAE/100 g) and flavonoids contributing to strong antioxidant activity (Zhang *et al.*, 2020; Silva and Sirasa, 2018). Although longan is rich in bioactive compounds, market instability causes price fluctuations, highlighting the need for product diversification. Incorporating longan into baked crackers may increase its value and provide consumers with novel, healthier snack options, but fruit and vegetable enrichment in crackers has been associated with increased hardness due to higher dietary fiber (Thi *et al.*, 2024; Yayah *et al.*, 2017). In this context, the present study aimed to formulate baked crackers with three types of flour-tapioca starch (TS), glutinous rice flour (GRF), and non-glutinous rice flour (NGRF)-and to incorporate longan at varying levels, in order to evaluate their effects on product quality and nutritional value according to Thai standards.

2. Materials and Methods

Tapioca starch (TS; Five stars fish brand, Thailand), glutinous rice flour (GRF; Erawan brand, Thailand), and non-glutinous rice flour (NGRF; Erawan brand, Thailand) were purchased from a local supermarket. Granulated sugar (Mitr Phol brand, Thailand), pepper (Rai Thip brand, Thailand), and salt (Prung Thip brand, Thailand) were used according to the traditional '*Khao Griab*' recipe. Dried longan (*Dimocarpus longan* Lour. cv. E-Daw) was obtained from a local agricultural farm in Northern Thailand.

2.1 Comparison of starch/flour types for crackers ('*Khao Griab*') by baking process

Three formulations of crackers were produced, each composed of a different type of flour TS, GRF, and NGRF. The proportions were as follows: 96% of each type of flour, 2.5% sugar, 0.6% garlic, 0.6% pepper, and 0.3% salt. Hot water was added to the solid ingredients in a ratio of 1:2.5. The mixture was kneaded by hand until a smooth dough was formed. The dough was then accurately weighed and placed into a mold (4.5 x 7.5 x 5 cm, W x L x H), and steamed for 40 minutes. After steaming, the cooked dough was allowed to cool at room temperature before being stored in the refrigerator for 12 hours. Once set, the dough was sliced into thin pieces (1 mm thick) and baked at 160°C for 15 minutes.

2.2 Assessment and characterization

2.2.1 Moisture content

The moisture content of crackers before and after baking was determined using the standard AOAC method 925.10 (AOAC, 2019).

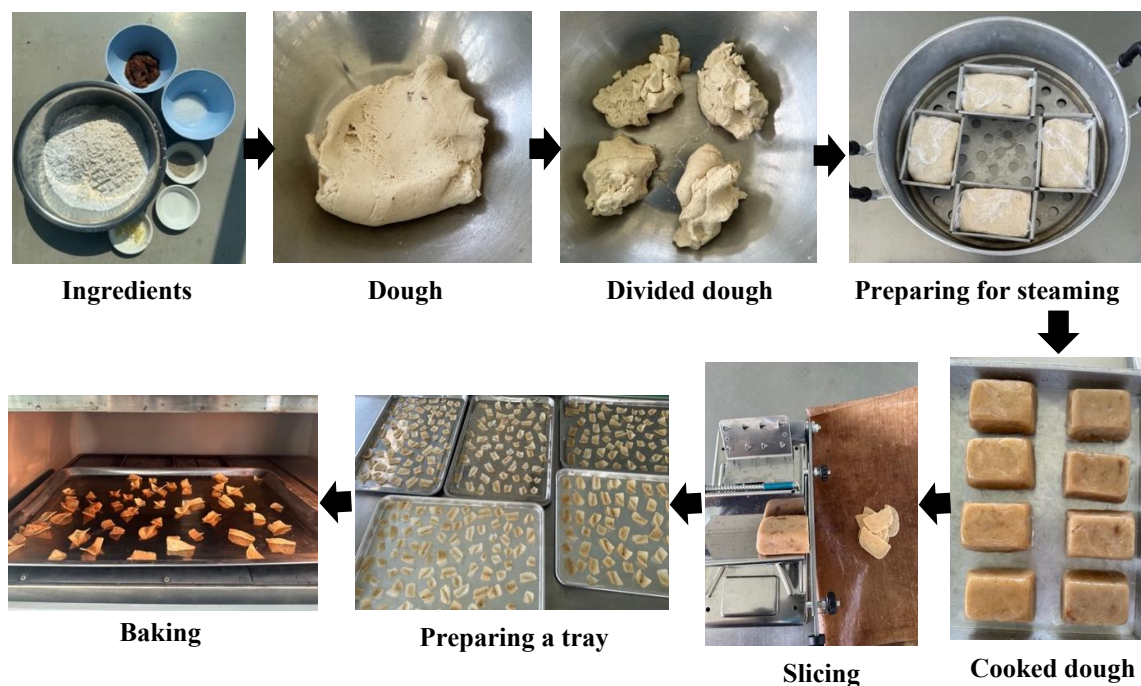


Figure 1 The processing of baked crackers ('Khao Griab').

2.2.2 Texture characteristic

The textural properties of 10 crackers from each treatment were determined using a texture analyzer (TA-XT Plus model; Stable Micro Systems Ltd., UK), following the method of Say *et al.* (2022). The data acquisition rate was 500 points per sec. Pre-test, test, and post-test speeds were set at 10, 1, and 10 mm/s, respectively. The cracker samples were placed on an aluminum cylinder (HDP/CFS crisp fracture support rig) to allow the sphere probe (ball P/0.25s) to pass through after penetrating the sample. The maximum force (kg), number of force peaks, and peak area (kg·mm) were recorded.

2.2.3 Expansion ratio

The expansion ratio of the crackers was determined using the method of Say *et al.* (2022) to measure the thickness of the crackers before and after baking with a vernier caliper. The expansion ratio was calculated according to Equation (1).

$$\text{Expansion ratio} = \left(\frac{\text{thickness after baking} - \text{thickness before baking}}{\text{thickness before baking}} \right) \times 100 \quad (1)$$

2.2.4 Color evaluation

Color values of powders were measured using a hand-held Chroma Meter (Konica Minolta, CR-400, Japan.) in terms of L^* , a^* , and b^* values.

2.2.5 Sensory evaluation

The sensory evaluations were conducted by 30 untrained panelists (aged 15-55 years) to evaluate product acceptability using a 5-point hedonic scale (1= dislike extremely to 5=like extremely). Each formulation was served to the panelists in a clear plastic cup labeled with a three-digit

random code. A cup of drinking water was served to the panelists to clean their palates before and after the sensory test of each sample. The panelists evaluated acceptability on color, aroma, crispiness, taste and overall liking.

2.3 Development of longan crackers using the baking method

The suitable type of flour for producing baked crackers was selected prior to incorporating longan. Dried longan (initial moisture 11.8%) was rehydrated with water at a 1:10 ratio, boiled for 30 min, and then blended for 3 min. Longan was added at 5%, 10%, and 15% of the total ingredients and mixed with the other dry components before adding hot water. The subsequent steps for cracker preparation followed the procedure described above. Each treatment of longan-fortified crackers was prepared in two replicates and assessed as outlined in Section 2.2.

2.4 Nutritional content of developed longan crackers

The nutritional content of the developed longan crackers was analyzed to determine calories, total fat, saturated fat, cholesterol, protein, total carbohydrates, sugar, sodium, and potassium, according to the AOAC method. (AOAC, 2023).

2.5 Statistical analysis

The experimental data were evaluated using analysis of variance (ANOVA). Duncan's new multiple range test was employed to determine the differences between means, with significance defined at $p < 0.05$.

3. Results and Discussion

3.1 Characteristics of crispy crackers ('Khao Griab') by baking process

The moisture content and water activity of the three cracker treatments are shown in Table 1. The moisture content of the sliced dough gel produced from the three types of flour ranged from 39.24% to 44.90%. The dough gel from NGRF exhibited the highest moisture content, followed by TS and GRF. A similar finding by Pereira *et al.* (2020) reported that the moisture content of emulsion-type cooked sausage with added rice flour, tapioca starch, and glutinous rice flour was 65.72%, 65.36%, and 65.17%, respectively. This suggests that the functional properties of amylopectin in glutinous rice starch could enhance moisture absorption during the gelatinization process. Additionally, higher amylose content also influences the moisture content of foods. Widjajaseputra (2012) showed that levels of amylose contributed to the homogeneity of moisture distribution. An increase in amylose content resulted in higher moisture content in rice flour-based spring roll wrappers. This effect is related to the function of amylose as a gel former, where amylose molecules align through hydrogen bonds and release water molecules (Dogan, 2004). Since the amylose content is highest in rice flour, followed by cassava flour, and lowest in waxy rice flour (Saeleaw and Schleining, 2010), this variation may affect the moisture content of the dough gel.

After baking, the moisture content of the crackers decreased to between 0.80% and 2.36%. The results indicated that the trend of moisture content after baking was consistent with that before baking, with NGRF maintaining the highest moisture content, followed by TS and GRF. All moisture content levels of the finished products complied with the Thai Community Product Standard for 'Crispy Snack' (107/2554), which specifies that moisture should not exceed 4%.

The trend in water activity of baked products mirrored that of moisture content, with NGRF showing the highest values, followed by TS and GRF. The water activity of all dough gels was similar, at 0.998, and decreased to values between 0.133 and 0.287 after baking. From a microbiological perspective, water activity below 0.6 is considered safe (Saha, 2020). Additionally, both water activity and moisture content serve as indicators of crispness. Findings from Kulchan *et al.* (2010) reported that specific values of water activity and moisture content 0.54 and 6%, respectively could be regarded as critical points for the loss of crispness.

The expansion ratios of the three cracker samples varied between 21.67% and 56.67%, with NGRF-based crackers exhibiting the lowest expansion, followed by those made from GRF and TS. Saeleaw and Schleining (2010) found a negative correlation between expansion and protein content. They reported that, regarding protein content, rice flour had the

highest value (6.55%), followed by waxy rice flour (5.79%) and cassava starch (0.13%). These results are consistent with the expansion findings from this study. The textural properties of three different crackers are presented in Table 2. The number of peak counts relates to porosity. The crust of porous structures resists the compressed force, resulting in a peak force, and then collapses with further compression applied (Say *et al.*, 2022). Thus, peak count indicates a crispy texture, while peak area suggests the hardness of the cracker. As shown in Table 2, the hardness (or peak area) of crackers made from NGRF was significantly the lowest, followed by those made from TS, while the highest hardness was observed in those made from GRF. The correlation analysis between cracker hardness and amylose content revealed a negative relationship (Kim and Koh, 2019). According to Saeleaw and Schleining (2010), rice flour had a higher amylose content (35.43% on a dry basis), followed by cassava starch (27.10% on a dry basis) and waxy rice flour (7.10% on a dry basis), conforming to the hardness properties observed in this study. Similarly, crispiness mirrored hardness, with NGRF crackers being least crispy, TS-based crackers moderate, and GRF-based crackers the crispiest. This agrees with Nammakuna *et al.* (2009) reported that rice-flour crackers are crumbly, have low expansion, and tend to crack easily.

As shown in Table 3, there were significant differences ($p < 0.05$) in L^* , a^* , and b^* values. All three crackers were white, with L^* values greater than 50. The TS-based cracker exhibited the highest L^* value but the lowest b^* value, indicating a light yellow color, along with a negative trend in a^* , suggesting proximity to the green axis of the color space. The NGRF-based cracker had the lowest L^* values and the highest levels of redness ($+a^*$) and yellowness ($+b^*$) compared to the others, indicating that it was slightly dark brown. The brown color of the crackers resulted from a chemical reaction between reducing sugars and a primary amino group, known as the Maillard reaction. Rice flour, as mentioned by Saeleaw and Schleining (2010), had a high protein content, and thus the resulting crackers exhibited the lowest lightness. The cracker samples made from three types of flour/starch were showed in Figure 2.

Mean sensory property scores of three cracker samples are shown in Table 4. No significant differences were observed between TS-based samples and the GRF-based sample for color, aroma, texture, taste, and overall liking ($p > 0.05$). Sensory scores indicated that the TS-based cracker exhibited higher scores for all attributes compared to the GRF-based cracker; thus, TS was selected as the appropriate base for fortifying with longan.

Table 5 presents the moisture content, water activity, and color values of longan-fortified crackers after baking. Both parameters increased with higher levels of longan incorporation, but moisture content at all levels remained within the limit specified by the Thai Community Product Standard for "Crispy Snacks" (107/2554), not exceeding 4%. Increasing longan

content also decreased the L^* value while increasing the a^* and b^* values, indicating a darker and more intensely colored product. Similar results were reported by Changso and Sanon (2024)

found that steamed cupcake containing 15% dried longan juice exhibited the darkest color compared with those containing 0, 5, or 10%, likely due to the inherent color of dried longan.

Table 1 Moisture content and water activity of crackers before and after baking.

Flour type	Before baking		After baking	
	Moisture content (%)	Water activity ^{ns}	Moisture content (%)	Water activity
Tapioca starch (TS)	42.38±1.89a	0.998±0.000	1.10±0.23b	0.199±0.000b
Glutinous rice flour (GRF)	39.24±0.73b	0.998±0.000	0.80±0.19b	0.133±0.001c
Non glutinous rice flour (NGRF)	44.90±2.36a	0.998±0.000	2.36±0.03a	0.287±0.000a

Values are means ± SD.

Means value ± SD with different superscript letters in the same column are significantly different ($p < 0.05$).

Table 2 Expansion ratio and texture properties of three baked crackers.

Flour type	Expansion ratio (%)	Texture properties		
		Peak count	Max. Force (kg)	Peak area (kg.mm)
Tapioca starch (TS)	56.67±5.77a	13.00±1.98a	1.65±0.69b	1.70±0.42a
Glutinous rice flour (GRF)	31.67±2.89b	16.58±2.35a	3.12±0.91a	2.64±1.12a
Non glutinous rice flour (NGRF)	21.67±2.89c	7.68±0.75b	0.67±0.21b	0.21±0.09b

Values are means ± SD.

Means value ± SD with different superscript letters in the same column are significantly different ($p < 0.05$).

Table 3 Color values in terms of L^* a^* and b^* of three baked crackers.

Flour type	Color		
	L^*	a^*	b^*
Tapioca starch (TS)	71.56±0.55a	-2.19±0.01c	13.43±0.12c
Glutinous rice flour (GRF)	66.05±0.79b	1.86±0.08b	21.84±0.94b
Non glutinous rice flour (NGRF)	62.18±0.41c	4.40±0.00a	24.33±0.06a

Values are means ± SD.

Means value ± SD with different superscript letters in the same column are significantly different ($p < 0.05$).

Table 4 Sensory scores (5-point hedonic scale) of three baked crackers.

Flour type	Color	Aroma ^{ns}	Crispiness	Taste	Overall liking
Tapioca starch (TS)	4.00±0.76a	3.60±0.83	4.00±0.53a	3.93±0.70a	4.07±0.80a
Glutinous rice flour (GRF)	3.93±0.88ab	3.47±0.83	3.63±0.63ab	3.73±0.70a	3.73±0.46a
Non glutinous rice flour (NGRF)	3.30±0.98b	3.27±0.70	3.00±1.13b	2.93±0.88b	2.93±0.80b

Values are means ± SD.

Means value ± SD with different superscript letters in the same column are significantly different ($p < 0.05$).

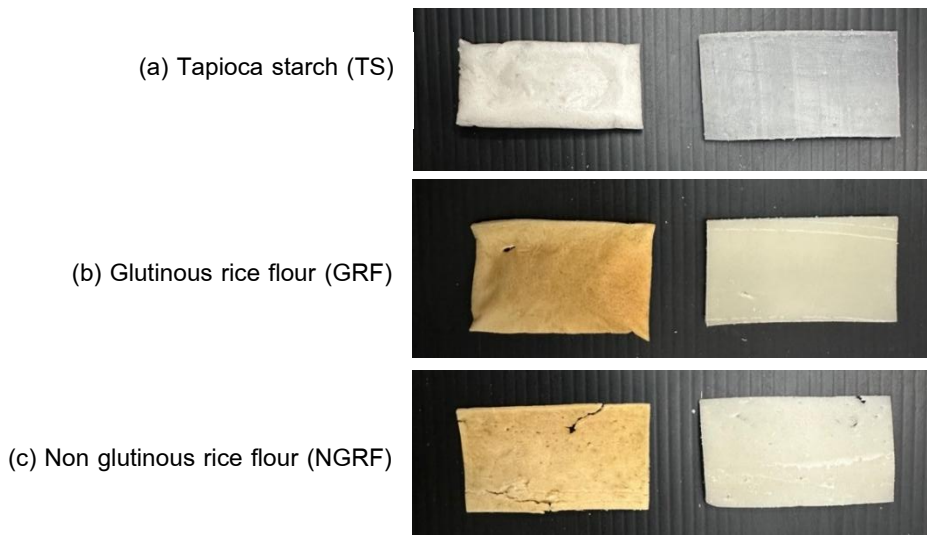


Figure 2 The cracker samples made from three types of flour/starch.

As shown in Table 6, the addition of longan negatively affected the expansion ratio of the crackers, likely due to a reduction in amylopectin content in the starch. Increasing amounts of longan also increased crispiness and hardness. This effect occurs because added ingredients can interfere with

starch expansion by interacting with starch granules. Similarly, Mahmoud *et al.* (2023) reported that the inclusion of freeze-dried banana peel and pulp increased cracker hardness. Such ingredients may inhibit starch expansion, resulting in denser and thicker filaments, which ultimately increase hardness.

Table 5 Moisture content, water activity and color values of longan crackers.

Longan (%)	Moisture content after baking (%)	Water activity after baking	Color		
			L^*	a^*	b^*
0	1.10±0.23c	0.199±0.000b	71.56±0.55a	-2.19±0.01d	13.43±0.12d
5	2.15±0.22b	0.217±0.010b	75.48±0.65b	2.19±0.02c	10.46±0.13c
10	3.17±0.31a	0.286±0.006a	68.06±0.17c	2.79±0.00b	15.87±0.02b
15	3.84±0.51a	0.300±0.002a	50.02±0.37d	7.86±0.03a	21.73±0.93a

Values are means ± SD.

Means value ± SD with different superscript letters in the same column are significantly different ($p < 0.05$).

Table 6 Expansion ratio and texture properties of longan crackers.

Longan (%)	Expansion ratio (%)	Texture properties		
		Peak count	Max. Force (kg)	Peak area ^{ns} (kg.mm)
0	56.67±5.77a	13.07±1.31a	1.65±0.69a	1.70±0.42
5	43.33±5.77b	20.97±3.35b	2.56±1.29ab	3.52±2.29
10	33.33±5.77b	26.04±4.54c	4.60±1.37b	3.97±1.94
15	15.00±5.00c	30.94±3.64d	7.78±1.24a	5.39±1.65

Values are means ± SD.

Means value ± SD with different superscript letters in the same column are significantly different ($p < 0.05$).

Mean sensory property scores for three baked longan cracker samples and the control (without longan) are shown in Figure 3. No significant differences were observed between the control and the samples fortified with 5% and 10% longan for any of the attributes ($p > 0.05$), except for the longan aroma attribute. Sensory scores indicated that the 10% longan-fortified cracker exhibited the highest aroma score, while the cracker with the highest amount of longan (15%) exhibited the lowest scores for all attributes ($p < 0.05$). This may be due to the

darker color, harder texture, and burnt taste from the longan during baking. Incorporation of 10% longan produced high overall liking, color, longan aroma, texture, and taste, with scores ranging from 4.00 to 4.20 on a 5-point hedonic scale, which corresponds to a liking level between "slightly liked" and "extremely liked." This proportion was chosen as the optimal amount of longan to fortify the baked TS-based cracker. The 10% longan-fortified baked TS-based cracker prototype is shown in Figure 4.

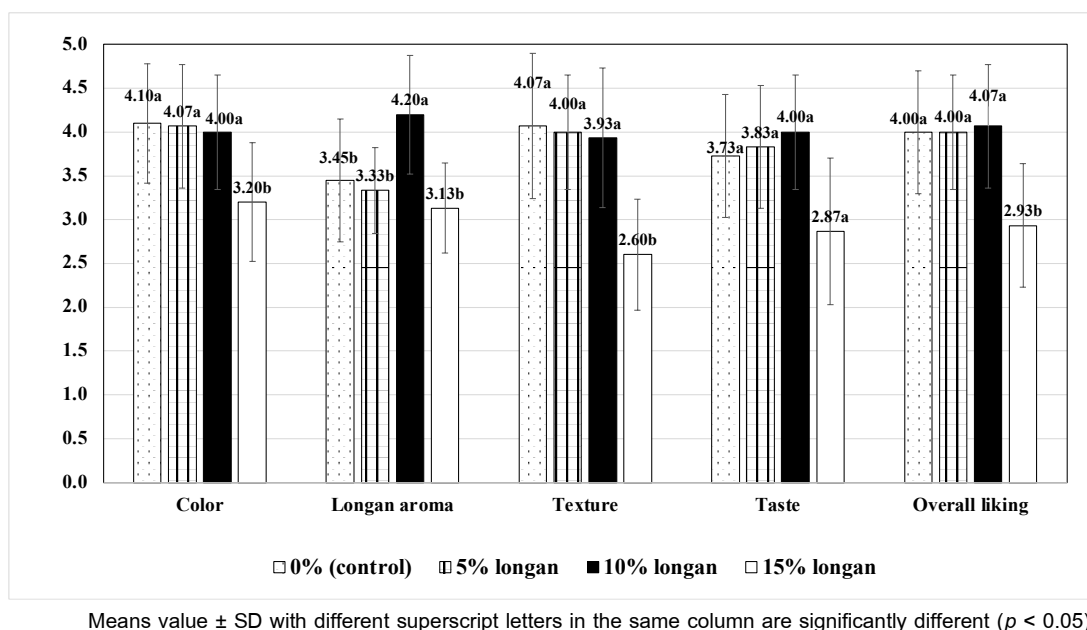


Figure 3 Sensory scores (5-point hedonic scale) of longan crackers.



Nutrition facts

Servings per container: 2

Amount per serving ½ bag (30 g)

Calories 120

% Daily value*

Total fat 0.5 g 1%

Saturated fat 0 g 0%

Cholesterol 0 mg 0%

Protein 2 g

Total carbohydrate 26 g 9%

Sugar 2 g

Sodium 30 mg 2%

Potassium 40 mg 1%

*Percent daily values based on a 2,000 calories diet.

Daily values may be higher or lower depending on individual calories needs.

Figure 4 The 10% longan-fortified baked TS-based cracker prototype (60 gram) and the nutritional composition.

3.2 Nutritional value of baked longan cracker

The nutritional composition of the baked longan cracker (Figure 4) indicates that one serving (30 g) provides 120 kcal, 2 g of protein, 0.5 g of total fat, and 30 mg of sodium, corresponding to 1% of the daily value (%DV) for fat and 2% for sodium. By comparison, commercially available fried crackers deliver 180 kcal, 12 g of total fat, and 280 mg of sodium per serving. Similarly, baked crackers enriched with vegetables have been reported to contain 137–141 kcal per 30 g (Galal *et al.*, 2023), while baked products on average provide about 780 mg of sodium per 30 g serving (Timic *et al.*, 2020). Excessive intake of fat-particularly saturated and trans fatty acids-and sodium is associated with an increased risk of cardiovascular disease in adults (Glassner, 2018; Wang *et al.*, 2020). Accordingly, the relatively low fat and sodium contents of the baked longan cracker position it as a healthier alternative. Beyond its nutritional advantages, this product enhances the utilization of Thailand's agricultural raw materials, responds to growing consumer demand for healthier options, and offers a practical production process suited for small-scale local producers.

4. Conclusion

Baked crackers were developed by adapting the traditional method for local fried crackers, using affordable materials and equipment. Among the flours tested, TS-based crackers showed the highest expansion, lightness, and sensory scores, while NGRF and GRF produced harder, less preferred crackers. Incorporation of longan at 5%, 10%, and 15% in TS-based crackers increased moisture, water activity, redness, yellowness, crispiness, and hardness, but higher levels reduced sensory acceptance. The 10% longan-fortified TS cracker achieved the highest overall liking, color, longan aroma, texture, and taste, and was therefore selected as the optimal formulation. Nutritionally, this product is classified as low-fat (less than 3 g per serving) according to Thai regulations, combining both improved sensory quality and health benefits.

5. Suggestions

Future studies should investigate protein fortification as a strategy to enhance the nutritional quality and health benefits of crackers.

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Research Article

The First Record of *Elysia* Species from the Mangrove Ecosystem of the Kamphuan Canal, Ranong Province, Thailand

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ABSTRACT

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One of the most fascinating organisms inhabiting mangrove ecosystems is the sacoglossan sea slug of the genus *Elysia*. Although *Elysia* species are globally distributed, their diversity and distribution within mangrove ecosystems, particularly in Thailand, remain understudied. This study reports the first recorded occurrence of *E. bangtawaensis* and *E. leucolegnote* in the Kamphuan mangrove forest, Ranong Province, Thailand. Both species were found inhabiting small tide pools and footprints in areas where gaps in the mangrove canopy allowed light gap to reach the forest floor. The specimens showed comparable size ranges to those reported in previous studies, which have documented their distribution in Thailand, including the Gulf of Thailand (Chumphon, Surat Thani, Nakhon Si Thammarat, and Pattani) and the Andaman Sea (Phang Nga, Krabi, and Trang). However, no previous records have been reported from Ranong Province. Organic matter contents were analyzed in areas with and without the presence of these species. Significantly higher organic matter levels were observed in habitats where *Elysia* species were found ($p < 0.05$), suggesting a positive correlation between habitat quality and species occurrence. The presence of *Elysia* in this mangrove ecosystem indicates that the Kamphuan mangrove forest provides favorable environmental conditions for *Elysia* species. This study represents the first record of *E. bangtawaensis* and *E. leucolegnote* in Ranong Province, expanding the known distribution range of the genus *Elysia* in Thailand and providing baseline data for future biodiversity and conservation research.

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1. Introduction

The mangrove forest of The Kamphuan canal is an ecologically significant area that encompasses important coastal zones and serves as a habitat with high biological diversity. This ecosystem is rich in biodiversity and productivity, making it an ideal location for researchers to study and investigate the diversity of plants and animals (Rachmuangkwan, 2014).

One of the most fascinating organisms inhabiting the mangrove forest is the sacoglossan sea slug of the genus *Elysia*. These sea slugs are known for their bright coloration and unique ability to photosynthesize by retaining functional chloroplasts from the algae they consume, a phenomenon known as kleptoplasty (Rumpho *et al.*, 2008). This adaptation allows them to survive in nutrient-poor environments.

Sacoglossian opisthobranchs have no jaws, and their radula comprises a single, longitudinal row of teeth, the older teeth being held in an ascus during their life. *Elysia* is the most speciose genus. The clearest feature of *Elysia* is the presence of wing-like parapodia, which play an important role in increasing the surface area for light absorption, thereby enhancing photosynthetic efficiency through kleptoplasty. This structure is closely related to environmental factors, as *Elysia* tends to thrive in habitats with suitable light intensity and abundant epiphytic algae, conditions that indicate good environmental quality (Buatip *et al.*, 2022), making *Elysia* an intriguing subject for scientific research.

Although *Elysia* species are globally distributed, their diversity and distribution within mangrove ecosystems, in

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Thailand, remain understudied. Previous studies by Swennen (1998, 2011) and Buntip *et al.* (2022) have documented the presence of *Elysia* along the Andaman coast of Thailand and the Gulf of Thailand, including the provinces of Krabi, Phang Nga, and Pattani. Five *Elysia* species have been reported from mangrove ecosystems, including *E. bangtawaensis* Swennen, 1998, *E. leucolegnote* Jensen, 1990, and *E. siamensis* Swennen, 2011, which are found in Thailand; *E. singaporensis* Swennen, 2011 from Singapore; and *E. bengalensis* Swennen, 2011 from the Bay of Bengal, India. Although there have been reports from other regions, information on the genus *Elysia* in Ranong Province is still lacking, and studies on the diversity of these sea slugs within the mangrove ecosystem have not yet been conducted.

Consequently, this study aims to investigate the species diversity of *Elysia* in the Kamphuan Canal mangrove ecosystem.

2. Materials and Methods

2.1 Study area

The study area is located in the southeastern part of the Andaman Coastal Research Station for Development, southern Thailand (Figure1), and connected to the Andaman Sea. The mangrove forest covers approximately 1.4 hectares (0.014 km²), as shown in Table 1.

Rhizophora apiculata is the dominant species. The mangrove forest area is part of the Kamphuan Canal, which is influenced by runoff and connected to the Andaman Sea coast. A random walking survey was conducted on 4 December 2024, after the rainy season during low tide, covering an area of approximately 16 m² in total. The site receives sufficient sunlight reaching the forest floor.

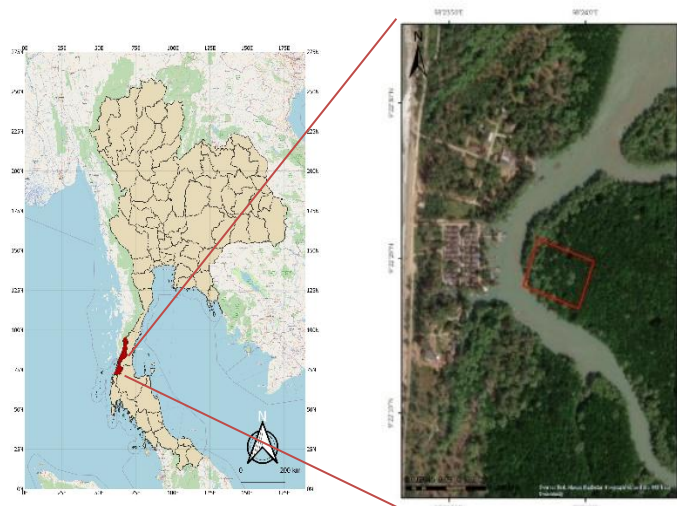


Figure 1 Sampling areas in the Mangrove Ecosystem of Kamphuan Canal, Ranong Province.

2.2 Sampling method

Elysia specimens were surveyed from the innermost part of the mangrove forest to the mangrove area adjacent to the canal.

In the field, morphological characteristics and coloration were observed.

Fifteen individuals of *Elysia* per observed type were randomly collected to measure body length and width using vernier calipers, and weight was measured with a digital scale in the laboratory. Species identification was conducted following the guidelines of Swennen (2011) and Jensen (1996).

Table 1 Geographic coordinates of survey area.

Corner	Geographic co-ordinates
Top left	9.372630° 98.398996°
Top right	9.372240° 98.399971°
Bottom left	9.371744° 98.398843°
Bottom right	9.371483° 98.399805°

2.3 Environmental factors

Environmental parameters were measured in the field to describe the baseline conditions of the habitats where both species occur. A total of 10 sampling sites were investigated, consisting of 5 sites where *Elysia* individuals were observed and 5 sites where *Elysia* were absent. The measured environmental parameters are summarized in Table 2.

2.4 Statistical analysis

Data were analyzed to compare %Organic matter between *Elysia*-observed and *Elysia*-absent areas. An independent t-test was conducted using Microsoft Excel to determine significant differences between the two groups

3. Results and Discussion

3.1 Species

The survey found two species of *Elysia*: *Elysia bangtawanensis* and *Elysia leucolegnote*. The absence of previous records of *Elysia* in Ranong Province may be attributed to the extensive and complex mangrove ecosystems in the region, covering approximately 30,000 hectares (Doydee and Buot, 2011). Such large and structurally diverse mangrove areas are difficult to survey comprehensively. Moreover, *Elysia* species are small, making them challenging to detect in the field.

Elysia bangtawanensis Swennen, 1998

Live coloration: There are marked rosy to bright red and orange glandular spots along the parapodia borders. White spots of various sizes and fine rosy dots are scattered on the dorsal and ventral parts, including the foot base. The green ductulus of the digestive gland covers the renal part in many specimens; it does not reach the tips of the rhinophores. The tips are pale or shaded with white and orange spots. (Swennen, 1998; Swennen, 2011)

Table 2 The environmental factors were measured from the sampling areas.

Environmental factors	Equipment and Methodology
Salinity, ppt	Refractometer
Temperature, °C	YSI Model Pro1020
pH	YSI Model Pro1020
Dissolved Oxygen, mg·L ⁻¹	YSI Model Pro1020
Depth, m	Ruler
Organic matter, %OM	Walkley Black titration method

Fifteen individual slugs of various sizes were measured, with lengths ranging from 16.5 to 50.4 mm, widths from 9.89 to 30.75 mm, and weights from 0.085 to 1.197 g.

Elysia leucolegnote K. R. Jensen, 1990

Live coloration: A narrow white line runs along the borders of the parapodia and is often locally expanded. A white triangular mark on the head is connected to a white line extending over the dorsal surfaces of the rhinophores. Some specimens exhibit a few white spots on the renopericardial prominence, while white spots are rarely observed on the dorsal sides of the parapodia. The tips of the rhinophores, as well as frequently the posterior region of the renocardial prominence, lack tubules of the digestive gland (Swennen, 2011)

Fifteen individual slugs of various sizes were measured, with lengths ranging from 3.6 to 17.3 mm, widths from 1.38 to 9.22 mm, and weights from 0.009 to 0.537 g.

E. bangtawaensis can have a length of 35–52 mm (Swennen, 1998; 2011), and lengths of 35–40 mm have been recorded in India (Jagtap *et al.*, 2009). The lengths observed in this study were similar to those reported in previous studies.

Swennen (2011) reported that *E. leucolegnote* in Thailand can reach up to 41 mm in length in live specimens. In Indonesia, Assuyuti and Wardiatno (2020) recorded specimens ranging from 6 to 18 mm in length, while in the Philippines, Sanchez-Escalona (2019) reported lengths ranging from 30 to 35 mm. The specimens recorded in this study exhibited smaller but comparable sizes to those reported in previous studies (Figure 2).

They were distributed in small tide pools and shallow footprints. In some tide pools, two species were found coexisting, whereas in other pools and footprint depressions, only one species was present (Figure 3).

All sites were covered by *Rhizophora apiculate*. The habitat where *Elysia* was observed in the upper mangrove forest exhibited canopy gaps, allowing greater light penetration to the forest floor (Figure 4A). In contrast, areas where *Elysia* was absent were characterized by dense mangrove coverage, which limited light availability (Figure 4B). This difference in light levels may influence the growth and distribution of microalgae. Previous research has indicated that light plays an important

role in algae production (Kathiresan and Ingam, 2001) and that algae are the main food source of *Elysia* (Jensen, 1992). Moreover, Studies have shown that *Elysia* can use chloroplasts obtained from algae to help absorb energy from sunlight and improve their ability to survive in environments with low light or limited food resources (Jensen, 1992; Rumpho *et al.*, 2008)

E. bangtawaensis was first discovered in Pattani Province, Thailand. It is distributed in the intertidal zone. and the mangrove forest habitats (Swennen, 1998). This species occurs on both the Gulf of Thailand (Nakhon Si Thammarat, Pattani) and the Andaman Sea coast (East of Krabi) in mangrove habitats (Swennen, 2011; Buatip *et al.*, 2022)

In Thailand, *E. leucolegnote* has been reported along both the Gulf of Thailand and Andaman Sea coasts. In the Gulf of Thailand, it has been observed in Chumphon, Surat Thani, Nakhon Si Thammarat, and Pattani, while in the Andaman Sea, its distribution includes mangrove habitats at Ko Libong and the eastern mangrove forests of Krabi (Swennen, 2011). which was first discovered in Hong Kong (Swennen, 2011). Previous studies have not documented the presence of *E. bangtawanensis* and *E. leucolegnote* in Ranong Province.

3.2 Environmental factors

Water quality in the Kamphuan mangrove forest area, where *Elysia* was observed, is shown in Table 3. Organic matter values were categorized into two distinct groups: regions where *Elysia* species were present and regions where they were absent (Figure 5). Shenai-Tirodkar *et al.* (2012) reported the ecological parameters in the habitat of *E. bangtawaensis* in the Mondovi estuary, Goa, along the west coast of India, from November 2007 to October 2008, included a water temperature range of 25–30 °C, pH levels between 6 - 7.59, and salinity ranging from 0.08 - 29.57 psu, and Buatip *et al.* (2022) reported in the newly-grown mangrove habitats, Pattani, included a water temperature range of 25.2-27.5 °C, pH levels between 7.33-7.61, salinity ranging from 13.5-16.5 psu, and dissolved oxygen ranging from 2.07-3.11 mg·L⁻¹. In comparison, this study recorded a water temperature of 26 °C, pH levels between 6.33 - 7.72, salinity 20 ppt, and dissolved oxygen ranging from 2.07-3.11 mg·L⁻¹. However, in this study, the environmental factor values were similar in both areas.

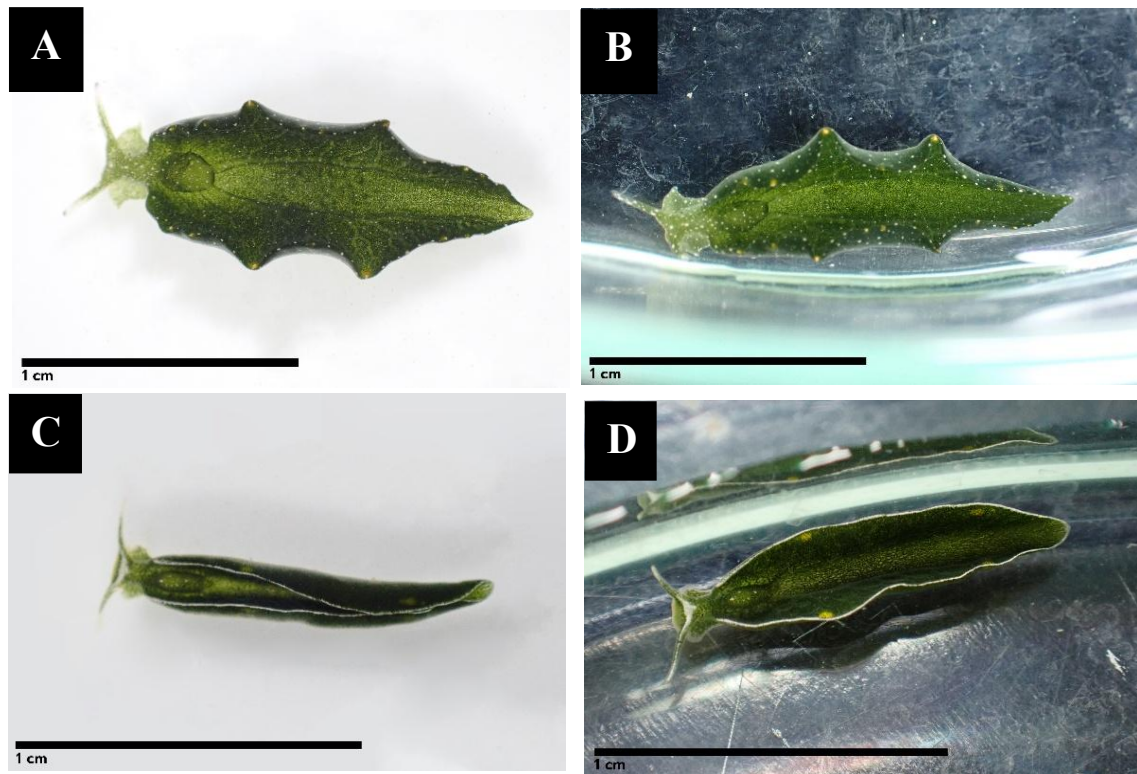


Figure 2 Specimens photographed under laboratory conditions. A–B: *E. bangtawaensis*; C–D: *E. leucolegnote*.

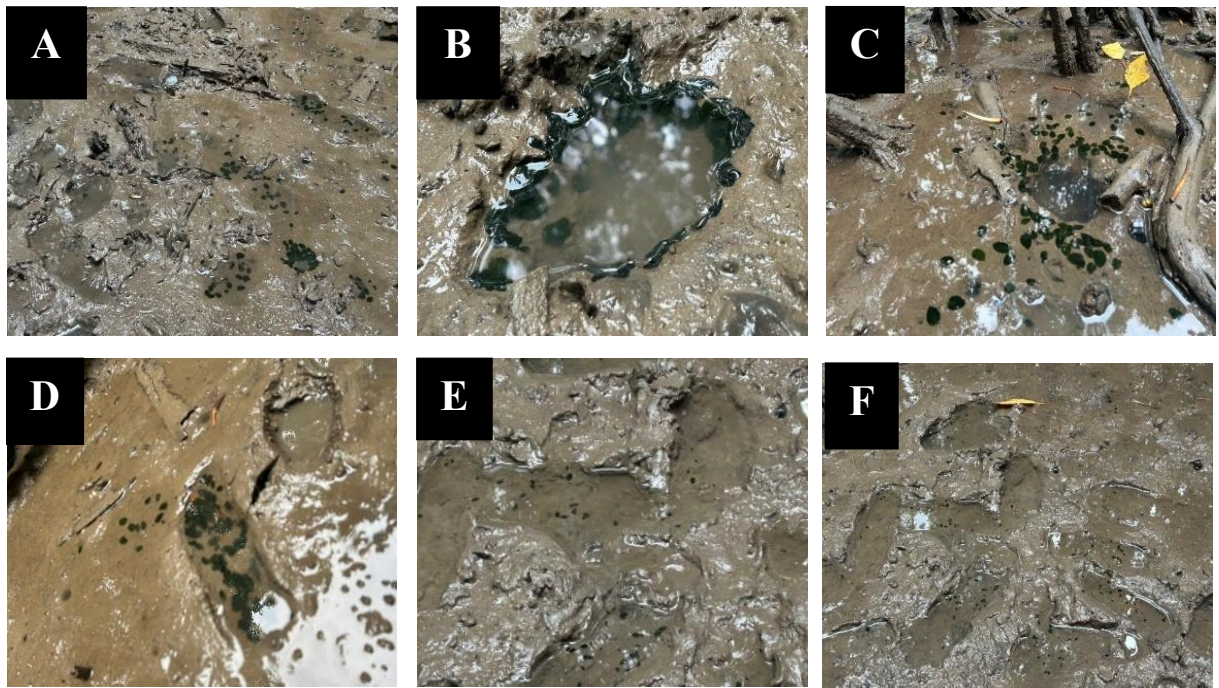


Figure 3 Specimens photographed in the field. A: a small tide pool where two species were found living together. B, C, D: *E. bangtawaensis* found in small tide pools and footprint depressions. E, F: *E. leucolegnote* found in footprint depressions.

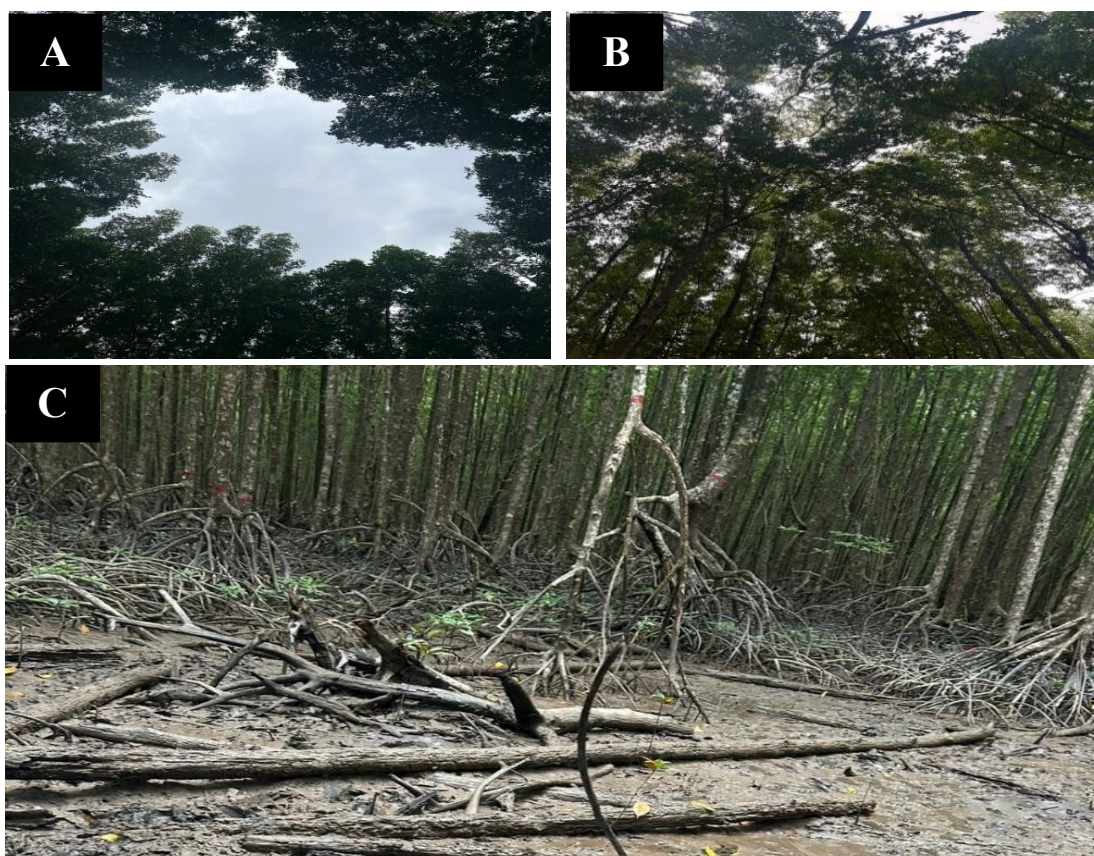


Figure 4 Habitat where *Elysia* was found. A: Upper mangrove forest exhibiting canopy gaps; B: Upper mangrove forest with no canopy gaps; C: Sites covered by *Rhizophora apiculata*.

Table 3 Environment parameters in the mangrove ecosystem of the Kamphuan Canal, Ranong Province.

Parameter	Volume Data	
	<i>Elysia</i> - observed	<i>Elysia</i> -absent
Salinity, ppt	20	20
Temperature, °C	26.00	26.00
pH	6.33-7.72	5.33-7.30
Dissolved Oxygen, mg·L ⁻¹	3.38-4.32	3.22-3.92
Depth, cm	1.5-8.0	1.2-6.0

The organic matter content in areas where *Elysia* species were observed was $4.77 \pm 0.68\%$, whereas in areas where they were absent, values were $3.20 \pm 0.35\%$. These findings align with the study by Buatip *et al.* (2022), which reported a range of 2.33% to 4.73%, indicating comparable levels of organic matter. As shown in Figure 5, organic matter concentrations were significantly higher in regions where *Elysia* species were present. An independent t-test confirmed a statistically significant difference between the two areas ($p < 0.05$). This is consistent with the study by Shenai-Tirodkar *et al.* (2012) in the Mondovi estuary, Goa, India, which found that *Elysia bangtawaensis* is commonly found in areas with high organic matter content, supporting the relationship between the presence of *Elysia* and the amount of organic matter in the environment. It was found that *Elysia* was frequently observed

in areas with a high percentage of organic matter, which may be related to the abundance of food sources such as epiphytic algae that thrive in organic-rich environments (Nakpan *et al.*, 2023). These conditions provide sufficient food resources to support the survival of *Elysia*. In addition, areas with high organic matter often contain elevated nutrient concentrations and exhibit high primary productivity, creating favorable environmental conditions for small organisms, including *Elysia* (Barrón *et al.*, 2014).

Although *Elysia* sp. can obtain energy through photosynthesis via retained chloroplasts (kleptoplasty), this process serves only as a supplementary energy source. The primary energy source for *Elysia* remains the direct consumption of algae (Pierce and Curtis, 2012; Schmitt *et al.*, 2014). Therefore, areas with higher organic matter that promote algal

growth provide abundant food availability, explaining the higher occurrence of *Elysia* in such environments.



Figure 5 The organic matter in *Elysia*- observed and *Elysia* - absent regions

However, the existence of these two types of sea slugs still needs to be monitored on an annual basis and combined with seasonal reports to understand their biology and ecology. There should be further expansion of the area in the mangrove forest. There may be a spread in nearby areas. Mangrove forests are highly productive ecosystems that support diverse marine life and provide suitable habitats for many species. Their ecological complexity may facilitate the discovery of previously unreported or new species, highlighting the importance of conservation and research in these areas. Studying the biology of sea slugs (*Elysia* spp.) is particularly valuable for understanding their ecological roles, distribution, and adaptive mechanisms. Expanding knowledge on sea slugs in this region will contribute to biodiversity assessments and inform conservation strategies for mangrove ecosystems.

4. Conclusion

This study documented the presence of *Elysia leucoleognote* and *E. bangtawaensis* in the mangrove forest of Kamphuan, Ranong Province, in areas characterized by light gaps and high organic matter content. These findings represent the first record of these species in this location, indicating that the Kamphuan mangrove forest provides a suitable habitat for *Elysia* species. This discovery contributes new insights into the distribution of this genus in Thailand and emphasizes the significance of this area for future conservation and ecological research.

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Research Article

Comparative Analysis of Activated Carbon Derived from Coconut Shell and Oil Palm Biomass at Various Carbonization Temperatures

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This study compared the optimal conditions for producing activated carbon from coconut shell and oil palm biomass via chemical activation using 70% H₂SO₄. Carbonization was conducted at 400, 500, and 600 °C for 2 h. At 600 °C, partial combustion occurred in both precursors, leading to ash formation, whereas no such effects were observed at 400 °C and 500 °C. Therefore, activated carbons obtained at 400 °C and 500 °C were further characterized using Fourier Transform Infrared (FTIR) Spectroscopy, Scanning Electron Microscopy (SEM), and Brunauer–Emmett–Teller (BET) surface area analysis. FTIR spectra of both coconut shell and palm-derived samples showed broad O–H stretching bands around 3440–3450 cm⁻¹ and peaks at 1610–1630 cm⁻¹ corresponding to C=O and C=C stretching vibrations. Notably, the palm-based sample carbonized at 500 °C displayed slight variations in its FTIR spectra compared with the other three conditions. Consistently, SEM images revealed that the P500 sample exhibited distinct surface morphologies compared with the others. BET analysis further indicated that the specific surface areas of C400, C500, P400, and P500 were 342.82, 322.67, 196.93, and 208.13 m²/g, respectively, demonstrating that coconut shell-derived carbons developed substantially higher surface areas than palm-based carbons. The high surface areas and well-developed porosity of these activated carbons suggest their suitability for applications in wastewater treatment, heavy metal and organic pollutant adsorption, and potential use as adsorbents in catalysis or separation processes.

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1. Introduction

Activated carbon (AC), characterized by its high porosity, has been extensively applied in fields such as water purification, gas adsorption, and chemical recovery, owing to its large surface area, strong adsorption capacity, and chemical stability (Ioannidou and Zabaniotou, 2007). Growing environmental concerns and the demand for sustainable production have, in recent years, driven increasing attention toward the use of agricultural waste as a precursor for activated carbon production. Among the different agricultural residues, coconut shells and oil palm biomass especially empty fruit bunches

(EFB) and palm kernel shells (PKS) have been highlighted as promising precursors because of their richness in carbon, low ash levels, and wide availability in tropical regions (Tan *et al.*, 2015). These materials, often considered waste, present a valuable and renewable source for producing high-quality activated carbon through physical or chemical activation methods. AC derived from coconut shells is well known for its hardness and microporous structure, making it ideal for gas-phase adsorption applications. On the other hand, oil palm waste offers a cost-effective and sustainable alternative due to its availability in large volumes, particularly in palm oil-producing countries such as Indonesia, Malaysia, and Thailand (Ahmed *et*

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et al., 2016). The utilization of these wastes not only enhances the economic value of agricultural residues but also represents a sustainable approach to waste management and environmental preservation.

A comprehensive review of coconut-derived biomass highlights that coconut shell possesses a well-defined lignocellulosic structure, consisting predominantly of lignin, cellulose, and hemicellulose in proportions that differ markedly from those of coconut husk and other agricultural residues. Proximate and ultimate analyses consistently report that coconut shell contains relatively low moisture and ash contents, coupled with high levels of volatile matter and substantial fixed carbon. Its elemental composition further reveals a notably high carbon fraction, typically around 52.6 wt%, which is considerably higher than that of many comparable biomass feedstocks. This combination of physicochemical characteristics particularly the elevated fixed-carbon content, structural rigidity associated with high lignin content, and low inorganic impurities collectively contributes to the superior thermal stability and carbon yield of coconut shell during thermochemical conversion processes. Consequently, coconut shell is widely recognized as an excellent and efficient precursor for the production of biochar and activated carbon, offering favourable textural development, enhanced porosity, and improved adsorption performance in various environmental and industrial applications (Ajien *et al.*, 2023). In contrast, studies on palm derived biomass, particularly palm kernel shell a major byproduct of the palm oil industry emphasize its widespread availability and low production cost, which make it an economically attractive feedstock for valorization. Chemical analyses reveal that palm kernel shell possesses a favourable composition, characterized by relatively high carbon content and low ash levels, alongside moderate volatile matter and fixed carbon fractions. These intrinsic properties not only enhance its thermal stability during pyrolysis but also promote the development of porous structures during activation processes. As a result, palm kernel shell has gained considerable attention as a sustainable and efficient precursor for the production of activated carbon, offering promising potential for applications in adsorption, catalysis, and environmental remediation (Herawan *et al.*, 2013).

The escalating global demand for sustainable materials has intensified interest in converting agricultural residues into value-added products. Traditionally derived from coal, the production of AC from renewable biomass sources, particularly coconut shells and oil palm residues, has gained prominence due to their abundance in tropical regions and favourable physicochemical properties. Coconut shells and oil palm residues are rich in carbon content and exhibit low ash formation, making them ideal precursors for AC production. Recent studies have demonstrated the efficacy of chemical activation methods, employing agents like phosphoric acid (H_3PO_4), potassium hydroxide (KOH), and zinc chloride (ZnCl_2), in enhancing the

surface area and porosity of AC derived from these biomasses. Some studies report that sulfuric acid (H_2SO_4) is highly reactive, facilitating the dehydration of carbohydrates and the breakdown of organic precursors during chemical activation to produce carbon. In addition, H_2SO_4 promotes the removal of mineral matter (ash) from lignocellulosic biomass, effectively acting as a de-ashing agent and thereby enhancing the quality and purity of the resulting carbon material (Kundu *et al.*, 2024). For instance, research (Chew *et al.*, 2023) highlighted the potential of various activating agents in optimizing the properties of AC produced from agricultural residues. The optimization of AC production involves adjusting parameters such as impregnation ratio, activation temperature, and activation time to achieve desired characteristics. Studies have shown that these parameters significantly influence the yield and quality of AC. For example (Lee *et al.*, 2023) investigated the effects of activation conditions on the surface properties of AC derived from palm kernel shells, emphasizing the importance of process optimization.

This study aims to conduct a comprehensive comparative analysis of AC production from coconut shells and oil palm residues using chemical activation by optimizing key parameters, the research seeks to identify the most effective precursor and activation conditions, thereby contributing to the sustainable utilization of agricultural residues and the advancement of environmental remediation technologies.

AC derived from biomass is typically obtained through a carbonization step, in which the raw material undergoes thermal decomposition at elevated temperatures. During this process, activating agents may be applied to generate a porous structure, thereby increasing the surface area and adsorption capability of the carbon. In general, two principal activation approaches are employed: (i) physical activation and (ii) chemical activation (Siipola *et al.*, 2018). The resulting material exhibits high adsorption efficiency, making it suitable for the removal of impurities and hazardous contaminants.

Activated carbon is commonly available in powdered, granular, and pellet forms, with the selection depending on the specific application. It has been widely employed across various industries, such as decolorization in the sugar industry, odor removal in beverage, beer, and wine production, and solvent purification for reuse in synthetic fiber and printing industries (Nilufur *et al.*, 2023). In water treatment, AC is utilized for color and odor removal in municipal water supplies, in household and industrial purification systems, as well as in wastewater treatment. It is also applied in air purification systems and as a key material in protective gas masks. More recently, producers have introduced innovative consumer products, such as aesthetically designed air fresheners for use in cars and refrigerators, reflecting the growing diversity of activated carbon applications (Scholz, 2023).

2. Materials and Methods

2.1 Materials

Coconut shells were obtained from market in Mueang District, Narathiwat Province, while oil palm biomass was collected from a palm plantation at the Faculty of Agriculture, Princess of Naradhiwas University. The raw materials were washed thoroughly with distilled water to remove adhering dirt and soluble impurities, followed by oven-drying at 110 ± 2 °C for 24 h to reduce their moisture. The dried materials were subsequently ground and sieved to obtain particle sizes of <2 mm prior to further processing. Sulphuric acid (H_2SO_4) was purchased from QRec and employed as activating agent in chemical activation. Deionized water was used for washing during sample preparation and post-activation neutralization.

2.2 Carbonization process

The physicochemical properties of the activated carbons were evaluated using standard characterization techniques. Coconut shell and palm kernel shell precursors were first washed, dried, and ground to a uniform particle size before chemical activation. The activation was performed using H_2SO_4 at a predetermined impregnation ratio. The carbonization process was carried out in a tubular furnace under a continuous nitrogen (N_2) flow to maintain an inert atmosphere and prevent oxidation. The samples were heated at a controlled rate of 10 °C/min to the target temperatures of 400 °C and 500 °C and held for 1 h to ensure complete carbonization. After cooling to room temperature under N_2 , the activated carbons were washed thoroughly with deionized water to remove residual chemicals and dried at 105 °C.

Surface area and porosity were determined using nitrogen adsorption–desorption isotherms and calculated via the Brunauer–Emmett–Teller (BET) method (Micromeritics ASAP 2460). The surface morphology was examined using Scanning Electron Microscopy (SEM; Model: SEM-Apreo), while functional groups were identified by Fourier Transform Infrared Spectroscopy (FTIR; Model: INVENIO S, Bruker) over the range of 400–4000 cm^{-1} . These analyses collectively provided comprehensive insights into the structural, textural, and chemical properties of the produced activated carbons.

2.3 Chemical activation

The carbonized materials were impregnated with the selected activating agents (H_2SO_4). The mixtures were stirred at room temperature for 12 h to ensure uniform penetration of the activating agent. After impregnation, the samples were dried at 110 °C for 24 h. Activation was performed in a tubular furnace under a continuous nitrogen flow of 100 mL/min. The impregnated samples were heated at activation temperatures ranging 400, 500 600 °C with a holding time of 60 min. The activated carbon obtained was cooled, thoroughly washed with hot distilled water until the pH of the filtrate was approximately neutral, and then oven-dried at 110 °C for 12 h.

2.4 Characterization of activated carbon

The physicochemical properties of the activated carbons were evaluated using standard characterization techniques. Surface area and porosity were assessed via nitrogen adsorption–desorption isotherms using the BET method (Micromeritics ASAP 2460). The surface morphology of the samples was examined by SEM, while functional groups were identified through FTIS over the range of 400–4000 cm^{-1} .

3. Results and Discussion

Activated carbon were synthesized from coconut shell and oil palm biomass through chemical activation using 70% H_2SO_4 . The carbonization process was performed at three different temperatures: 400, 500, and 600 °C. At 600 °C, partial combustion occurred in both raw materials, leading to significant ash formation. Therefore, the activated carbon obtained at 400 °C and 500 °C were selected for further characterization using FTIR spectroscopy, SEM, and BET surface area analysis.

To facilitate discussion, the samples were designated with abbreviated codes according to their raw material and activation temperature. Coconut shell-derived carbons are denoted as C, while oil palm-derived carbons are denoted as P. The numbers following the abbreviations indicate the carbonization temperature (°C). The sample codes are summarized in Table 1.

Table 1 Sample code from coconut shell and oil palm.

Raw material	T (°C)	Sample code
Coconut shell	400	C400
	500	C500
Oil palm	400	P400
	500	P500

3.1 FTIR spectroscopy

The FTIR spectra of the activated carbon samples revealed the presence of characteristic functional groups on the carbon surface. A broad band observed at 3450–3440 cm^{-1} corresponded to O–H stretching vibrations of hydroxyl groups, which may originate from alcohols, phenols, or adsorbed water. Additionally, the band at approximately 1630–1610 cm^{-1} was assigned to C=C stretching vibrations of aromatic rings, confirming the graphitic backbone structure of the activated carbon. The peaks observed at 1236.4 and 1240.2 cm^{-1} are attributed to C–O stretching vibrations of alcohols, ethers, and phenolic groups in the C500 and P500 samples, respectively. The FTIR spectra are presented in Figure 1.

The FTIR spectra confirmed that the produced activated carbon contained abundant oxygenated functional groups, including hydroxyl (–OH), carbonyl (C=O), carboxyl (–COOH), and ether (C–O) groups. These functionalities are critical in determining the adsorption behavior of activated carbon. The broad O–H stretching band around 3400 cm^{-1} is particularly

significant, as hydroxyl groups can promote hydrogen bonding interactions with polar adsorbates, thereby enhancing adsorption performance (Yang *et al.*, 2019). The observed aliphatic C–H vibrations suggest the presence of hydrophobic domains, which facilitate the adsorption of non-polar organic molecules (Rao *et al.*, 2006). Meanwhile, the C=O stretching peak near 1700 cm^{-1} indicates the presence of acidic surface groups, which enhance cation exchange and metal ion binding capacity (Foo and Hameed, 2012). The presence of aromatic C=C bonds around 1600 cm^{-1} further supports the carbonaceous structure, which is known to promote π – π interactions with aromatic pollutants. Moreover, the C–O vibrations detected in the range of 1100 – 1250 cm^{-1} suggest the existence of ether and phenolic groups that contribute to adsorption through electron donor–acceptor mechanisms (Zhu *et al.*, 2016).

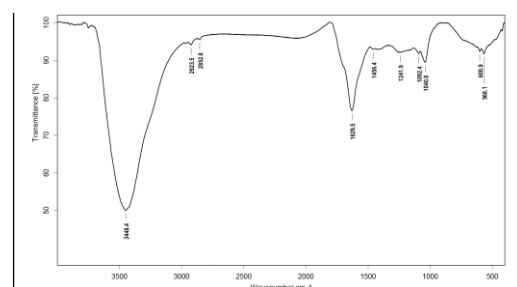
Overall, these findings indicate that the functional groups identified by FTIR spectroscopy not only confirm successful activation but also suggest enhanced potential for adsorption of both organic and inorganic pollutants. The coexistence of hydrophilic and hydrophobic functional groups makes the produced activated carbon a promising material for environmental remediation applications, particularly in wastewater treatment.

3.2 SEM analysis

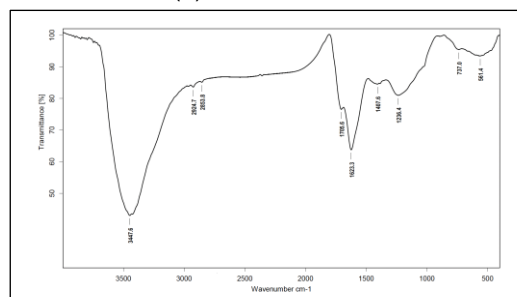
The surface morphology of the samples was examined using SEM images, and the representative micrographs are presented in Figure 2. The SEM images reveal that the surface structure is highly porous with irregular cavities and heterogeneous particle distribution. Such morphology is consistent with the expected structural changes induced during the preparation process, which promotes the development of pores and increases the surface area available for adsorption.

Distinct variations in surface texture, pore structure were observed among the samples, indicating the strong influence of activation conditions on the development of porosity. At $400\text{ }^{\circ}\text{C}$ activation temperatures, the SEM micrographs revealed relatively smooth surfaces with limited pore formation. Only a few irregular cavities were observed, suggesting incomplete decomposition of volatile matter and insufficient development of micropores. This observation is consistent with earlier reports that lower activation temperatures often hinder effective pore development due to limited devolatilization and structural rearrangement (Foo and Hameed, 2012).

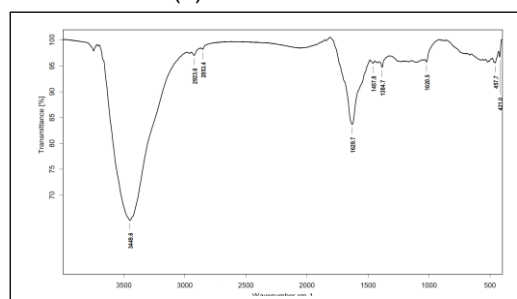
In contrast, the sample activated at $500\text{ }^{\circ}\text{C}$ exhibited a significantly rougher surface with numerous well-developed pores distributed across the carbon matrix. The pore walls appeared thinner and more fragmented, reflecting the enhanced release of volatiles and the opening of internal channels. This morphological improvement corresponds with an increase in surface area and pore accessibility, which are crucial for adsorption applications (Ahmed *et al.*, 2016).



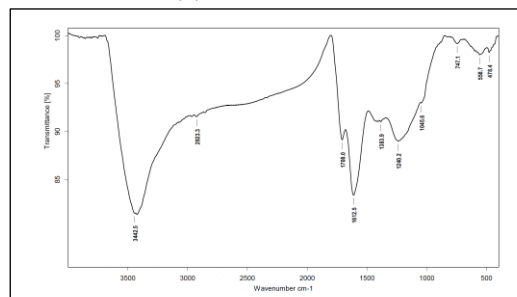
(a) FTIR of C400



(b) FTIR of C500



(c) FTIR of P400



(d) FTIR of P500

Figure 1 FTIR spectra of activated carbon-based coconut shell and oil palm at different temperatures.

Furthermore, differences between the precursors were noticeable. Oil palm–derived samples (P500) activated carbon generally exhibited a denser structure with more uniform micropores, whereas coconut shell–derived (C500) displayed irregular and heterogeneous pores. These morphological differences are attributed to the inherent structural composition of the raw materials, such as lignin and cellulose content, which strongly influence carbon matrix formation during thermal treatment (Ioannidou and Zabaniotou, 2007).

Overall, SEM analysis confirmed that both activation temperature and precursor type play critical roles in the development of porous morphology. Optimal conditions (around $500\text{ }^{\circ}\text{C}$ under controlled activation) yielded activated carbon with

a well-developed pore structure, whereas low temperatures resulted in poor morphological characteristics. These observations align with the physicochemical analyses reported

in related studies and highlight the importance of carefully optimizing activation parameters for efficient production of activated carbon.

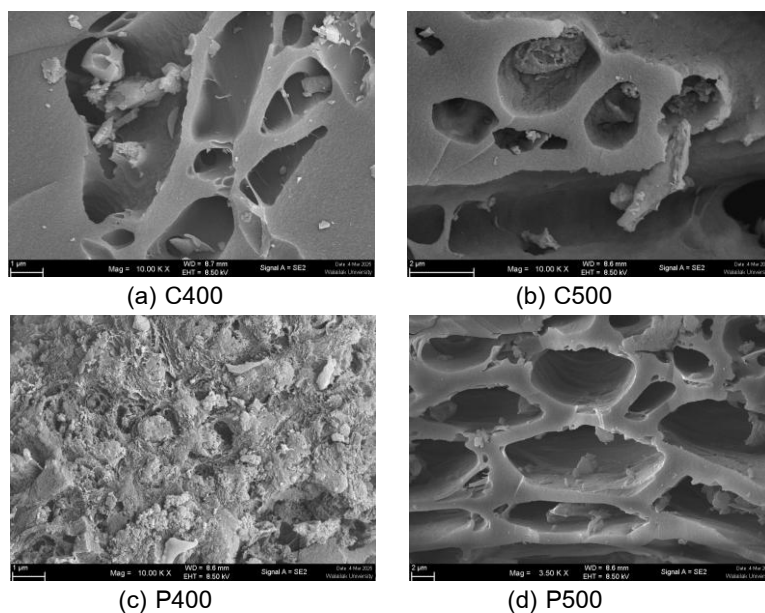


Figure 2 SEM micrographs of activated carbon samples prepared under different conditions: (a) C400 (1 μm), (b) C500 (2 μm), (c) P400 (1 μm), and (d) P500 (2 μm).

3.3 BET analysis

The textural properties of the activated carbon samples were evaluated using nitrogen adsorption–desorption isotherms, and the results are summarized in Table 2. The BET surface areas of the samples varied notably, reflecting the influence of both the precursor type and activation temperature.

The BET surface areas obtained in this work (coconut shell: C400 = 342.8172 m^2/g , C500 = 322.6710 m^2/g ; oil-palm shell: P400 = 196.9333 m^2/g , P500 = 208.1293 m^2/g) are moderate compared with values reported in the literature. Coconut-shell activated carbons have been reported with a wide range of BET surface areas depending on the activating agent and process conditions from several hundred to over 2000 m^2/g under aggressive chemical activation or optimized steam/ CO_2 activation. For example, Gratueto *et al.* and Yang *et al.* reported coconut-shell AC with surface areas in the hundreds to >2000 m^2/g depending on activation route and process parameters (Gratueto *et al.*, 2008)

Among the coconut shell–based samples, C400 exhibited the highest BET surface area followed by C500. In contrast, the palm-based samples showed comparatively lower surface areas, with P400 and P500. The higher surface areas observed in the coconut shell–derived carbons can be attributed to their more rigid and heterogeneous structure, which facilitates the formation of a highly porous network during chemical activation. Interestingly, increasing the activation temperature from 400 $^\circ\text{C}$ to 500 $^\circ\text{C}$ resulted in a slight decrease in the BET surface area of the coconut shell sample, likely due to partial collapse or widening of micropores into mesopores.

The average pore diameters, calculated from adsorption data, were 19.1273, 19.5205, 19.6759, and 21.1993 $\text{\AA}$ for C400, C500, P400, and P500, respectively. These values indicate that all samples predominantly possessed mesoporous structures, with a slight increase in pore size observed for palm-based carbons at higher activation temperature. The formation of wider pores in P500 may compensate partially for the lower surface area, enhancing accessibility for larger adsorbate molecules

Overall, the BET results showed that coconut shell–derived activated carbons have superior surface area, whereas palm-based carbons tend to develop slightly larger mesopores. These structural characteristics are expected to influence adsorption performance, with C400 potentially exhibiting the highest adsorption capacity due to its combination of high surface area and well-developed mesoporous network.

4. Conclusion

This study successfully synthesized activated carbon from coconut shell and oil palm precursors through chemical activation at different carbonization temperatures. Comprehensive characterization techniques were employed to evaluate the structural, morphological, and textural properties of the resulting materials. FTIR analysis confirmed the presence of oxygen-containing functional groups, such as hydroxyl, carbonyl, and C–O groups, which contribute to enhanced surface reactivity and adsorption capacity. SEM images revealed heterogeneous surfaces with well-developed porous structures, particularly for P500, indicating efficient pore development during activation. BET surface area and pore

structure analyses further corroborated these findings, showing that coconut shell-derived carbons possessed higher surface areas (C400: 342.82 m²/g; C500: 322.67 m²/g) than palm-based carbons (P400: 196.93 m²/g; P500: 208.13 m²/g). The average pore diameters ranged from 19.13 to 21.20 Å, suggesting a predominance of mesoporous structures. Although palm-based carbons exhibited slightly larger pore sizes, coconut shell-

derived carbons demonstrated superior overall textural properties and greater adsorption potential. Overall, the findings highlight that both the choice of precursor and the activation conditions play critical roles in determining the physicochemical characteristics of activated carbon, with C400 emerging as the most promising candidate for adsorption and environmental remediation applications.

Table 2 BET surface area and pore structural parameters of activated carbon samples.

Sample name	Degas Temperature of sample cleaning (°C)	Parameters	Unit	Results
C400	200 °C (15 hours) by heating ramp rate 10 °C/min	BET	m ² /g	342.8172
		surface area		
Adsorption average pore diameter		Å	19.1273	
C500		BET	m ² /g	322.6710
		surface area		
Adsorption average pore diameter		Å	19.5205	
P400		BET	m ² /g	196.9333
		surface area		
	Adsorption average pore diameter	Å	19.6759	
	P500	BET	m ² /g	208.1293
surface area				
		Adsorption average pore diameter	Å	21.1993

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Research Article

Design and Development of Work Chairs Using Quality Function Deployment, Analytic Hierarchy Process, and Ergonomic Techniques

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ABSTRACT

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Low back pain is a health issue that arises from risk factors such as an improperly sized desk and chair, as well as prolonged sitting at work. Therefore, to reduce the risk of low back pain, the Quality Function Deployment (QFD) technique has been applied to design work chairs, along with the Analytic hierarchy process (AHP) and ergonomics techniques, because the lack of application of QFD techniques alongside AHP and ergonomics is notable. The objective is to design and develop work chairs that meet the users' needs. QFD is a structured product development methodology that focuses on listening to the customer's voice and converting these needs into technical specifications that lead to product improvement. The AHP technique is then used to score the importance of technical requirements, and the ergonomics principle is applied, using relevant body proportions as data for designing and developing work chairs. The sample group consisted of 90 office workers. The results showed that the most important technical requirements, which are guidelines for designing and developing work chairs, include the materials selection, with a weight of 33.37%, followed by adjustable height, applying the principles of ergonomics, appropriate sizes and shapes, and having a stable and strong structure. The results of applying QFD techniques together with AHP and ergonomics resulted in users being more satisfied with the work chairs. Before the improvement, the satisfaction score was 2.96 points, and after the improvement, the satisfaction score increased to 4.04 points. The findings demonstrated that using ergonomic principles in the design and development of tools and equipment resulted in instruments that are well-suited to the proportions of the human body.

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1. Introduction

Back and neck pains or work-related muscular soreness is a health problem that many people have to face in their daily lives, whether they are office workers in government or private agencies who spend a lot of time sitting down. In particular, waist-related back pain could appear like a minor issue. However, if untreated for an extended period of time, it may develop into a health problem that interferes daily life and employment. Risk factors include improper work postures, inappropriate workstations and work environments, and daily behaviors, such as inappropriately sized work desks and chairs,

sitting for long periods of time, and hunching over. For example, research by Srijaroen (2022) studied the assessment of physical risks of office workers. The results of the research found that office workers are at risk of ergonomics, causing abnormalities in the musculoskeletal system from the work of office workers, which is caused by inappropriate workstations and working over extended lengths of time.

Improper workstations, such as desks that are too high and chairs that are too low, are one of the causes of back pain at work. This is due to the fact that employees bend, lean, or twist while working at desks or chairs that are not the proper size and

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cannot be modified to fit each employee's proportions. In addition, sitting for long periods of time causes aches and pains or fatigue from work, resulting in back pain and work-related injuries. Therefore, designing a work chair that is in line with the body proportions and the needs of the user is necessary to help reduce risk factors from such impacts and increase comfort at work. Although there are many styles of work chairs on the market, the designs do not support the body proportions and needs of the users, such as having inappropriate backrests, no armrests, and being unable to adjust the level. Solving this problem requires an efficient design method that meets the diverse needs of users. Therefore, ergonomic principles have been applied to the design and development of work chairs, along with Quality Function Deployment (QFD) techniques and the Analytical Hierarchy Process (AHP), to produce a work chair that is the right size for the human body proportions and meets the diverse needs of the users.

Since ergonomics principles is a science that adjusts work conditions to suit the operator or improves working conditions by systematically studying operators in the work environment. This is so that operators can work happily without pain, fatigue, injury, or illness due to work postures throughout the work period. Such as the research of Satieanrangsarith and Chaithanee (2024) who used body proportions as information in designing and improving work stations to be suitable for employees to reduce muscle fatigue and work injuries from sitting for long periods of time; and the research of Auesujaridwong *et al.* (2011) who used body proportions as information in designing and improving employees' work stations to reduce fatigue and work injuries from sitting for long periods of time; and the research of Phieboolsilapa *et al.* (2023) designed and developed a welding table by applying the QFD technique together with the ergonomics principle, including the research of Jitman *et al.* (2021) who designed and developed an adjustable chair that caters to various user heights and postures. This combination of innovative design and ergonomic principles aims to enhance comfort and productivity in work environments, ultimately leading to improved overall well-being for users. ed a bamboo saw by applying the QFD technique together with the ergonomics principle.

QFD is a product design and development technique that is popularly used in the design and development of products or services. This is because the steps start from listening to the voices or needs of customers or users and then converting customer needs into technical requirements or specifications for components that need to be improved, resulting in products or services that meet customer needs. Such as the research of Rodjananugoon *et al.* (2023) the implementation of QFD has shown significant improvements in customer satisfaction and product quality. By prioritizing customer feedback throughout the development process, organizations can more effectively align their offerings with market demands and enhance their

competitive edge. who applied the QFD technique to the design and development of a bamboo table and chair set products in conjunction with Kansei engineering; the research of Rawangwong *et al.* (2023) who applied the QFD technique to the design and development of ceramic lamp products; and the research of Rawangwong *et al.* (2022) who applied the QFD technique to the design and development of bag-type bulrush reed products.

While the AHP is a technique that helps score the importance of each technical requirement by comparing pairs of technical requirements to see how they relate to customer needs. Then, the obtained data is used to create a comparison result metric table. After that, the importance weight of each column is calculated, and the average of each row is found. Then, the consistency or reasonableness of the comparison is checked (Ransikarbum, 2022; Tragkanont *et al.*, 2023). Such as the research of Cockalo *et al.* (2020) who used the QFD and AHP technique to defined customer demands and develop Industrial transmitter, and Rachman *et al.* (2024) who used the AHP technique to select strategies of building design. Including the research of Felice and Petrillo (2010) who used the AHP technique to the assessment of customer needs, and Cetin and Ucler (2023) who used the AHP-QFD to customer-focused aircraft seat design.

Since the integration of QFD techniques with AHP and ergonomics can help design and develop products that both meet user needs and support physical usage, this research focuses on integrating QFD and AHP with ergonomics to design and develop office chairs that meet the needs of users with diverse needs while reducing health risks and increasing work efficiency. The results will help create guidelines for designing and developing work chairs that are appropriate and sustainable, linking user needs with practical design principles.

2. Materials and Methods

2.1 Collecting and analyzing customer needs

Gathering and grouping customer needs regarding the characteristics of work chairs desired from related research and reports from various related agencies, including direct customer surveys, found that there were 8 characteristics of work chairs that users wanted, including (1) appropriate size and proportions (2) easy to move, (3) easy to adjust (4) comfortable to sit (5) does not slide when sit (6) not easily (7) strong and durable and (8) good weight loading. Then group them into categories using a tree diagram as shown in Figure 1.

2.2 Creation and verification of research tools

2.2.1 Creating a questionnaire is the process of taking the obtained data and creating a questionnaire, then checking the accuracy and reliability of the questionnaire by 3 experts.

2.2.2 Survey of user needs regarding the characteristics of the desired work chair. However, since the population is

unknown, the sample size was determined according to W.G. Cochran's formula, which is consistent with the research of Rawangwong *et al.* (2023) and Rawangwong *et al.* (2022) It was found that the sample size was calculated in the case of an unknown population according to W.G. Cochran's formula as in Equation (1).

$$n = \frac{P(1-P)Z^2}{d^2} \quad (1)$$

where n = sample size, P = proportion desired to be selected from the total population (given that $P = 0.30$), d = level of sampling error to be allowed (given that $d = 0.10$), and Z = confidence level (given that $Z = 1.65$), since there is a 90% confidence level.

$$n = \frac{0.30(1-0.30)1.65^2}{0.10^2} = 58$$

Therefore, the number of users who need to be asked about the characteristics of the desired work chair is at least 58 people.

This research asked about the needs of 90 users about the characteristics of the desired work chair.

2.2.3 Finding the geometric mean is the process of taking the data obtained from the survey and calculating the geometric mean to be used as the importance level (importance: IMP), which can be calculated from the formula.

$$IMP = \sqrt[n]{N_1 \times N_2 \times N_3 \times \dots \times N_n} \quad (2)$$

where N is the value obtained from the questionnaire and n = number of respondents.

2.3 The application of QFD technique to design work chairs, together with AHP has the following steps

2.3.1 Place the desired user characteristics of the work chair on the left side of the House of Quality (HOQ), which is phase 1 of QFD product planning, and use the geometric mean as the importance level (IMP) value as shown in Figure 2.

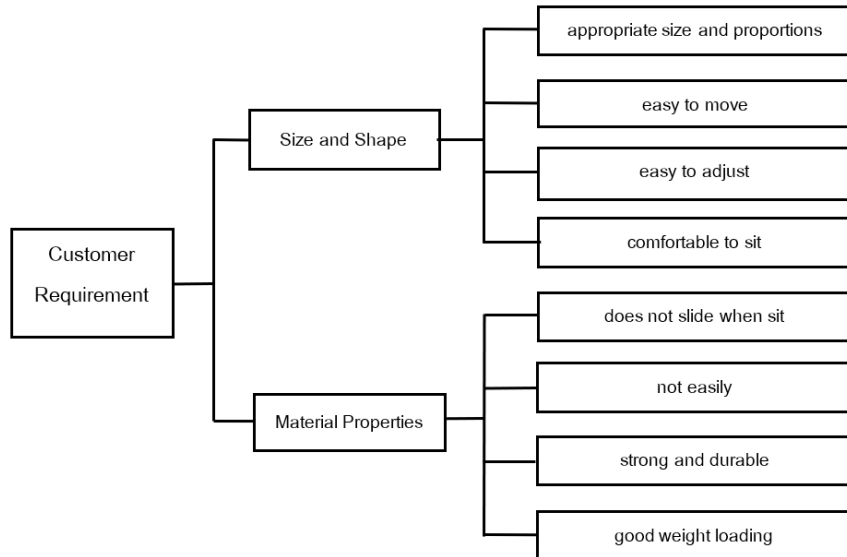


Figure 1 Grouping of customer requirement.

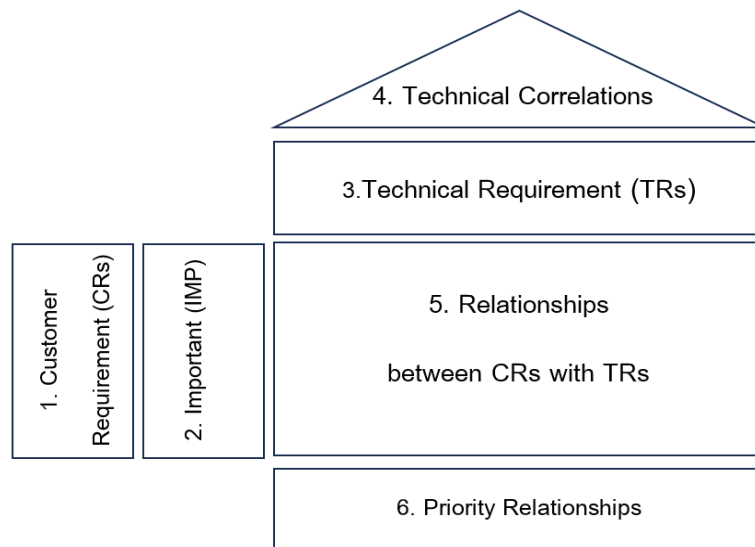


Figure 2 House of Quality (HOQ). (Rawangwong *et al.*, 2022)

2.3.2 The determination of technical requirements in accordance with user requirements. All user requirements must be met by technical requirements, but technical requirements may be repeated.

2.3.3 Evaluation of the relationship level between customer requirement and technical requirements by using AHP to assist in the evaluation, which has the following steps:

1) Create a comparison table and compare pairs of technical requirement, labeled 1 for equally preferred, 2 for equally to moderately, 3 for moderately preferred, 4 for moderately to strongly, 5 for strongly preferred, 6 for strongly to very strongly, 7 for very strongly preferred, 8 for very strongly to extremely, and 9 for extremely preferred.

2) Take the data obtained from the comparison and create a comparison result table, then calculate the importance weight of each column. After that, calculate the average of each row.

3) Calculation of the consistency of cause and effect (Consistency Index : CR) is a comparison between the calculated consistency index (CI) and the random inconsistency index (RI) as shown in Table 1. If the CR value is less than or equal to 0.10 or 10%, it is considered acceptable. However, if the CR value is greater than 0.10 or 10%, it is considered unacceptable. The weighting of the comparative scores in that criterion must be reviewed again until an acceptable CR value is obtained. The CR value can be calculated as in Equation (3).

$$CR = CI / RI \quad (3)$$

where

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

and CI = Consistency Index, RI = Random Consistency Index, and λ_{max} is a value calculated by taking the sum of the diagnostic values of each criterion in each row and multiplying it by the sum of the average values in each horizontal row and then adding the products together or finding the sum between the results in the vertical and the average values of each row, which the result is equal to the total number of criteria that are compared. If the diagnostics in that criterion are completely consistent, it will result in the value $\lambda_{max} = n$.

4) Set the target values and direction for the development of the technical requirements by specifying the circle symbol (○) to mean that the specified value is appropriate, the upward arrow symbol (↑) to mean that the higher the specified value is better, and the downward arrow symbol (↓) to mean that the lower the specified value is better.

5) Evaluate the level of relationship between technical requirements by indicating a plus sign (⊕) to mean a positive relationship, which is a supportive relationship, and a cross sign

(⊗) to mean a negative relationship, which is a subtractive relationship.

6) Importance weight (IW), technical importance relative weight (%Relative), and ranking of technical requirements (TRs) according to their importance.

2.4 The application of ergonomic principles in designing and developing work chairs is the use of human body proportions as data in designing and developing work chairs that are suitable for workers (Auesujaridwong et al., 2011; Satieanrangsarith and Chaithanee, 2024), with details as follows:

2.4.1 Use the height from the floor to the lower thigh (popliteal height) as data to determine the height of the work chair so that the operator can sit and work comfortably for long periods of time without getting tired, using the principle of designing for the highest value (design for extreme value), that is, using the 95th percentile as data to design the work chair because it is a value that most people can use, as shown in Figure 3.

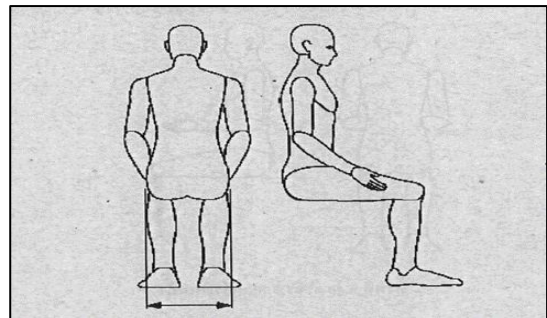


Figure 3 Popliteal height.

(Sukhothai Thammathirat Open University, 2012)

2.4.2 Use the distance from the buttock to the knee joint (buttock-knee length) as information for designing the depth of the work chair because it will allow the operator to sit and work with full hips, resulting in being able to sit and work for long periods of time comfortably without fatigue. The principle of designing for the maximum value (design for extreme value) will be used; that is, using the 95th percentile as information because it is a value that most people can use, as shown in Figure 4.

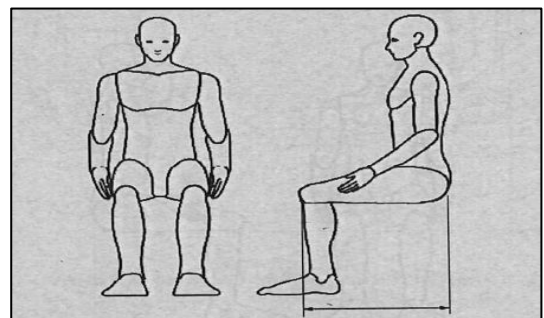


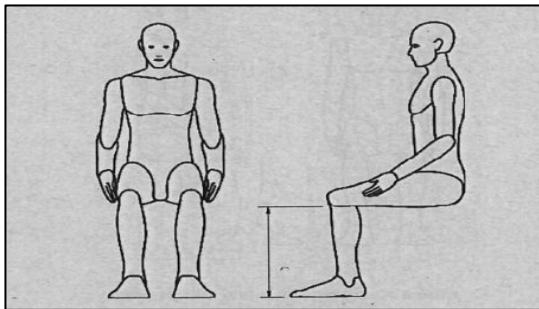
Figure 4 Buttock-knee length.

(Sukhothai Thammathirat Open University, 2012)

Table 1 Random consistency index (RI). (Ransikarbun, 2022)

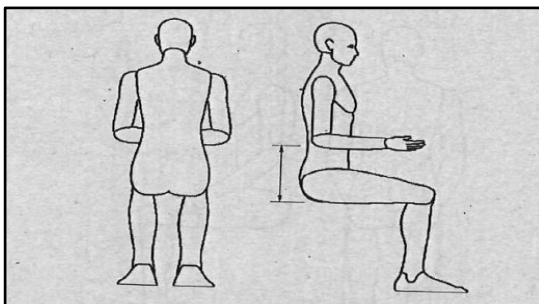
N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.46	1.49

2.4.3 Use the hip breadth while sitting (hip breadth) as information in designing the width of the chair because it will allow the operator to sit and work with full hips, making them sit comfortably without getting tired. The principle of designing for the maximum value (design for extreme value) will be used, which is using the 95th percentile as information because it is a value that most people can use, as shown in Figure 5.

**Figure 5** Hip breadth.

(Sukhothai Thammathirat Open University, 2012)

2.4.4 Use the height from the floor to the elbow (elbow rest height) as information to determine the level of the armrest to reduce fatigue while working. The design principle will be based on using the lowest value, which is the 5th percentile, as the design information because it is a value that most people can use, as shown in Figure 6.

**Figure 6** Elbow rest height.

(Sukhothai Thammathirat Open University, 2012)

2.4.5 Specify the use of memory foam as a material for making cushions and backrests of office chairs. Because memory foam is a porous material, it allows good air circulation. When sitting for a long time, there will be no dampness due to heat being trapped in the hip area. This allows one to sit and work continuously for a long time without getting dampness (Viriyaarakij *et al.*, 2014).

2.4.6 The backrest angle is set to 90-120 degrees because it allows one to sit and work continuously for long periods of time without getting tired and with efficient work.

2.5 Creating a prototype work chair

Creating a prototype work chair, is the application of data obtained from the QFD technique to the design of work chairs, together with AHP and ergonomics principles, to create a prototype work chair. Three prototype work chair shapes were created: the 5th, 95th percentile, and average.

2.6 Satisfaction testing of work chair users

Satisfaction testing of work chair users, with a total sample of 30 people, who were given the opportunity to try out the chairs before the improvements and the prototype work chairs that were created, with 10 people sitting in each type and then asked about their satisfaction.

3. Results and Discussion

3.1 From the survey of the needs of users regarding the characteristics of the desired work chairs by interviewing a total of 90 people using a questionnaire and calculating the geometric mean (geometric mean) to be used as the importance level (Importance: IMP), can be calculated as follows:

Appropriate size and proportions

$$= \sqrt[90]{5 \times 4 \times 4 \times \dots \times 5} = 4.01$$

Easy to move

$$= \sqrt[90]{3 \times 4 \times 4 \times \dots \times 5} = 3.90$$

The remaining calculations can be found in Figure 7.

3.2 Results from designing and developing work chairs by applying QFD techniques together with AHP and ergonomics, which have steps starting from studying user needs, converting user needs into technical requirements that need to be improved, finding the importance scores of technical requirements using AHP techniques, and applying ergonomics principles by using body proportions as data in designing and developing work chairs, the steps are as follows:

3.2.1 Determination of technical requirements in accordance with customer requirements, a total of 5 technical requirements can be determined: material selection, appropriate size and shape, adjustable height, apply ergonomic principles and stable and strong structure as shown in Table 3.

3.2.2 Compare technical requirement into a comparison table and compare them one by one to see how they affect customer needs.

For example, the customer's requirement case does not slide when sitting, with results as shown in Table 3.

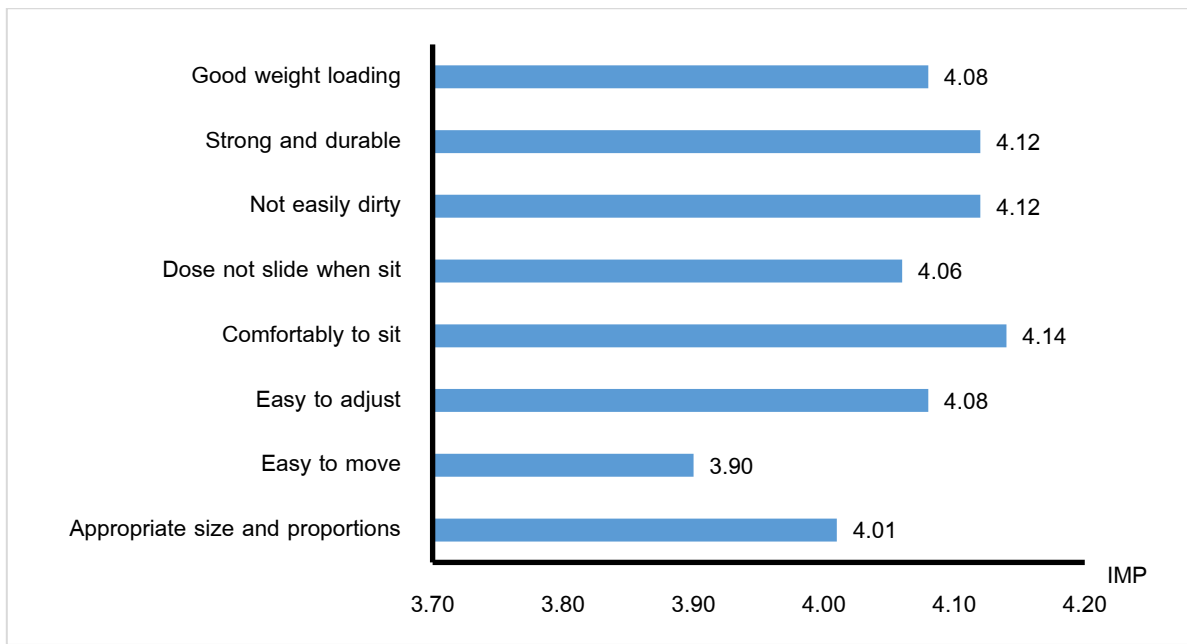


Figure 7 Results of a survey on the characteristics of work chairs that users want.

Table 2 The determination of technical requirements in accordance with customer requirements.

No	Customer Requirement (CRs)	Technical Requirement (TRs)
1	Appropriate size and proportions	Apply the principles of ergonomics
2	Easy to move	Appropriate size and shape
3	Easy to adjust	Adjustable height
4	Comfortably to sit	Material selection
5	Dose not slide when sit	Material selection
6	Not easily dirty	Material selection
7	Strong and durable	Material selection
8	Good weight loading	Stable and strong structure

Table 3 Pair-by-pair factor comparison the customer's requirement case does not slide when sitting.

Factor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Factor
A			X															B
A			X															C
A							X											D
A			X															E
B								X										C
B								X										D
B								X										E
C									X									D
C									X									E
D									X									E

Remark: A = Material selection, B = Appropriate size and shape, C = Adjustable height, D = Apply ergonomic principles and E = Stable and strong structure.

Table 4 Vertical total score finding.

TRs \ TRs	A	B	C	D	E
A	1	7	7	7	7
B	0.14	1	1	1	1
C	0.14	1	1	1	1
D	0.33	1	1	1	1
E	0.14	1	1	1	1
Total	1.75	11	11	11	11

Table 5 The average of the technical specifications of each row.

TRs \ TRs	A	B	C	D	E	Average
A	0.57	0.64	0.64	0.64	0.64	0.62
B	0.08	0.09	0.09	0.09	0.09	0.09
C	0.08	0.09	0.09	0.09	0.09	0.09
D	0.19	0.09	0.09	0.09	0.09	0.11
E	0.08	0.09	0.09	0.09	0.09	0.09
Total	1.00	1.00	1.00	1.00	1.00	1.00

Table 6 Importance scoring results with the AHP technique of customer's requirement.

Technical Requirement (TRs) Customer Requirement (CRs)		IMP	A	B	C	D	E	CR
Material properties	1) Does not slide when sitting	4.06	0.62	0.09	0.09	0.11	0.09	5.89%
	2) Not easily dirty	4.12	0.62	0.09	0.09	0.11	0.09	5.89%
	3) Strong and durable	4.12	0.59	0.07	0.07	0.07	0.19	0.31%
	4) Good weight loading	4.08	0.39	0.11	0.08	0.09	0.33	7.68%
Size and shape	1) Appropriate size and proportions	4.01	0.05	0.13	0.38	0.38	0.05	8.29%
	2) Easy to move	3.90	0.23	0.49	0.09	0.09	0.09	1.40%
	3) Easy to adjustable	4.08	0.04	0.16	0.54	0.18	0.07	8.47%
	4) Comfortably to sit	4.14	0.10	0.08	0.37	0.37	0.06	2.16%

and can be calculated as follows in the Figure 8.



Figure 8 Results of design and development of work chairs.

3.2.3 Compare technical requirement one by one How the technical requirements affect the customer's needs.

For example, compare between material selection (A) and appropriate size and shape (B) affect the needs of customers in the case of does not slide when sitting, with results as shown in Table 3.

3.2.4 Then add up the scores vertically, can be calculated as follows;

$$A = 1 + 0.14 + 0.14 + 0.33 + 0.14 = 1.75$$

$$B = 7 + 1 + 1 + 1 + 1 = 11$$

The remaining calculations can be found in Table 4.

3.2.5 Weighing the importance of decision criteria in each column, can be calculated as follows:

$$A = 1/1.75 = 0.57, 0.14/1.75 = 0.08, 0.14/1.75 = 0.08, 0.33/1.75 = 0.19, 0.14/1.75 = 0.08$$

$$\text{Total} = 0.57 + 0.08 + 0.08 + 0.19 + 0.08 = 1.00$$

$$B = 7/11 = 0.64, 1/11 = 0.09, 1/11 = 0.09, 1/11 = 0.09, 1/11 = 0.09$$

$$\text{Total} = 0.64 + 0.09 + 0.09 + 0.09 + 0.09 = 1.00$$

The remaining calculations can be found in Table 5.

3.2.6 The average in the horizontal direction, can be calculated as follows:

$$A = (0.57 + 0.64 + 0.64 + 0.64 + 0.64) / 5 = 0.62$$

$$B = (0.64 + 0.09 + 0.09 + 0.09 + 0.09) / 5 = 0.09$$

The remaining calculations can be found in Table 5.

3.2.7 The calculation of the consistency index (CR) of cause and effect can be calculated as follows:

$$\lambda_{\max} = (1.75 \times 0.62) + (11 \times 0.09) + (11 \times 0.09) + (11 \times 0.11) + (11 \times 0.09) = 5.265$$

$$CI = (5.265 - 5) / (5 - 1) = 0.066$$

$$CR = 0.066 / 1.12 = 0.059 \text{ or } 6\%$$

Based on the results of the calculations, it was found that the CR value was 6%, it is considered can be concluded that the

comparison results are consistent. The remaining calculations can be found in Table 6.

3.2.8 Determine the importance score of each technical requirement, can be calculated as follows:

$$A = (4.01 \times 0.05) + (3.90 \times 0.23) + (4.08 \times 0.04) + (4.14 \times 0.10) + (4.06 \times 0.62) + (4.12 \times 0.62) + (4.12 \times 0.59) + (4.08 \times 0.39) = 10.77$$

$$B = (4.01 \times 0.13) + (3.90 \times 0.49) + (4.08 \times 0.16) + (4.14 \times 0.08) + (4.06 \times 0.09) + (4.12 \times 0.09) + (4.12 \times 0.07) + (4.08 \times 0.11) = 4.89$$

The remaining calculations can be found in Figure 8.

3.2.9 Weighting of importance (%) of each technical requirement, can be calculated as follows:

$$A = (10.77 / 32.27) \times 100 = 33.37\%$$

$$B = (4.89 / 32.27) \times 100 = 15.15\%$$

The remaining calculations can be found in Figure 8.

3.3 Using technical requirements as a guideline for designing and developing work chairs by considering important technical requirements first, with details as follows.

3.3.1 Material selection is the most important technical requirement, weighing 33.57%. Because the choice of material as a technical requirement influences many customer requirements, such as (1) Does not slide when sitting (2) Not easily dirty (3) Strong and durable (4) Good weight loading and (5) Easy to move, it has a higher priority score than other technical requirement. The materials used to make the work chair must be appropriate and consistent with the function of each part. The chair structure supports the weight of the sitter. General hot-rolled structural steel should be used, and the parts should be welded together. The seat and backrest support the weight of the sitter and allow the sitter to sit for a long time without getting stuffy and allow good ventilation. Therefore, memory foam is selected because its porous structure allows for good ventilation and air circulation, preventing stuffiness. Therefore, it is suitable for sitting for a long time.

3.3.2 Adjustable height is a technical requirement with the second most important weight, with an importance of 21.57%. Since workers have different body proportions, the chair is designed to be height adjustable, using the 5th and 95th percentiles as data. Therefore, it is set to be lower than the 5th percentile and higher than the 95th percentile. To allow flexibility in working, the chair is set to be adjustable in the range of 30-50 centimeters.

3.3.3 Applying the principles of ergonomics to the design and development of office chairs is a technical requirement with the third most important weight, with an importance weight of 17.65%, by using relevant body proportions as data in the design and development of office chairs.

3.3.4 Appropriate size and shape is a technical requirement with the fourth weight, with an importance weight of 15.15%. Since the work chair is a place where the operator has to sit and work continuously for a long time, the work chair must be designed with an appropriate size and shape. The seat pad must be rectangular and 25 millimeters thick. The backrest must be rectangular, with a backrest angle of 90-120 degrees, a height of 50 centimeters, and a backrest width of 45 centimeters. The chair legs must be rectangular, 25 millimeters wide, and 25 millimeters long, and the seat base must be rectangular.

3.3.5 Stable and strong structure is the last important technical requirement, with a weight of 12.24%. In order for the structure of the work chair to be stable and strong, to have a long service life and to be able to support the weight of the sitter without damage, the stress occurring in each leg of the chair and the pressure occurring on the work chair must be calculated.

From Figure 7, it was found that the technical requirement with the highest weight was being comfortable to sit, with an importance weight of 4.14 points, followed by strength & durable and not easily dirty, both with 4.12 points, followed by good weight loading, easily to adjust, does not slide when sit, appropriate size and proportion, and easy to move, with 4.08, 4.08, 4.06, 4.01, and 3.90 points (respectively).

From Figure 9, it was found that the materials selection (A) is the most important technical requirement, with an importance weight of 33.37 percent, followed by adjustable height (C), with an importance weight of 21.57 percent, followed by apply the principles of ergonomics (D), appropriate size and shape (B), and having a stable and strong structure (E) ,with importance weights of 17.65, 15.15, and 12.24 percent (respectively).

3.4 Applying ergonomic principles to the design and development of work chairs by using relevant body proportions as data in the design and development of work chairs, which are detailed as follows:

1) Use the height from the floor to the lower thigh (popliteal height) as data to determine the height of the work chair, which will use the design principles for the highest and lowest values, that is, using the 5th and 95th percentiles and the mean, which will determine the height of the chair as a range of data from 36 to 44 centimeters so that the worker can adjust the level according to the size and proportion of the body, as shown in Table 7.

2) Use the distance from the buttocks to the knee joint (buttock-knee length) as data for designing the depth of the work chair so that the operator can sit and work with full hips. The design principle will be used by using the lowest value, which is the 5th percentile, to cover almost the entire population because it is a value that most people can use. Use this data for designing, which is 39 centimeters, but minus the allowance

for space of 5 centimeters. Therefore, the depth of the chair is set to be 34 centimeters, as shown in Table 7.

3) Use the hip width while sitting (hip breadth) as information in designing the width of the chair because it will allow the operator to sit with full hips and sit comfortably without

getting tired. The design principle will use the highest value, which is the 95th percentile, as information, which is 43 centimeters, because it is a value that most people can use, as shown in Table 7.

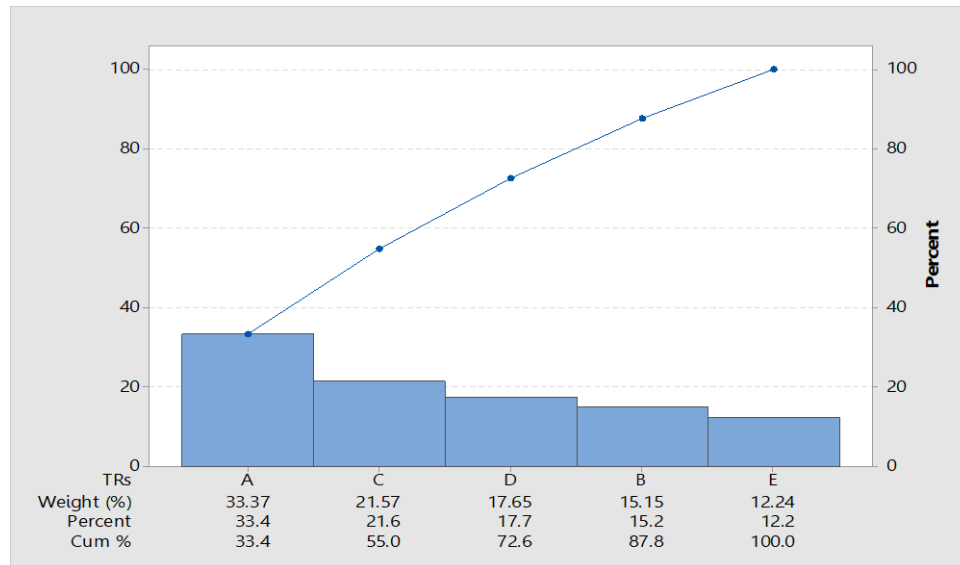


Figure 9 Priority ranking of technical requirements.

Table 7 Body proportions used in designing and developing work chairs. (Auesujaridwong *et al.*, 2011; Satieanrangsarith and Chaithanee, 2024)

Body Proportions	Application	Mean	5 th percentile	95 th percentile
1. Popliteal height	Chair height (cm.)	39.24	35.98	43.31
2. Buttock-knee length	Chair Depth (cm.)	44.54	39.20	50.22
3. Hip breadth	Chair width (cm.)	37.01	32.49	43.20
4. Elbow rest height	Armrest height (cm.)	21.80	17.46	27.50

4) Use the height from the floor to the elbow as data (elbow rest height) to determine the level of the armrest in order to reduce fatigue while working. The design principle will be based on using the lowest value, which is the 5th percentile, as data for designing, which is 18 centimeters, because this is a value that most people can use, as shown in Table 7

3.5 Using the obtained data to create a prototype work chair by creating 3 prototype work chairs, namely the 5th, 95th percentile, and mean values.

3.6 User satisfaction test by having a sample group of 30 people sit on the work chair before improvement and the prototype chair according to their body proportions.

Ten people with a height of approximately 162 centimeters sat on the work chair before improvement and the prototype chair at the 5th percentile. Ten people with a height of approximately 169 centimeters sat on the work chair before improvement and the prototype chair on the mean. Ten people with a height of 180 centimeters sat on the work chair before

improvement and the prototype chair at the 95th percentile. Then, the satisfaction was asked. It was found that before improvement, the satisfaction was 2.96 points. After improvement, the satisfaction of users increased to 4.04 points.

The results of the design and development of work chairs by applying the QFD technique together with the AHP technique and ergonomics principles led to guidelines for the design and development of work chairs that meet the needs of users and are of an appropriate size and proportion for users. To enhance the accuracy and completeness of the research, Finite Element Analysis (FEA), a computer simulation technique used to solve engineering problems, should be utilized in the future to support more efficient design. This reduces the risk factors of back pain due to work, which is consistent with the research of Boonla and Chaiklieng (2021) who systematically reviewed research on ergonomic management to reduce skeletal abnormalities of industrial production workers, namely, improving workstations to be suitable for work. Work chairs are part of the workstation and the research of Somupahard *et al.* (2024) who designed work

chairs for health by applying Kansei engineering and the Kano model. The results of the research study found that consumers' feelings towards work chairs for health have a total of 8 words: balance, comfort, ergonomics, work features, good quality, relaxation, simplicity, and strength. Including the research of Khanthusaeng *et al.* (2022) who improved the workstation to reduce ergonomic risks of microscope users by designing and developing chairs used in the work to be suitable for the body and nature of the work. By providing a backrest that supports the lumbar spine and allowing the chair to be adjusted high and low, including making the seat cushion softer, and the research of Auesujaridwong *et al.* (2011) who designed a chair for the fish blood scraping process by taking the height from the floor to the lower thigh to determine the height of the chair, taking the distance from the buttocks to the knee joint to determine the depth of the chair, and the width of the hips while sitting to determine the width of the chair. To enhance the accuracy and comprehensiveness of future research, it is advisable to utilize an electromyography (EMG) instrument for measuring muscle fatigue. Additionally, including images of the design and development results would be beneficial.

4. Conclusion

This research is the design and development of work chairs by applying the QFD technique together with the AHP and the principles of ergonomics. It starts with collecting the user requirements for the characteristics of the work chairs and then grouping the requirements into categories. After that, the user requirements are converted into technical requirements that need to be improved. The importance of the technical requirements is assessed using the AHP technique, the relationship between the technical requirements is assessed, the weight is calculated, the priority is ranked according to the importance of the technical requirements, and the ergonomics principle is applied. Body proportion is used as data in designing and developing work chairs. The results of the research study found that the most important user requirements are comfortable to sit, with a weight of 4.14, followed by strong and durable and not easily dirty, with a weight of 4.12, and good weight loading, easy to adjust, dose not slide when sit, appropriate size and proportion and easy to move, with weights of 4.08, 4.08, 4.06, 4.01, and 3.90 (respectively). It was found that the most important technical requirements are material selection accounting for 33.37 percent, adjustable height accounting for 21.57 percent, apply the principles of ergonomics accounting for 17.65 percent, appropriate size and shape accounting for 15.15 percent, and stable and strong structure accounting for 12.24 percent. The body proportions used in the design and development of office chairs include the height from the floor to the lower thigh, the distance from the buttocks to the knee joint, the width of the hips while sitting, and the armrests. After that, the obtained data was used to create 3 prototype

work chairs: the 5th percentile, the 95th percentile, and the average. Then, a sample of 30 people were asked to try the chair before the improvement and the prototype work chair that was created, with 10 people tested for each model and asked about their satisfaction. It was found that before the improvement, the users were satisfied with 2.96 points. After the improvement, the satisfaction increased to 4.04 points. The results of the research will use the obtained data to create an ergonomic work chair that can be adjusted in the range of 36-44 centimeters so that employees can adjust the level according to the size and proportion of their body.

5. Acknowledgments

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Research Article

Influence of Garlic Marinade on Maillard Reaction and Polycyclic Aromatic Hydrocarbon Formation in Grilled Chicken

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ABSTRACT

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Garlic, a common ingredient in Thai cuisine, is a natural source of antioxidants and may influence chemical reactions during cooking, such as the Maillard reaction and the formation of polycyclic aromatic hydrocarbons (PAHs), which are potential carcinogens. This study investigated the effect of garlic-containing marinades on these processes in grilled chicken. Marinades with 8%, 15%, and 26% garlic were prepared, and chicken breasts were marinated for 12 hours. A non-marinated sample served as the control. All samples were grilled on a hotplate at 350 °C for 10 minutes. Antioxidant activity of the marinades and marinated chicken was assessed using DPPH assay (2,2-diphenyl-1-picrylhydrazyl) and ABTS assay (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid), and total phenolic content was measured. The Maillard reaction was evaluated through color change and melanoidin absorbance, while 16 PAHs were quantified using Gas Chromatography–Mass Spectrometry. The results showed that higher garlic concentrations enhanced the antioxidant activity of the marinades but did not significantly affect Maillard reaction markers or PAH formation. The limited PAH levels observed are likely due to the grilling method—specifically, the use of a hotplate heat source, its temperature, and the cooking duration—which may not induce substantial PAH production. These findings suggest that garlic enhances antioxidant properties in marinades but may have limited impact on PAH mitigation under the cooking conditions used.

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1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are a group of chemical compounds primarily formed during the incomplete combustion of organic matter. In the context of cooking, they are commonly produced when fat and meat juices drip onto hot surfaces, such as charcoal, generating smoke that carries PAHs which then deposit onto the food (Janoszka, 2020). Numerous studies have confirmed that PAH formation is significantly influenced by cooking temperature, time, and method. For example, charcoal grilling typically produces higher PAH levels than electric or gas grilling due to direct flame and smoke exposure (Yurchenko and Mölder, 2021). Meat type and fat content also play a crucial role; fattier meats

tend to generate more smoke, resulting in higher levels of PAHs (Ni *et al.*, 2021).

PAHs are chemically inert and hydrophobic, but once ingested, they undergo metabolic transformation in the human body into reactive metabolites. These metabolites can bind covalently to DNA, leading to mutations and replication errors that initiate carcinogenesis (Phillips, 1999). Due to their toxicity and health risks, the U.S. Environmental Protection Agency (US EPA) has identified 16 PAHs as priority pollutants. Similarly, the European Union's Scientific Committee on Food has designated four PAHs: benzo[a]anthracene (B[a]A), chrysene (Chr), benzo[b]fluoranthene (B[b]F), and benzo[a]pyrene (B[a]P), as key indicators of carcinogenic PAHs in food (Lee *et al.*, 2016).

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Several strategies have been studied to reduce PAH formation in grilled meats. Farhadian *et al.* (2011) demonstrated that preheating and wrapping beef or chicken before charcoal grilling could completely eliminate benzo[a]pyrene and benzo[b]fluoranthene formation. Recent studies highlight the effectiveness of marinades, particularly those rich in antioxidants such as lemon juice, garlic, or wine in significantly reducing PAH levels by inhibiting fat and protein pyrolysis (Zhang *et al.*, 2022). In addition to reducing PAHs, marination can also lower the formation of heterocyclic aromatic amines (HCAs), another class of carcinogens generated during high-temperature cooking (Gibis, 2007). Marinades are traditionally used to enhance the sensory qualities of meat (texture, color, flavor) and have been shown to influence PAH formation (Wongmaneeprapit and Vangnai, 2017). Since both HCAs and PAHs are formed through radical-driven reactions, antioxidants can interfere with these processes and inhibit their formation (Lu *et al.*, 2018). For example, phenolic antioxidants have been shown to inhibit the formation of imidazoquinoline-type HCAs via free radical Maillard intermediates (Min *et al.*, 2018). Marinating pork belly with tea has also been shown to increase radical-scavenging activity, preserving meat quality and reducing benzo[a]pyrene formation during grilling (Park *et al.*, 2017).

Garlic, a member of the *Allium* family, is rich in antioxidants, particularly organosulfur compounds like diallyl sulfide (DAS) and diallyl disulfide (DAD) (Mellado-García *et al.*, 2015). These compounds contribute to garlic's aroma and exhibit strong radical-scavenging activity that may inhibit harmful compounds formed during high-temperature cooking. Garlic essential oil has significantly reduced benzo[a]pyrene in charcoal-grilled pork sausages due to its sulfide content (Hu *et al.*, 2021). Garlic marinades also reduce PAH formation by limiting lipid oxidation and protein pyrolysis (Zhang *et al.*, 2022; Lu *et al.*, 2018). In Thai cuisine, garlic is a key marinade ingredient, valued for both flavor and functional health benefits.

The present study aimed to investigate how varying concentrations of garlic in marinades (8%, 15%, and 26%) affect key chemical reactions during grilling, specifically the Maillard reaction and the formation of polycyclic aromatic hydrocarbons (PAHs) in chicken breast grilled on a hotplate. The dependent variables included Maillard browning (color changes and melanoidin absorbance), antioxidant capacity (DPPH, ABTS, and total phenolics), and levels of 16 PAHs (measured by GC-MS). This study explores how the antioxidant properties of garlic in marinades may influence these chemical reactions and potentially reduce the formation of carcinogenic PAHs during grilling, thus contributing to safer and healthier consumption of grilled chicken in Thai cuisine.

2. Materials and Methods

2.1 Preparation of chicken breast sample

Chicken breasts were obtained from Betagro Public Co., Ltd. (Thailand), vacuum-packed, and stored at -20 °C until use. Prior to experimentation, the samples were thawed at 4 °C for 12 hours in a refrigerator to minimize moisture loss and microbial growth. After thawing, any visible fat and connective tissue were trimmed, and the chicken was cut into uniform pieces approximately 3 × 4 × 1 cm (length × width × thickness).

2.2 Preparation of marinade

Before grilling, the chicken breast samples were marinated at a 1:1 weight ratio (meat to marinade) for 12 hours at 4 °C. The marinade base was composed of water, sugar, oyster sauce, and salt. Fresh garlic was added to the base at concentrations of 8%, 15%, and 26% (w/w) for the treatment groups. The control group was included, in which chicken was marinated using the same base formula without garlic.

Fresh garlic bulbs were sourced from a single supplier to ensure batch consistency. Before incorporation, garlic cloves were peeled, washed under running water, and minced using a sanitized food processor. The minced garlic was immediately weighed and mixed into the marinade. All marinades were freshly prepared on the same day of use, and stored at 4 °C prior to marination to maintain ingredient integrity. Preparation and handling were carried out under hygienic conditions to ensure quality control.

2.3 Grilling method

The chicken breast samples were grilled on a preheated hot plate at 350 °C for 5 minutes on each side before analysis, as shown in Figure 1.

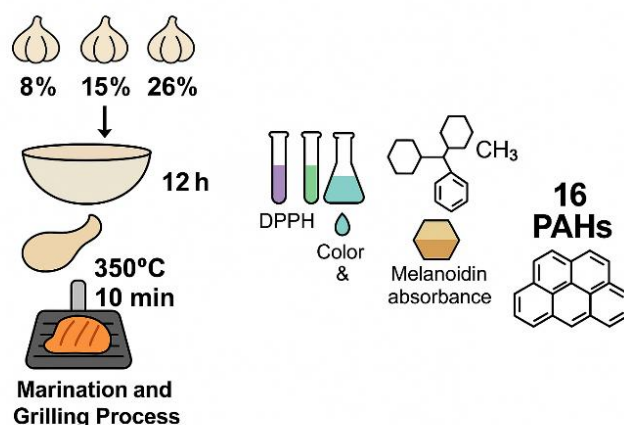


Figure 1 Marination and grilling process.

2.4 Evaluation of antioxidant activity and quantification of phenolic compounds in both marinade and marinated chicken breast

2.4.1 Sample preparation

Marinade and marinated chicken breast samples were ground prior to analysis. The preparation method was adapted from Park *et al.* (2017). Five grams of the ground sample were placed into a stomacher bag containing 45 mL of 0.1 M sodium phosphate buffer (pH 7.0). The buffer was prepared using sodium dihydrogen phosphate (Junsei Chemical, Japan) and disodium hydrogen phosphate (Sigma-Aldrich, USA). The mixture was homogenized for 2 minutes and then filtered through Whatman No. 1 filter paper to remove particulate matter. The filtrate was centrifuged at 12,000 rpm (approximately $14,800 \times g$) for 30 minutes at 4 °C. The resulting supernatant was collected and used for subsequent analysis of antioxidant activity and total phenolic content.

2.4.2 DPPH assay

A volume of 1 mL of 0.2 mM DPPH solution (Sigma Aldrich, USA) prepared in methanol (Merck, Germany) was added to 200 μ L of the sample supernatant and 800 μ L of distilled water in a 12-well plate. The mixture was gently mixed and incubated in the dark for 30 minutes. The control consisted of 1 mL methanol mixed with 1 mL of 0.2 mM DPPH solution, while the blank was 2 mL of methanol. Absorbance was measured at 517 nm using a microplate reader (U-2900UV/VIS Hitachi, Japan) (Park *et al.*, 2017).

2.4.3 ABTS assay

The ABTS solution (Sigma Aldrich, USA) was prepared according to the method described by Serpen *et al.* (2012). The working solution of $\text{ABTS}^{\bullet+}$ was adjusted to an absorbance of 0.75–0.80 at 734 nm. In a 96-well plate, 200 μ L of the $\text{ABTS}^{\bullet+}$ working solution was added to 10 μ L of the sample supernatant and incubated in the dark for 6 minutes. A blank was prepared by mixing 200 μ L of $\text{ABTS}^{\bullet+}$ solution with 10 μ L of buffer. The absorbance of the samples and blank was measured at 734 nm using a microplate reader (U-2900UV/VIS Hitachi, Japan).

The inhibition percentage of the DPPH and $\text{ABTS}^{\bullet+}$ radicals was calculated using the following equation:

$$\% \text{ inhibition}_{\text{sample}} = \frac{[(Abs_{\text{control}} - Abs_{\text{blank}}) - (Abs_{\text{sample}} - Abs_{\text{blank}})]}{Abs_{\text{control}} \times 100}$$

2.4.4 Determination of total phenolic compounds

The total phenolic compound was determined using a modified method based on Tsai *et al.* (2005). Two milliliters of the sample were mixed with 5 mL of 10% Folin-Ciocalteu reagent (Merck, Germany) and allowed to react for 3 minutes. Subsequently, 2 mL of 7.5% (w/v) aqueous sodium carbonate solution (Sigma Aldrich, USA) was added, and the mixture was incubated at room temperature for 1 hour. The absorbance of

the resulting blue color was measured at 765 nm using a microplate reader (U-2900UV/VIS Hitachi, Japan). Total phenolic content was quantified by comparison to a gallic acid standard curve. The total phenolic content (TPC) of the samples was calculated using the following equation:

$$\text{The total phenolic content (TPC)} = \frac{C \times V}{m}$$

where C is the concentration of gallic acid equivalents obtained from the calibration curve (mg/mL), V is the volume of extract (mL), and m is the weight of the sample (g). The results were expressed as milligrams of gallic acid equivalents per gram of sample (mg GAE/g)

2.4.5 pH measurement

The pH (HI5222, USA) of the marinade and marinated chicken breast samples was determined following the method described by Park *et al.* (2017). Five grams of ground sample were homogenized with 45 mL of distilled water for 30 seconds using a blender. The pH of each homogenate was measured at room temperature using a calibrated pH meter. Each sample's pH value was recorded as the average of three independent measurements.

2.5 Non-specific marker of Maillard reaction

2.5.1 Color measurement

Color measurements of grilled chicken were performed using a colorimeter equipped (Color Quest XE, USA) with a D65/8° illumination source, reporting CIELAB values (L^* , a^* , b^*). Measurements were conducted at room temperature ($25 \pm 3^\circ\text{C}$). For each treatment group, three separate samples were evaluated, with color readings taken at four random locations on each sample, avoiding visibly charred areas on the surface.

2.5.2 Absorbance measurement

Melanoidin content was assessed by measuring absorbance at 420 nm, following the method described by Andrade *et al.* (2010). Five grams of the sample were suspended in 10 mL of deionized water, vortexed vigorously for 15 seconds, and then subjected to sonication using an ultrasonic disintegrator for 10 minutes. The mixture was vortexed again for 5 seconds and centrifuged at $14,000 \times g$ for 10 minutes at 4°C. The resulting supernatant was appropriately diluted, and its absorbance was measured at 420 nm using a microplate reader (U-2900UV/VIS Hitachi, Japan). All analyses were conducted in triplicate.

2.6 Determination of PAHs in the sample

2.6.1 Extraction of PAHs

The extraction of PAHs was conducted using a method adapted from Chen and Lin (1997). Chicken samples were ground and freeze-dried, then placed in round filter paper positioned within the center of a Soxhlet extractor. A 500 mL

round-bottom flask containing 200 mL of methanol (Merck, Germany) and 25 mL of 50% aqueous potassium hydroxide (Ajax Finechem, Australia) was attached to the Soxhlet unit for simultaneous PAH extraction and lipid saponification. The mixture was refluxed for 3 hours.

After cooling to 40°C, 150 mL of n-hexane (RCI Labscan, Thailand) was added to the flask with intermittent swirling. The contents were then transferred to a 500 mL separatory funnel containing 150 mL of water. The flask was rinsed twice with 10 mL of methanol, and the rinses were also transferred to the funnel. The funnel was shaken vigorously and left to stand until phase separation occurred. The aqueous layer was discarded, and the remaining aqueous phase was extracted twice more with 150 mL and 100 mL of n-hexane, respectively.

The combined hexane extracts were washed three times with 100 mL of water, dried over anhydrous sodium sulfate (Carlo Erba, Italy), and concentrated to 1 mL using a rotary evaporator. The concentrated extract was applied to a Sep-Pak Florisil cartridge pre-conditioned with 10 mL of methylene chloride (Merck, Germany) and 20 mL of hexane. The cartridge was eluted sequentially with 10 mL of hexane followed by 8 mL of a hexane/methylene chloride mixture (1:1, v/v). The collected eluate was evaporated to dryness, and the residue was reconstituted in 1 mL of methanol/methylene chloride (1:1, v/v).

The final solution was filtered through a 0.2 µm membrane filter and stored in a vial flushed with nitrogen gas until gas chromatography–mass spectrometry (GC-MS) analysis.

2.6.2 PAHs analysis using GC/MS

The extracted samples were analyzed for polycyclic aromatic hydrocarbons (PAHs) using a gas chromatograph (7890A GC System, Agilent Technologies, Canada) equipped with an autosampler and coupled to a mass spectrometer. Separation was achieved using a DB-5MS capillary column (30 m length × 0.25 mm i.d., 0.25 µm film thickness; Agilent Technologies, USA).

A 1 µL aliquot of the sample was injected into the system. The GC oven temperature was initially held at 55°C for 1 minute, then ramped to 320°C at a rate of 25°C/min, and held at 320°C for 3 minutes. Helium served as the carrier gas at a constant flow rate.

The mass spectrometer was operated in electron ionization (EI) mode at 70 eV, with a source temperature of 280°C. Mass spectra were acquired in the range of 45–450 m/z using selective ion monitoring (SIM) mode for increased sensitivity and specificity. Identification and quantification of 16 priority PAHs were performed based on comparison with standard calibration curves, retention times, and characteristic ions, as described in our previous study (Chaemsai *et al.*, 2016). Detailed information on molecular weights and characteristic ions for each PAH is presented in Table 1, while

retention index, retention time, primary, and secondary ions are summarized in Table 2.

2.7 Statistical analysis

All experiments were performed in triplicate, with each sample analyzed three times. Data were expressed as mean ± standard deviation (SD). Statistical analysis was conducted using Minitab 17 (Minitab LLC, USA). One-way ANOVA followed by Fisher's LSD test was used to determine significant differences among groups at $p < 0.05$.

3. Results and Discussion

3.1 Effect of garlic on antioxidant activity and total phenolic content in marinade and marinated chicken breast

The antioxidant activity of marinades and marinated chicken breast samples was assessed using DPPH and ABTS radical-scavenging assays, with results expressed as percentage inhibition. Both assays were used to evaluate the influence of increasing garlic concentrations in the marinade.

As shown in Figure 2, the radical-scavenging activity of the marinade increased with higher garlic content. The marinade containing 26% garlic (marinade 3) exhibited the highest antioxidant activity, followed by those with 15% (marinade 2), 8% (marinade 1), and 0% garlic (control). The percentage inhibition values for both DPPH and ABTS assays were significantly different among treatment groups ($p < 0.05$).

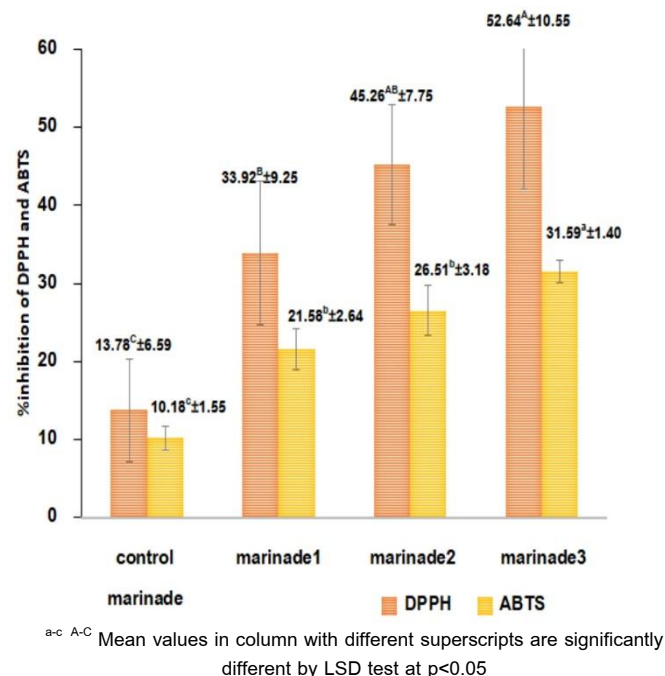
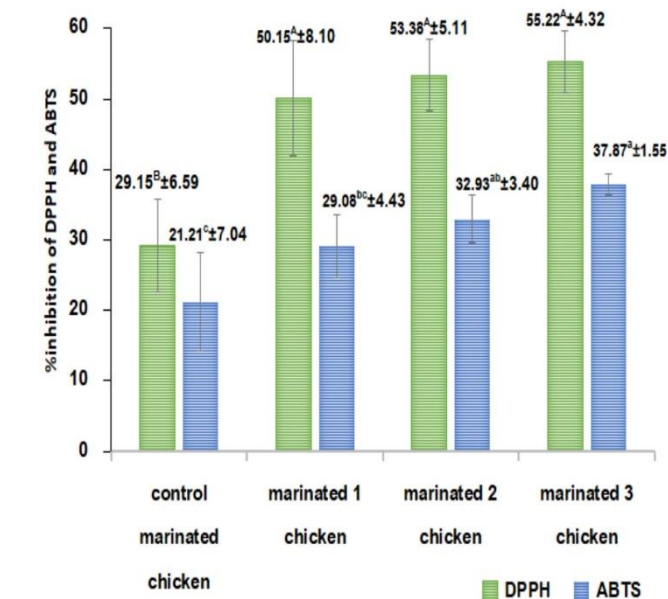


Figure 2 %inhibition of DPPH and ABTS in marinade.

After 12 hours of marination, the DPPH radical-scavenging activity of chicken breast samples was evaluated (Figure 3). The marinated samples showed significantly higher antioxidant activity compared to the control ($p < 0.05$). Although the DPPH activity tended to increase with higher garlic concentrations, there were no statistically significant differences among the

samples marinated with 8%, 15%, and 26% garlic ($p \geq 0.05$). In contrast, ABTS inhibition values differed significantly ($p < 0.05$) among these groups, indicating a garlic concentration-dependent response.

Total phenolic content was quantified using a gallic acid standard curve (0–100 mg/mL), and results were expressed as milligrams of gallic acid equivalents per gram of dry weight (mg GAE/g DW). As shown in Figures 4 and 5, total phenolic content in both the marinade and the marinated chicken breast increased proportionally with the garlic concentration. This trend corresponded closely with the observed antioxidant activity in both DPPH and ABTS assays.



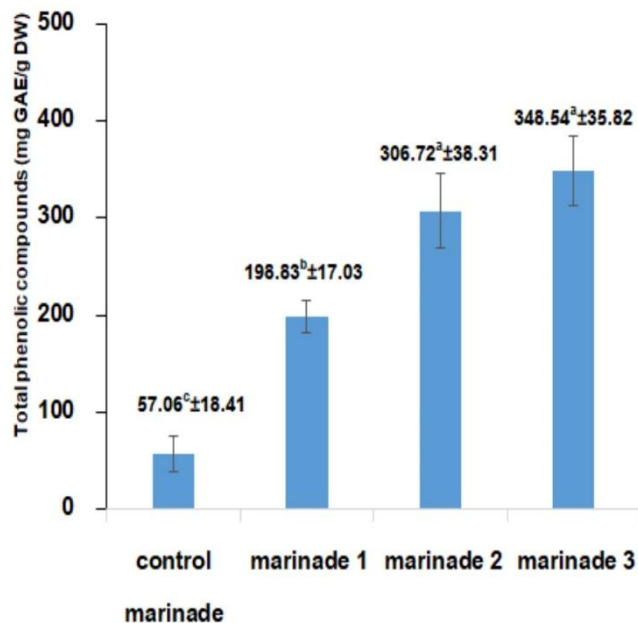
a-c A-C Mean values in column with different superscripts are significantly different by LSD test at $p < 0.05$

Figure 3 %inhibition of DPPH and ABTS in marinated chicken breast.

This divergence may be attributed to the different chemical sensitivities of the two assays. The DPPH assay primarily detects hydrophobic antioxidants in an organic solvent environment and is more sterically hindered, which may limit its interaction with antioxidant compounds in the chicken matrix after grilling. Furthermore, lipophilic compounds from garlic may undergo degradation during cooking or may not be efficiently retained in the meat, reducing their contribution to DPPH radical scavenging. This aligns with findings by Zhang *et al.* (2022), who reported that antioxidant retention post-cooking can be limited by thermal instability and compound solubility.

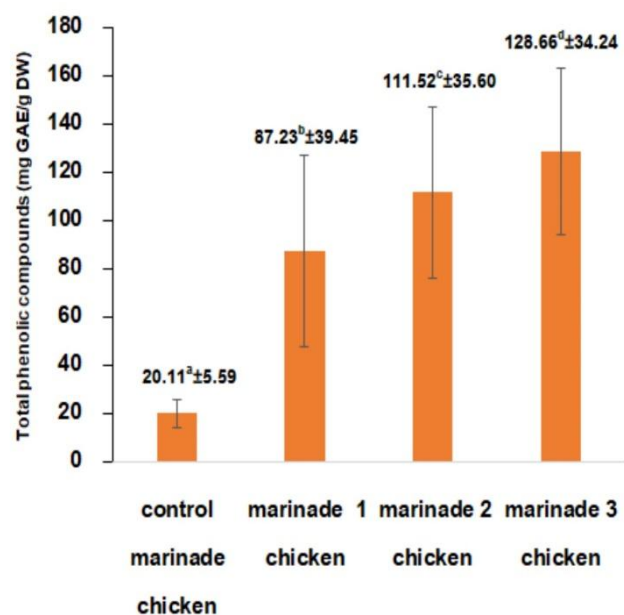
In contrast, the ABTS assay can detect both hydrophilic and lipophilic antioxidants and is generally more responsive to a broader range of phenolic compounds, including those retained in cooked meat. Thus, the increasing trend in ABTS values among marinated samples more accurately reflects the retention of antioxidant capacity post-marination and grilling.

These findings correspond with previous studies such as Mellado-García *et al.* (2015) and Park *et al.* (2017), who found ABTS assays to be more sensitive in detecting phenolic-based antioxidant activity in thermally treated meats.



a-c Mean values in column with different superscripts are significantly different by LSD test at $p < 0.05$

Figure 4 The total phenolic compound of marinade.



a-d Mean values in column with different superscripts are significantly different by LSD test at $p < 0.05$

Figure 5 The total phenolic compound of marinated chicken breast.

Total phenolic content in the marinated chicken breast samples also increased with garlic concentration, supporting the observed antioxidant activity trends. Marinated samples with higher garlic concentrations (marinades 2 and 3) showed significantly greater phenolic content than the control.

The DPPH and ABTS inhibition values observed in this study were relatively low compared to previous findings,

possibly due to the grilling method and duration. Studies such as Lu *et al.* (2018) and Min *et al.* (2018) demonstrated that longer cooking times or more intense heat can degrade antioxidant compounds, lowering measured radical-scavenging activity. In this study, chicken breast samples were grilled for

10 minutes, which was selected to reflect common household cooking practices while minimizing overcooking and sample drying. Extending the grilling time beyond 10 minutes may have resulted in further degradation of antioxidant compounds, leading to even lower DPPH and ABTS values.

Table 1 Characteristic ions and molecular weight for 16 PAHs.

PAHs	Molecular weight	Linear equation
Naphthalene	128.18	$Y = 4.7211 \times 10^5(X) - 7.1305 \times 10^3$
Acenaphthylene	152.20	$Y = 4.3000 \times 10^5(X) - 1.6520 \times 10^4$
Acenaphthene	154.20	$Y = 2.5950 \times 10^5(X) - 4.0760 \times 10^3$
Fluorene	166.23	$Y = 3.1920 \times 10^5(X) - 1.0390 \times 10^4$
Phenanthrene	178.24	$Y = 5.2400 \times 10^5(X) - 1.4540 \times 10^4$
Anthracene	178.24	$Y = 5.2510 \times 10^5(X) - 1.6980 \times 10^4$
Fluoranthene	202.26	$Y = 5.0470 \times 10^5(X) - 1.2670 \times 10^4$
Pyrene	202.26	$Y = 5.5570 \times 10^5(X) - 1.6800 \times 10^4$
Benzo[a]anthracene	228.30	$Y = 4.2980 \times 10^5(X) - 1.2520 \times 10^4$
Chrysene	228.30	$Y = 4.2900 \times 10^5(X) - 1.2590 \times 10^4$
Benzo[b]fluoranthene	252.32	$Y = 5.4470 \times 10^5(X) - 2.2810 \times 10^4$
Benzo[k]fluoranthene	252.32	$Y = 5.4470 \times 10^5(X) - 2.2810 \times 10^4$
Benzo[a]pyrene	252.32	$Y = 4.2110 \times 10^5(X) - 1.8400 \times 10^4$
Benzo[g,h,i]perylene	276.34	$Y = 3.4150 \times 10^5(X) - 1.6680 \times 10^4$
Dibenzo[a,h]anthracene	278.35	$Y = 3.0960 \times 10^5(X) - 1.8380 \times 10^4$
Indeno[1,2,3-c,d]pyrene	276.34	$Y = 3.2440 \times 10^5(X) - 1.8800 \times 10^4$

Y= abundance, X= concentration (ppm)

Table 2 Retention index, retention time, primary and secondary ions of 16 PAHs.

PAHs	Retention index	Retention time (min)	Primary ion	Secondary ion
Naphthalene	1211	5.28	128	129, 127, 51
Acenaphthylene	1370	6.85	152	153, 151, 76
Acenaphthene	1395	7.02	153	154, 152, 76
Fluorene	1450	7.53	166	165, 167, 82
Phenanthrene	1620	8.49	178	176, 179, 76
Anthracene	1630	8.54	178	179, 176, 177
Fluoranthene	1880	9.68	202	203, 200, 201
Pyrene	2150	9.88	202	203, 200, 201
Benzo[a]anthracene	2200	11.11	228	226, 229, 114
Chrysene	2210	11.11	228	226, 229, 114
Benzo[b]fluoranthene	2520	12.05	252	253, 250, 126
Benzo[k]fluoranthene	2530	12.06	252	253, 250, 126
Benzo[a]pyrene	2550	12.44	252	253, 250, 126
Indeno[1,2,3-c,d]pyrene	2790	13.82	276	277, 274, 138
Dibenzo[a,h]anthracene	2800	13.86	278	279, 276, 139
Benzo[g,h,i]perylene	2810	14.20	276	277, 138, 137

3.2 Effect of garlic in marinade on non-specific markers of the maillard reaction in marinated chicken breast

Marination is a widely employed technique in poultry preparation, aimed at enhancing flavor, tenderness, and moisture retention in the final product (Alvarado and McKee, 2007). The composition of the marinade can significantly influence chemical reactions during cooking, particularly the Maillard reaction. While reducing sugars in marinades are known to promote Maillard reaction products, certain spices and acidic ingredients such as onion, lemon juice, and garlic

have been reported to inhibit Maillard reaction products formation (Gibis, 2007).

This study investigated the effect of garlic concentrations in marinades on non-specific markers of the Maillard reaction in grilled chicken breast. Four marinade formulations were examined: a control (no garlic), and three garlic-containing marinades with 8%, 15%, and 26% garlic, respectively. Evaluations included instrumental color analysis and UV–Vis spectrophotometric absorbance at key wavelengths indicative of Maillard reaction progression.

Table 3 Appearance and non-specific indicators of Maillard reaction development in different marinade grilled chicken breast.

Sample	Appearance	Color		
		L* value ^{ns}	a* value ^{ns}	b* value
Control marinated (0% garlic) chicken breast		71.94 ± 1.59	4.81 ± 0.73	21.69 ± 0.54 ^a
Marinated 1 (8% garlic) chicken breast		72.34 ± 1.09	4.49 ± 1.67	22.01 ± 0.73 ^a
Marinated 2 (15% garlic) chicken breast		72.14 ± 1.34	4.55 ± 0.53	21.81 ± 1.27 ^a
Marinated 3 (26% garlic) chicken breast		72.29 ± 1.17	4.26 ± 1.26	19.73 ± 0.49 ^b

Color parameters (L*, a*, and b*) of grilled chicken breast samples were evaluated to assess visual changes associated with the formation of Maillard reaction products. No statistically significant differences ($p \geq 0.05$) were observed in L* (lightness) and a* (redness) values among the different treatments, with L* ranging from 71.94 to 72.34 and a* from 4.26 to 4.81. However, significant differences ($p < 0.05$) were detected in the b* (yellowness) parameter. Specifically, the sample marinated with 26% garlic (marinated 3) exhibited a lower b* value (19.73) compared to the control (0% garlic), 8% garlic (marinated 1), and 15% garlic (marinated 2) samples, which did not differ significantly from each other. These findings suggest that while garlic concentration did not affect lightness or redness, higher garlic levels influenced the yellowness of the grilled chicken breast. Color measurements were performed using a chromameter, with readings taken at three different positions across each chicken breast sample surface to account for non-uniform color distribution. The values were then averaged to provide a more representative color profile. This approach aligns with standard colorimetric practices for

heterogeneous food matrices (Andrade *et al.*, 2010). Sample pH values ranged from 5.89 to 6.03 across all treatments.

To monitor Maillard reaction development, absorbance was measured at 280 nm (early-stage compounds), 360 nm (intermediate products), and 420 nm (melanoidins). Absorbance at 420 nm ranged from 0.16 to 0.48, indicating mild browning in all samples. The b* values further supported these findings, reflecting a yellow hue characteristic of Maillard reaction progression (Andrade *et al.*, 2010).

These results suggest that increasing garlic concentration in the marinade did not significantly alter the color or absorbance properties related to non-specific markers of the Maillard reaction in grilled chicken breast.

3.3 Effect of garlic in marinade on polycyclic aromatic hydrocarbons (PAHs) in marinated chicken breast

Grilled chicken breast samples marinated with four different formulations were analyzed for the presence of 16 priority polycyclic aromatic hydrocarbons (PAHs). According to EU Regulation No. 835/2011, which applies to smoked and heat-treated meat products including those subjected to grilling and

barbecuing benzo[a]pyrene serves as a marker compound for PAH contamination. The regulation stipulates a maximum permissible level of 0.005 µg/g wet weight for benzo[a]pyrene, and a combined maximum of 0.03 µg/g wet weight for benzo[a]pyrene, chrysene, benzo[a]anthracene, and benzo[b]fluoranthene.

Among the grilled chicken breast samples marinated for 12 hours, phenanthrene was detected in the control sample at a concentration of 0.04 µg/g. Phenanthrene is a low-molecular-weight PAH composed of three fused benzene rings and is classified by the International Agency for Research on Cancer (IARC) (International Agency for Research on Cancer, 1993) as group 3, meaning it is not classifiable as to its carcinogenicity to humans.

In the sample marinated with Marinade 3 (containing 26% garlic), benzo[b]fluoranthene was detected at a concentration of 0.006 µg/g. This compound is classified by IARC as group 2B, indicating it is possibly carcinogenic to humans. However, the detected level did not exceed the safety thresholds established by EU Regulation No. 835/2011.

In the present study, increasing concentrations of garlic in the marinade did not result in statistically significant differences in Maillard reaction product formation or polycyclic aromatic hydrocarbon (PAH) levels in grilled chicken breast. Nevertheless, a clear increase in radical-scavenging activity was observed with higher garlic content, indicating an enhancement of antioxidant potential. This suggests that, although Maillard browning and PAH formation remained largely unaffected under the given cooking conditions, the antioxidative components in garlic may still contribute to mitigating oxidative and pyrolytic processes at the molecular level. Recent studies have also demonstrated the antioxidant-rich composition of garlic and its bioactive compounds such as allicin, S-allyl cysteine, and diallyl disulfide capable of modulating oxidative stress and reactive species in thermally processed foods (Batiha *et al.*, 2020; Hossen *et al.*, 2020).

A plausible explanation for the consistently low PAH levels observed across all treatment groups lies in the grilling method employed using a flat hot plate as the heat source. This method likely did not reach the high surface temperatures or direct flame exposure typically necessary to initiate extensive PAH formation. Modern studies support that PAH levels are markedly higher in food subjected to open flame grilling compared to controlled electric or flat-plate systems (Ramos *et al.*, 2019; Malarut and Oonsivilai, 2022). According to Alomirah *et al.* (2011), the occurrence and concentration of PAHs in grilled foods are strongly influenced by parameters such as heat intensity, duration, and cooking method. Similarly, Prathomtong *et al.* (2016) demonstrated that higher-molecular-weight PAHs were predominantly formed at grilling temperatures of 400°C compared to 250°C, underscoring the critical role of temperature. More recently, Alshahrani *et al.*

(2021) observed that flame orientation and grilling method significantly affect PAH distribution in meats, confirming that charcoal grilling and high temperatures pose greater risk. Farhadian *et al.* (2010) also reported that vertical gas flame grilling leads to reduced PAH content, likely due to lower fat-to-flame interaction.

Another contributing factor to the low PAH levels in this study is the inherent leanness of chicken breast. Unlike fattier cuts, chicken breast releases minimal lipid during cooking, reducing the likelihood of fat dripping onto heating elements and undergoing pyrolysis a primary PAH formation route. Recent work by Santonicola *et al.* (2021) confirms that fat content plays a decisive role in PAH generation, particularly when pyrolytic conditions are met. In high-fat meats, drippings combust upon contact with high heat or flames, producing free radicals and PAH intermediates. Therefore, the combination of low-fat meat and moderate cooking conditions likely contributed to the minimal PAH formation observed here.

The biochemical mechanism of PAH formation involves pyrolysis of organic material especially lipids and proteins under high heat, which leads to the release of free radicals. These radicals recombine to form thermally stable, multi-ring aromatic structures characteristic of PAHs (Zelinkova and Wenzl, 2015). As this process is radical-mediated, antioxidant compounds present in the marinade especially those found in garlic may act as chain-breaking inhibitors. Garlic is particularly rich in sulfur-containing compounds such as allicin and S-allyl mercaptocysteine, which are known to exhibit strong radical scavenging, metal-chelating, and antioxidant defense properties (Banerjee *et al.*, 2022). These molecules may suppress radical propagation pathways that contribute to PAH synthesis during grilling, even under thermally intense conditions.

Although this study did not observe significant reductions in PAH levels or Maillard reaction markers with increasing garlic concentration, the enhancement of antioxidant capacity in the marinades suggests a latent protective effect. This may become more pronounced under conditions that more strongly favor PAH formation, such as grilling fatty meats over charcoal or prolonged high-heat exposure. Future studies should investigate garlic's efficacy under such conditions, as well as explore synergistic effects with other antioxidant-rich ingredients in functional marinades (Shahraki *et al.*, 2024). Overall, the findings highlight garlic's potential not only as a flavoring agent but also as a functional additive for mitigating heat-induced toxicants in meat products.

4. Conclusion

This study evaluated the influence of garlic-containing marinades on Maillard reaction products and polycyclic aromatic hydrocarbon (PAH) formation in grilled chicken breast. PAHs were generally undetected across all samples,

with the exception of trace amounts of phenanthrene in the control and benzo[b]fluoranthene in the 26% garlic marinade. All detected levels were within the safety limits established by EU Regulation No 835/2011. Garlic concentration did not significantly influence Maillard reaction indicators or PAH levels under the tested grilling conditions. However, antioxidant activity, as measured by DPPH, ABTS, and total phenolic content, increased with higher garlic concentrations, suggesting a potential inhibitory effect on PAH formation. These findings support the use of garlic marinades to enhance the antioxidant properties of grilled chicken. Further studies are recommended to include sensory evaluations, as high garlic concentrations may negatively affect consumer acceptance.

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Research Article

Integrated Analysis of Climatic, Topographic and Geospatial Factors Affecting Durian Yield in Chanthaburi Province, Thailand

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ABSTRACT

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Durian (*Durio zibethinus*) cultivation in Chanthaburi Province plays a pivotal role in Thailand's fruit economy, yet it faces increasing vulnerability due to climate variability and topographic constraints. This study aimed to investigate the relationships between climatic factors and durian yield through an integrated analytical framework incorporating statistical analysis, time-series forecasting, and geospatial techniques. Climatic variables including temperature, rainfall, humidity, and solar radiation were collected from meteorological stations across the province from 2014 to 2024. Agricultural data were retrieved from the Office of Agricultural Economics, including cultivated area and total yield per district. Pearson correlation and multiple linear regression analyses were employed to quantify the influence of climatic parameters on yield. Results indicated that minimum and maximum temperatures, rainfall, and perennial area were significant predictors. The regression model achieved high explanatory power ($R^2 = 0.935$), while NDVI-based spatial analysis from Sentinel-2 imagery revealed a strong negative correlation ($r = -0.920$) between vegetation health and cultivated area and a weak positive correlation with yield ($r = 0.263$), suggesting ecological limitations to expansion under climate stress. Forecasting results for the period 2025–2030 indicated a gradual decline in durian yield, despite the continued expansion of cultivated areas. These findings underscore the complex interplay between climatic variability and spatial cultivation patterns in determining durian productivity. Furthermore, the results highlight the effectiveness of integrating statistical modeling and geospatial analysis as a robust framework for monitoring, evaluating, and supporting data-driven decision-making in agricultural systems.

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1. Introduction

Climate change has become a critical issue affecting the growth and productivity of crops, both directly and indirectly. At the global scale, climate variability has been widely recognized as a key driver of fluctuations in crop yields, particularly through changes in temperature regimes, rainfall patterns, and the increasing frequency of extreme weather events. The increasing frequency and intensity of climatic events have led to the displacement of agricultural areas and disruption of production systems. These impacts are especially significant in perennial

crop systems, where climatic stress can influence not only current yield but also long-term physiological processes such as flowering, fruit set, and subsequent production cycles. According to Ratree (2018), these changes have become major concerns driving national development, especially in alignment with the United Nations Sustainable Development Goal 13, which addresses climate action (Pakeechay *et al.*, 2020). Thailand's Twelfth National Economic and Social Development Plan emphasizes the need for national resilience to climate change, including natural resource management and disaster preparedness (Wangsaawang, 2020). In this context,

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understanding the interactions between climate variability and crop productivity is essential for developing climate-resilient agricultural systems, particularly in high-value perennial crops such as durian. Chanthaburi Province is a key durian-producing region in Thailand, contributing significantly to the national fruit economy. According to the Office of Agricultural Economics (OAE), the productive area increased from 273,648 rai in 2023 to 286,895 rai in 2024 ($\approx 5\%$), whereas total yield declined from 542,115 to 448,692 tons ($\approx -17\%$). This divergence indicates that productivity is increasingly constrained by environmental and climatic factors rather than land expansion alone. In 2025, total production increased to 575,611 tons (+28.3% relative to 2024), reflecting substantial interannual variability. This pattern underscores the influence of climatic variability on durian productivity. However, due to the limited availability of official statistics on cultivated area for 2025, the analysis primarily relies on the most recent complete dataset for 2014-2024.

Environmental factors, particularly rainfall, significantly affect durian production. Heavy rainfall during the flowering or fruit development stages can lead to premature leaf flushes and nutrient competition, resulting in poor fruit quality and yield losses (Pokaekat, 2013). Vorakuldamrongchai *et al.* (2015) noted that shifts in average maximum/minimum temperatures, relative humidity, and rainfall patterns can disrupt flowering cycles and fruit maturation. Consequently, durian trees often flower in multiple batches, increasing labor and input costs. To address this, researchers have applied climatic data and forecasting models to predict crop yield under specific regional and temporal contexts. Notable applications include modeling yield for wheat (Anwar *et al.*, 2007; Özdoğan, 2011) and rice (Masutomi *et al.*, 2009; Babel *et al.*, 2011), which support better planning and adaptation.

Therefore, this study aims to analyze the influence of climatic and topographic factors on durian yield in Chanthaburi Province using an integrated framework that combines statistical modeling, time-series forecasting, and NDVI-based geospatial analysis, in the context of increasing climate variability and extreme climatic events, thereby supporting the application of meteorological and GIS-based data for sustainable agricultural development in Thailand.

2. Materials and Methods

2.1 Data collection

This study focuses on the climate-related factors influencing durian yield in Chanthaburi Province. The climate variables analyzed include atmospheric pressure, rainfall, soil temperature at depths of 10 and 50 centimeters, relative humidity, average temperature, minimum temperature, maximum temperature, sunlight duration, and pan evaporation. The data span 2014 to 2024 and were obtained from the Thai Meteorological Department through two meteorological stations

located in Chanthaburi Province. Monthly climatic data were aggregated into annual values to ensure consistency with agricultural production data. Durian cultivation data, including standing area, productive area, total yield, and yield per productive area, were collected from the Office of Agricultural Economics Region 6. The dataset covers all districts in Chanthaburi Province for the same 10-year period. All datasets were processed and harmonized to ensure temporal alignment and data consistency prior to statistical analysis.

2.2 Statistical analysis

Descriptive statistics, including mean, median, variance, and range, were used to provide an overview and highlight variations across climatic variables and durian production metrics. Correlation analysis was applied to identify the linear relationship between climate variables and durian yield (Cohen *et al.*, 2003). Pearson's correlation coefficient (r) was used, ranging from -1 to +1. As Equation (1).

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \cdot \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (1)$$

Where r represents the correlation coefficient; X_i and Y_i are values of variables X and Y ; $\bar{X}$ and $\bar{Y}$ are the means of X and Y ; and n is the number of observations. The significance of correlation coefficients was tested using a t-test as Equation (2).

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (2)$$

Where r is the Pearson correlation coefficient and n is the number of observations. A p-value < 0.05 indicates a statistically significant correlation at the 95% confidence level (Kutner *et al.*, 2004).

Multiple regression analysis was performed to assess the combined influence of independent climatic variables on durian yield (Draper and Smith, 1998; Cohen *et al.* 2003; Montgomery *et al.*, 2012). The general form of the linear regression as Equation (3).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \varepsilon \quad (3)$$

In this model, Y represents durian yield, X_1 to X_n are climate variables, and ε is the error term. The regression was estimated using the least squares method to minimize the residual sum of squares as Equation (4) (Asmussen and Foss, 2022).

$$Z(k_0, k_1, \dots, k_i) = \sum_{x=1}^j (A_x - k_0 - k_1 a_{x1} - \dots - k_j a_{xi}) \quad (4)$$

Prior to model interpretation, statistical assumptions were evaluated to ensure model validity. Normality was assessed using the Shapiro-Wilk test and graphical inspection of

residuals, while homoscedasticity was examined using residual plots. Multicollinearity among independent variables was evaluated using variance inflation factors (VIF), with values less than 5 considered acceptable.

2.3 Forecasting model

In addition to regression, time-series forecasting was applied using ARIMA (Autoregressive Integrated Moving Average) models (Box *et al.*, 2015; Hyndman and Athanasopoulos, 2018). The general ARIMA as Equation (5).

$$Y_t = c + \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \dots + \phi_p Y_{t-p} + \theta_1 e_{t-1} + \theta_2 e_{t-2} + \dots + \theta_q e_{t-q} + \varepsilon_t \quad (5)$$

Where Y_t is durian yield at time t , ϕ and θ are autoregressive and moving average parameters, and e_t is white noise. Model parameters were determined through autocorrelation and partial autocorrelation functions.

Model identification was performed using autocorrelation function (ACF) and partial autocorrelation function (PACF) plots to determine appropriate orders of autoregressive (p), differencing (d), and moving average (q) components. Model selection was based on comparative evaluation of candidate models using performance criteria, including Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The performance of the forecasting model was evaluated using three commonly adopted statistical metrics. Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2), as shown in Equations (6), (7), and (8) respectively.

$$MAE = \frac{1}{n} \sum_{i=1}^n |Y_i - \hat{Y}_i| \quad (6)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2} \quad (7)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (8)$$

Where Y_i is the observed value, $\hat{Y}_i$ is the predicted value, and $\bar{Y}$ is the mean of observed values. High R^2 and low MAE/RMSE indicate better model fit.

Durian yield and price forecasts for the period 2025-2030 were generated using regression and ARIMA models to provide analytical insights into future production trends under climate variability. ARIMA model selection was based on the Akaike Information Criterion (AIC) and model adequacy was evaluated using residual diagnostics, including the Ljung-Box test for independence. All analyses were conducted using SPSS version 26.

2.4 Spatial analysis

This study employed a geospatial approach to investigate the relationship between vegetation health and durian cultivation under climatic variability in Chanthaburi Province from 2021 to 2024. Normalized Difference Vegetation Index (NDVI) data were derived from Sentinel-2 imagery and processed using QGIS version 3.34 (QGIS Development Team, 2023). NDVI was calculated using the standard formula, as presented in Equation (9).

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (9)$$

Cloud-contaminated pixels were excluded prior to analysis, and annual NDVI composites were generated using the maximum value composite method to minimize atmospheric noise. The processed NDVI data were resampled to a spatial resolution of 10 meters and clipped to the administrative boundaries of the province's ten districts based on official GADM shapefiles. District-level NDVI values were computed using spatial averaging (zonal statistics) rather than visual interpretation to ensure analytical consistency and reproducibility. Simultaneously, statistical data on productive durian cultivation area (rai) and total yield (tons) were obtained from the Office of Agricultural Economics. Yield per unit area was calculated for each year. Pearson correlation analysis was conducted using Microsoft Excel and SPSS version 26 to examine the association between NDVI values and both productive areas and total yield. NDVI was interpreted as a proxy for vegetation condition and not as a direct measure of yield.

3. Results and Discussion

3.1 Geographic scope

Chanthaburi Province, located in eastern Thailand at approximately 12.6110°N and 102.1030°E (Figure 1), is one of the country's major durian-producing regions. The province comprises ten administrative districts: Mueang Chanthaburi, Laem Sing, Na Yai Am, Kaeng Hang Maeo, Soi Dao, Pong Nam Ron, Makham, Khlung, Khao Khitchakut, and Tha Mai. Among these, Mueang Chanthaburi, Khao Khitchakut, and Makham are durian-producing areas. Geographically, the area consists of a mix of coastal lowlands and upland terrain, with elevations ranging from sea level to over 1,000 meters in mountainous zones. This variation in topography influences local microclimatic conditions and water drainage patterns, which are important factors affecting durian growth and yield. The province experiences a tropical monsoon climate with distinct wet (May-October) and dry (November-April) seasons. Annual rainfall ranges from 2,000 to 3,000 mm, and temperatures typically vary between 23°C and 35°C. These climatic and topographic conditions are suitable for durian cultivation but also contribute to variability in production under climate stress.

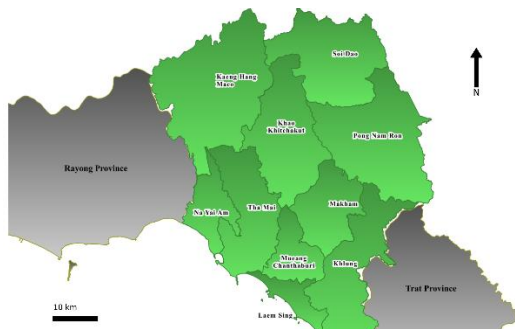


Figure 1 Administrative map of Chanthaburi Province with district boundaries.

Meteorological data were obtained from two weather stations in Chanthaburi Province, covering key variables including rainfall, temperature (minimum, maximum, and average), soil temperature, relative humidity, solar radiation, and evaporation over the period 2013-2024. Durian cultivation data, including productive area and total yield, were collected from the Office of Agricultural Economics Region 6 at the district level.

3.2 Correlation between environmental factors and durian yield in Chanthaburi Province

The Pearson correlation analysis revealed that several environmental factors significantly influenced durian yield in Chanthaburi. As shown in Table 1, rainfall, length of sunlight, pressure, and relative humidity exhibited statistically significant correlations with durian yield. Notably, rainfall and fruitful area showed strong positive correlations ($r = 0.737$, $p < 0.01$), while perennial area showed the strongest correlation ($r = 0.962$, $p < 0.01$). Conversely, relative humidity displayed a weak negative correlation ($r = -0.204$, $p < 0.05$), indicating that excess humidity could impair productivity.

In terms of magnitude, the correlation between perennial area and yield ($r = 0.962$) was substantially stronger than that of rainfall ($r = 0.737$), suggesting that land-use extent remains a dominant factor, whereas climatic variables exert a moderate but significant influence on yield variability. The relatively weak negative correlation with relative humidity ($r = -0.204$) indicates a secondary effect compared to other variables. From a physiological perspective, excessive rainfall and high humidity during critical phenological stages, particularly flowering and early fruit development, can disrupt reproductive processes, leading to poor pollination, increased flower and fruit drop, and heightened disease pressure (e.g., fungal infections). These conditions may also promote vegetative growth at the expense of reproductive development, thereby reducing effective yield.

These findings align with recent studies such as Matamala *et al.* (2023) and Tharaga (2022), who observed that excessive rainfall during fruit development stages negatively impacts fruit quality due to nutrient competition between young leaves and developing fruits. Similarly, Hu *et al.* (2024) emphasize that even minor fluctuations in environmental conditions such as

unexpected temperature shifts or irregular rainfall can have profound effects on crop physiology and yield.

Table 1 The relationship between environmental factors and durian yield in Chanthaburi Province.

Environmental Factors	Pearson Correlation (R)	p-value
Pressure	0.273	0.006**
Rainfall	0.737	0.000**
Soil temperature (10 cm)	-0.111	0.273
Soil temperature (50 cm)	-0.085	0.402
Humidity	-0.204	0.042*
Average temperature	0.037	0.712
Minimum temperature	0.021	0.839
Maximum temperature	0.171	0.090
Length of sunlight	0.309	0.002**
Evaporation	0.014	0.889
Perennial area	0.962	0.000**
Fruitful area	0.737	0.000**

*Significantly different level ($p < 0.05$), **significantly different level ($p < 0.01$)

3.3 Regression model for yield prediction

Multiple regression analysis was employed to predict durian yield based on significant environmental variables. Table 2 shows the model's coefficients and multicollinearity statistics. The predictors perennial area, minimum temperature, and maximum temperature were statistically significant. All VIF values were below 4 and tolerance values above 0.20, indicating no multicollinearity issues. The regression equation for durian yield (Y) prediction is as follows:

$$Y = 9447.182 + 1.420 * (\text{Perennial area}) + 3004.513 * (\text{Min Temp}) - 3033.194 * (\text{Max Temp})$$

Model validation showed strong performance with $R = 0.967$, $R^2 = 0.935$, and Adjusted $R^2 = 0.933$. The Durbin-Watson statistic (1.045) indicates no autocorrelation, and the overall model was statistically significant ($F = 462.492$, $p < 0.001$).

These findings indicate that perennial area and temperature variables are key determinants of durian yield. However, the strong positive relationship between perennial area and yield ($\beta = 1.420$) should be interpreted with caution, as it may primarily reflect the effect of land expansion rather than improvements in productivity per unit area. This suggests that total yield increases may be driven by increased cultivated area rather than enhanced production efficiency. Furthermore, there is a potential risk of spurious correlation, particularly when variables such as cultivated area and yield are inherently related. Without normalization (e.g., yield per rai) or additional controls, the strength of this relationship may be overestimated. Therefore, the regression results should be interpreted as indicative of association rather than direct causation. The negative coefficient of maximum temperature suggests that heat stress adversely affects durian yield, while minimum temperature shows a positive association. Rather than implying that farmers can

“maintain” temperature conditions, these results should be interpreted in terms of site suitability and climate variability, where optimal temperature ranges support flowering and fruit set. This is consistent with Kozai *et al.* (2014) and Zhao *et al.* (2021), who linked heat stress to reduced flowering and fruit set. Vorakuldamrongchai *et al.* (2015) also observed that climate variability disrupts flowering cycles and increases production

risks. The significance of land use is further supported by Deethong and Boonnam (2022), who noted that appropriate orchard spacing improves nutrient uptake and yield. However, expansion into marginal or suboptimal areas may reduce yield efficiency and increase production risks, reinforcing the need to distinguish between area-driven yield increases and true productivity gains.

Table 2 Variance inflation factor (VIF) and regression coefficients.

Factors	B	Std. error	Beta	T-test	p-value	Tolerance	VIF
Constant	9447.182	29039.255					
Perennial area	1.420	0.038	0.972	37.221	0.000	0.988	1.013
Minimum temperature	3004.513	787.464	0.130	3.815	0.000	0.581	1.722
Maximum temperature	-3033.194	1331.907	-0.077	-2.277	0.025	0.582	1.718

A previous model by Chalernngam and Thumcharoen (2018) explained only 30.9% of the variation in yield based on cultivated area. In contrast, the present study demonstrates a higher predictive capability by incorporating climatic variables, providing a more robust forecasting tool for sustainable durian production.

3.4 Forecasting durian yield and economic implications under climate stress

To assess the applicability of the developed model in forecasting future trends, durian yield from 2025 to 2030 was projected using the regression model and smoothed time series trends. As shown in Figure 2, durian yields are projected to fluctuate over the forecast period, with values ranging from approximately 530,000 to 580,000 tons, rather than exhibiting a consistent decline. This variability reflects the influence of climate-related factors and interannual variability, suggesting that yield responses are not linear but dynamically influenced by environmental conditions. Variability in rainfall and temperature has been shown to directly affect flowering and fruit set in durian production systems (Suwanseree and Yapwattanaphun, 2017). While some years show slight decreases, others indicate recovery or stabilization, highlighting the sensitivity of durian production to climatic fluctuations. Such interannual variability is consistent with broader findings that environmental instability can significantly alter crop physiological responses and yield outcomes (Jittamai *et al.*, 2025). Despite the continued expansion of cultivated areas, the projected yield pattern suggests that increases in production are not consistently sustained, which may indicate diminishing returns in certain years. However, this relationship should be interpreted with caution, as fluctuations may arise from both climatic variability and model limitations.

From a socioeconomic perspective, durian prices are anticipated to exhibit a gradual decline, decreasing from approximately 115–120 Baht/kg in 2026 to below 100 Baht/kg by 2030. Price dynamics are influenced by complex interactions

between supply, demand, and external trade conditions, which may amplify variability under changing environmental and economic contexts (Van den Hurk *et al.*, 2023).

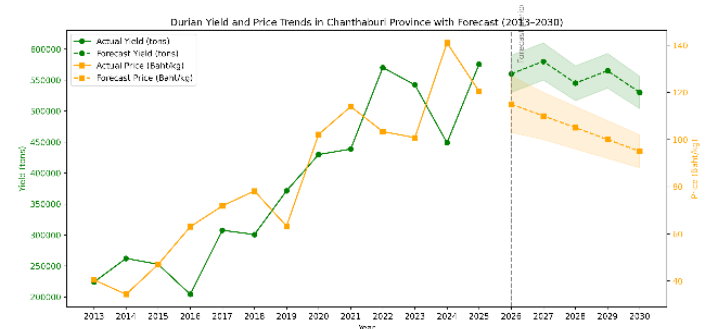


Figure 2 Forecasted durian yields in Chanthaburi Province (2026-2030).

Overall, the results suggest that future yield and price dynamics are characterized by variability rather than monotonic trends. These findings highlight the importance of adaptive management strategies and improved monitoring systems, while acknowledging the inherent uncertainty in model-based forecasts.

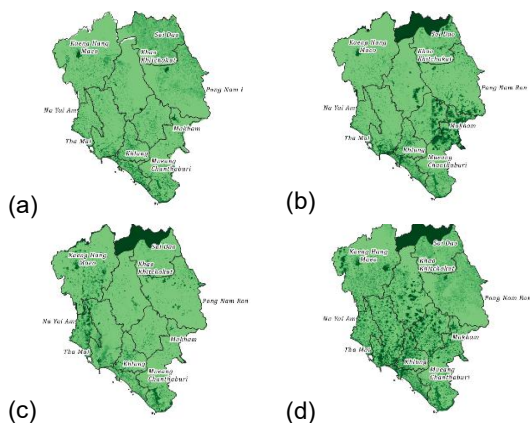
3.5 NDVI-based spatial and economic analysis for 2021–2024

The spatial and temporal analysis of NDVI and durian production data in Chanthaburi Province from 2021 to 2024 revealed significant patterns reflecting the impacts of climatic variability on crop performance. NDVI values, derived from Sentinel-2 imagery during the peak durian growing season (March–June), showed a declining trend from 0.74 in 2021 to 0.60 in 2024, indicating a reduction in overall vegetation health (Table 3). These trends were mapped using choropleth techniques in QGIS and visually interpreted at the district level (Figure 3).

Table 3 NDVI and durian yield metrics in Chanthaburi.

Years	NDVI (Estimate)	Productive area (rai)	Total yields (tons)	Yield per Rai (kg/rai)
2021	0.74	238,034	438,650	1,842
2022	0.72	259,815	570,137	2,194
2023	0.68	273,648	542,115	1,981
2024	0.60	286,895	448,692	1,563

When correlated with agricultural statistics from the Office of Agricultural Economics (OAE), a strong negative correlation ($r = -0.920$) was found between NDVI and productive area, suggesting that increased land use did not result in healthier vegetation and may reflect expansion into marginal or suboptimal areas under ecological stress. Conversely, the relationship between NDVI and total yield was weakly positive ($r = 0.263$), implying that although more land was cultivated, climatic stressors such as prolonged drought, off-season rainfall and intense wind limited the effectiveness of photosynthetic activity and fruit development. It should be noted that NDVI is an indirect proxy of vegetation vigor rather than a direct measure of yield. Therefore, the observed relationships should be interpreted with caution, as NDVI may not fully capture crop productivity, particularly under heterogeneous canopy structures and varying management practices.

**Figure 3** NDVI distribution maps of Chanthaburi Province for the years (a) 2021, (b) 2022, (c) 2023, and (d) 2024.

These observations are consistent with previous studies that demonstrate NDVI's effectiveness as a proxy for vegetation vigor and agricultural yield under environmental stress (Meena *et al.*, 2023). The decreasing NDVI values coincided with reports of physiological disorders in durian trees, including abnormal flowering, immature fruit drop, and increased vulnerability to pests and diseases —factors frequently attributed to erratic climate patterns (Tholkapiyan *et al.*, 2023; Suwanseree and Yapwattanaphun, 2017). In addition, uncertainties associated with remote sensing data should be considered, including potential effects of cloud contamination, atmospheric conditions, sensor resolution, and temporal compositing methods, which may influence NDVI accuracy and spatial interpretation. Beyond

the agronomic implications, economic consequences were also evident. In 2024, durian yield declined sharply in parallel with NDVI deterioration. However, contrary to basic supply-demand expectations, average farm-gate prices also decreased. Field-level surveys and industry interviews indicated that the decline was partly due to a significant reduction in the number of operational durian packing houses (longs), which curtailed buyer competition and weakened price leverage for producers. Consequently, farmers faced both lower output and suppressed pricing, intensifying their financial vulnerability. This pattern aligns with recent findings highlighting that climate-related stress can simultaneously affect crop physiology, product quality, and market dynamics (Jittamai *et al.*, 2025; Eyshi *et al.*, 2023).

Overall, these results underscore the importance of integrated mitigation strategies combining spatial monitoring tools (e.g., NDVI time series), climate-resilient cultivars, improved irrigation management, and strengthened post-harvest and market systems. However, further studies incorporating higher-resolution data and additional biophysical indicators (e.g., NDRE and EVI) are recommended to improve the robustness of remote sensing-based assessments.

4. Conclusion

This study provides an integrated assessment of climatic and topographic influences on durian (*D. zibethinus*) productivity in Chanthaburi Province by combining statistical modeling, time-series forecasting, and NDVI-based geospatial analysis. The results demonstrate that climatic variability, particularly maximum temperature and rainfall patterns, plays a significant role in shaping yield dynamics and production variability. A strong negative correlation between NDVI and productive area ($r = -0.920$) suggests that recent expansion of cultivation may have extended into less suitable areas, while the weak positive relationship between NDVI and yield ($r = 0.263$) indicates that vegetation vigor alone does not necessarily translate into higher productivity under climate-constrained conditions. This study contributes by integrating multi-source data (climate, yield statistics, and satellite-derived NDVI) to provide a comprehensive framework for assessing crop performance under climate variability. It also demonstrates the value of combining statistical and geospatial approaches for understanding yield variability in perennial crop systems. However, several limitations should be acknowledged. The analysis is based on provincial-level data, which may not capture fine-scale variability at the orchard level. In addition, NDVI was used as a proxy for vegetation condition rather than a direct measure of yield, and management practices were not explicitly included in the analysis. These factors may influence the interpretation of the observed relationships.

Overall, the findings suggest that future improvements in durian productivity may depend on better alignment between

environmental suitability and cultivation practices, supported by improved monitoring and data integration approaches.

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Research Article

Effects of Protein- and Carbohydrate-Based Foaming Agents on Foam Stability and Microstructure in Freeze-Dried Coffee

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ABSTRACT

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The development of high-quality instant coffee products is essential for increasing market accessibility and economic value for local coffee producers. This study investigates the effect of various foaming agents including maltodextrin, whey protein isolate, and egg white powder on the foam stability and microstructure of coffee extracts processed via foam-mat freeze drying. Coffee extract prepared from roasted Arabica beans sourced from Plang Yai community in Chiang Mai, Thailand, was combined with ten different formulations of foaming agents ranging from 0 – 10% (w/w) and evaluated through foam stability testing and scanning electron microscopy (SEM). The control group consisted of a sole coffee extract without foaming agents added. The results showed that egg white powder was the most effective foaming agent, yielding stable foams and uniform pore structures, particularly at concentrations above 5%. While maltodextrin and whey protein isolate alone did not produce stable foams, they enhanced structural stability when used in combination with egg white powder. SEM imaging further confirmed that the optimal formulations exhibited well-developed porous networks, crucial for drying efficiency and product rehydration. The highest foam stability (96.1%) was achieved with a balanced formulation of all three agents. These findings confirm the synergistic interaction between proteins and carbohydrates in foam stabilization, offering a robust method for producing premium instant coffee. The integration of this approach enables smallholder enterprises to expand product lines while maintaining quality, enhancing the economic sustainability of coffee farming communities.

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1. Introduction

Thailand's coffee industry has witnessed significant growth in recent years, particularly in the northern highlands, where the climate and elevation provide ideal conditions for Arabica coffee cultivation. Chiang Mai, one of Thailand's most well-known coffee-producing provinces, has a climate and elevation highly suitable for cultivating high-quality Arabica coffee. The province is home to over 8,000 hectares of coffee plantations, with annual production exceeding 6,000 tons (This Side Up, 2025). The majority of coffee farms in Chiang Mai are run by smallholder farmers, many of whom are part of local community enterprises aiming to create sustainable livelihoods through coffee production. The demand for Chiang Mai's specialty coffee has

been growing steadily, both domestically and internationally, with exports increasing by approximately 15% annually (Bangkok Post, 2024). However, despite the high-quality beans produced in the region, Plang Yai community enterprises primarily sell roasted coffee beans, limiting their access to broader consumer markets.

While roasted coffee beans generally provide better aroma and flavor, the preparation requires grinding and brewing before consumption. This might not be suitable to all potential customers. Many consumers, especially those seeking convenience, prefer instant coffee products that are ready to use. Freeze drying, also known as lyophilization, is a dehydration technique that involves freezing a material and then removing its moisture by sublimation under low pressure. This

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method is widely used in food processing due to its ability to preserve the structure, aroma, and nutrients of food products, making it particularly suitable for high-value commodities such as coffee (Bhatta *et al.*, 2020). Compared to traditional drying methods, freeze drying minimizes heat exposure, which helps retain volatile compounds responsible for coffee's flavor and aroma (Rizzi, 2016). Additionally, freeze-dried coffee exhibits improved solubility and shelf life, making it a preferred choice for instant coffee production (Chen and Zhang, 2022).

Despite its benefits, freeze drying has limitations, including high operational costs and long processing times. To improve efficiency, foam-mat drying is often employed as a pre-treatment step. Foam-mat drying involves whipping the liquid coffee extract with a foaming agent to create a stable foam structure, which is then dried at a controlled temperature before undergoing freeze drying (Anandharamakrishnan, 2019). This technique reduces drying time, enhances rehydration properties, and helps maintain the microstructure of coffee particles (Liu and Kim, 2020). The foam structure allows for uniform drying, improving the overall quality of the final product (Kaya and He, 2018).

The stability and effectiveness of the foam-mat drying process largely depend on the choice of foaming agents, which help stabilize air bubbles and prevent foam collapse. Commonly used foaming agents include maltodextrin, whey protein isolate, and egg white powder. Maltodextrin acts as a carrier and stabilizer, reducing the stickiness of coffee powder and improving its solubility (Michael, 2023). Whey protein isolate contributes to foam formation by lowering surface tension, but on its own, it provides limited stability (Waghmare and Kumar, 2024). Egg white powder, on the other hand, is the most effective foaming agent due to its high protein content, which enhances foam stability by forming a strong protein network around air bubbles (Lomakina and Míková, 2006). Studies have shown that formulations containing a combination of these three agents, particularly with a higher proportion of egg white powder, result in the most stable foams, which is crucial for efficient freeze drying (Muthukumaran *et al.*, 2021). Incorporation of the egg albumin (EA) at 4.95% concentration was found to be an optimization level for tomato powder production using foam-mat drying method (Hossain *et al.*, 2024).

By integrating foam-mat drying and selecting appropriate foaming agents, freeze-dried coffee can be produced more efficiently while preserving its key sensory and functional properties. Therefore, this study aims to evaluate the effects of different foaming agent formulations on the stability, microstructure, and overall quality of freeze-dried coffee produced from locally grown beans in Chiang Mai.

2. Materials and Methods

2.1 Coffee extract preparation

The dark roasted coffee beans according to a standard Light-Medium-Dark scale, were received from the "Plang Yai" local community enterprise. The roasted coffee beans were ground to a particle size of 400–600 µm using a burr grinder (Mahlkönig EK43, Germany) to ensure uniform extraction. A ratio of 1:15 (coffee:water, w/v) was used for the extraction process. The ground coffee was brewed using a hot water extraction method at $92 \pm 2^\circ\text{C}$ for 5 minutes. A coffee brewing system (Hario V60, Japan) was used to ensure uniform extraction. The brewed coffee was filtered using a 0.45 µm membrane filter (Millipore, USA) to remove any residual coffee grounds. The filtrate was immediately cooled to 4°C in an ice bath to prevent oxidation and degradation of volatile compounds. The cooled coffee extract was concentrated using a vacuum rotary evaporator (Büchi Rotavapor R-300, Switzerland) at 40°C under reduced pressure (100 mbar) until reaching a final total soluble solids (TSS) content of 20–25% which suitable foam-mat drying method. The TSS was measured using a hand refractometer (R10, ExTech, USA).

2.2 Foam stability of foaming agents

Foam stability was evaluated by measuring the height of the foam over time. After preparing the foam using the optimized formulation by a hand mixer (HR3741, Philips) at medium speed for 10 minutes). The generated foam was immediately transferred into a 50 mL beaker. The initial foam height (H_0) was recorded in millimeters (mm) using a ruler. Foam height was then measured at specific time intervals of 1, 5, 10, 15, and 30 minutes to assess the rate of foam collapse. The experiment was done in triplicate.

Foam stability was determined using the percentage of foam retained over time compared to the initial foam height (H_0). The experiment was carried out in a controlled environment with minimum airflow at temperature $25 \pm 2^\circ\text{C}$. The foam stability percentage at a given time (H_t) was calculated using Equation (1).

$$\text{Foam Stability}(\%) = (H_t/H_0) \times 100 \quad (1)$$

where H_0 = Initial foam height, (mm)

H_t = Foam height at a given time, (mm)

2.3 Freeze drying of coffee extract using foam-mat method

2.3.1 Optimization of foam formation in coffee extract using foaming agents

The experimental set was developed using Response Surface Methodology (RSM), specifically a Constrained D-optimal Mixture Design, to optimize the interaction between the three independent variables: maltodextrin (General Chemical, China) and whey protein isolate (KC, USA) and egg white powder (Lanagrow, Thailand). The independent variables included

varying concentrations of maltodextrin (1.9–9.6%), whey protein isolate (1.9–9.6%), and egg white powder (2.2–10%), resulting in 10 experimental treatments as shown in Table 1. Additionally, four control samples (C1–C4) were prepared, including a blank and individual component references. These concentration ranges were selected based on previous studies on coffee foams, such as Maciel *et al.* (2022), have demonstrated effective foam stability at lower protein concentrations (approx. 1.5–3.0%), guiding our selection of the lower experimental limits. The upper limit of ~10% was established to avoid excessive viscosity and foam density, which have been reported to interfere with moisture removal during freeze-drying and result in poor rehydration properties in similar food matrices (Hamad *et al.*, 2024). The experiment began with weighing the

required amount of egg white powder according to the specified formulation. Distilled water (175 mL) was then added to the egg white powder and mixed using a high-speed hand mixer for 2 minutes to initiate foam formation. After this initial foaming stage, the measured amounts of maltodextrin and whey protein were incorporated into the foamed mixture, followed by an additional 2-minute mixing period to enhance foam stability. Once the foam was sufficiently developed, 30 mL of coffee extract was prepared separately and gently combined with the foamed mixture to ensure uniform dispersion without disrupting the foam structure. The final mixture was then transferred into a transparent storage container and placed in a freezer at a controlled temperature of -18°C to -20°C prior freeze-drying.

Table 1 Different percentages of foaming agents.

Sample No.	Maltodextrin (%)	Whey Isolate (%)	Egg White Powder (%)
C1 (Blank)	0	0	0
C2	6.8	0	0
C3	0	6.8	0
C4	0	0	6.8
1	2	6	10
2	1.9	9.6	9.6
3	6.5	2.2	2.2
4	6	2	10
5	6	6	6
6	5.8	5.8	9.6
7	9.6	1.9	9.6
8	9.6	5.8	5.8
9	9.3	5.6	9.3
10	9.3	9.3	5.6

2.3.2 Freeze drying condition

The freeze-drying process was conducted using a vacuum freeze dryer (Food industry model, Kinetic Engineering Co., Ltd). The sample was initially frozen at -20.0°C for 60 minutes, with a ramp time of 20 minutes under atmospheric pressure (0.0 Pa vacuum). During the primary drying phase, the temperature was gradually increased to -20.0°C over 20 minutes, held for 60 minutes, then raised to -10.0°C over 20 minutes and maintained for 100 minutes, all under a vacuum of 20.0 Pa. In the secondary drying phase, the temperature was increased to +10.0°C over 20 minutes with a 100-minute hold time, then further increased to +40.0°C over 200 minutes, followed by a 1000-minute hold time, under 20.0 Pa vacuum.

Finally, the temperature was maintained at +40.0°C for an additional 1000 minutes under the same vacuum conditions until the final moisture content was less than 5%. The dried coffee sample was then collected and stored in airtight containers at room temperature (25±2 °C) until further analysis

2.4 SEM condition

The surface morphology of the samples was observed using a Scanning Electron Microscope (SEM, ThermoScientific: Prisma E). Imaging was performed at a high voltage (HV) of 10 kV with magnifications of 70× and 200× to examine the structural features of the samples.

2.5 Statistical analysis

The statistical analysis of variance using one-way analysis of variance (ANOVA) was conducted to assess variability. Furthermore, the significant differences in means among individual treatments were evaluated using Tukey's test at a confidence level of 95% ($p < 0.05$). The analysis was performed using Minitab v.21 software (USA), and each experimental condition was replicated three times. The data were presented as the mean values and the standard deviation errors.

3. Results and Discussion

3.1 Percentage of foam stability with various foaming agents

The foam stability results reveal that the presence and composition of foaming agents significantly influence foam retention as shown in Figure 1. The control samples (C1, C2, and C3) without egg white powder exhibited zero foam stability, indicating that maltodextrin and whey isolate alone do not contribute to foam formation. However, C4, which contained 6.8% egg white powder without other stabilizers, achieved a foam stability of 76.8%, demonstrating the critical role of egg white proteins in foam formation.

Among the tested formulations, sample 10 exhibited the highest foam stability at 96.1%, followed closely by sample 9 (94.3%) and sample 7 (92.3%). These samples contained a relatively high proportion of all three foaming agents, with maltodextrin and egg white powder concentrations ranging from 5.6% to 9.6%. This suggests that optimal foam stability is achieved when all three components are present in appropriate proportions, particularly when egg white powder is maintained above 5%.

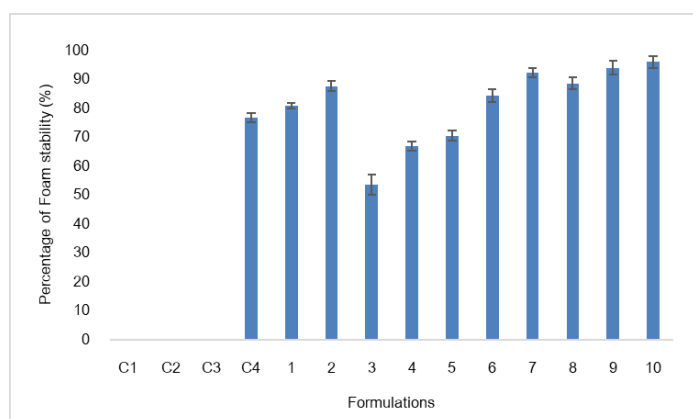


Figure 1 Foam stability (%) of freeze-dried coffee prepared with different proportions of foaming agents.

Moderate stability was observed in samples with lower total foaming agent concentrations, such as sample 5 (70.2%) and sample 4 (67.3%), where maltodextrin and whey isolate were present in smaller amounts alongside egg white powder. Notably, sample 3, which contained a higher proportion of maltodextrin (6.5%) but minimal egg white powder (2.2%), resulted in the lowest stability (54%), indicating that excessive

maltodextrin without sufficient protein-based stabilizers negatively affects foam retention.

Overall, these findings confirm that egg white powder plays a fundamental role in foam formation, while the combination of maltodextrin and whey isolate further enhances stability when used in balanced ratios. The highest foam stability (above 90%) was consistently observed in formulations with all three foaming agents present at relatively high levels, reinforcing the importance of ingredient synergy in optimizing foam retention.

The observed necessity of stabilizers is consistent with findings in similar processing contexts. Maciel *et al.* (2022) demonstrated that the use of stabilizers, particularly whey protein and maltodextrin, was crucial not only for foam integrity but also for improving the overall drying kinetics and the quality characteristics of the final coffee powder.

The findings underscore a critical synergistic effect wherein maltodextrin and whey isolate act as structural and stabilizing agents rather than foaming initiators. The supporting evidence from Ganaie *et al.* (2021) illustrates that whey protein conjugated with maltodextrin via Maillard reactions enhances functional properties like emulsification and solubility-traits beneficial for foam stabilization under processing stress. Similarly, Xiang *et al.* (2021) showed that combining whey protein and maltodextrin through freeze-drying significantly improved the stability of encapsulated probiotics, a phenomenon that parallels the improved foam integrity observed in multi-agent systems.

Moreover, the formulation containing 6.5% maltodextrin with only 2.2% egg white powder resulted in the lowest foam stability (54%), reinforcing the idea that an excessive carbohydrate component without adequate protein undermines the interfacial strength needed to retain air bubbles. This is supported by findings in Poopan *et al.* (2024) study, where maltodextrin beyond 5% did not enhance bioactive retention unless paired with protein-rich compounds, again illustrating its limited effect when used alone. This also supported by a study of Hamad *et al.* (2024), studying the effect of foaming agents in red dragon fruit powder, concluded that the type and ratio of foaming agents directly impact the final powder's physicochemical properties, including bulk density and antioxidant retention. Specifically, they found that higher protein content was essential for creating the low-density foam structure necessary for efficient drying. The poor stability observed in our high-maltodextrin, low-protein sample (6.5% maltodextrin, 2.2% egg white) is therefore consistent with the understanding that foam strength is determined by the protein's ability to create a viscoelastic film around air cells, which carbohydrates can support but not initiate.

The synergistic effect between these components where protein unfolding at interfaces, viscosity increase from carbohydrates, and potential Maillard reaction contributions suggested a multi-level mechanism where protein content

contributed to foam formation, and carbohydrate-protein interactions stabilize the formed structure. In summary, the results affirm that achieving optimal foam stability in food systems relies on both the presence of a strong foaming agent like egg white powder and the complementary structural and functional support provided by whey protein and maltodextrin in appropriate ratios.

3.2 Observation of physical appearance of freeze-dried coffee samples using SEM

SEM analysis revealed that foam morphology was significantly influenced by the relative concentrations of maltodextrin (MD), whey protein isolate (WPI), and egg white powder (EWP) (Figure 2). Among the control samples, C1 (without foaming agents) exhibited a compact, non-porous

structure, serving as a reference for non-aerated material. C2 (MD only) produced a fine but shallow porous structure. While MD contributed to a more viscous medium, its ability to generate or maintain foam structures was limited, consistent with its role as a bulking and film-forming agent rather than a foaming agent (Ratti, 2001). In contrast, C3 (WPI only) showed larger, less uniform pores with some collapse, illustrating that while WPI facilitates foam formation due to its amphiphilic nature, its foams are generally less stable without the presence of a secondary stabilizing agent (Dickinson, 2003). The most stable and uniform foam among the controls was observed in C4 (EWP only), characterized by well-defined, rounded pores. This agrees with prior studies citing EWP's superior surface activity and strong network formation at the air-water interface (Mine, 1995).

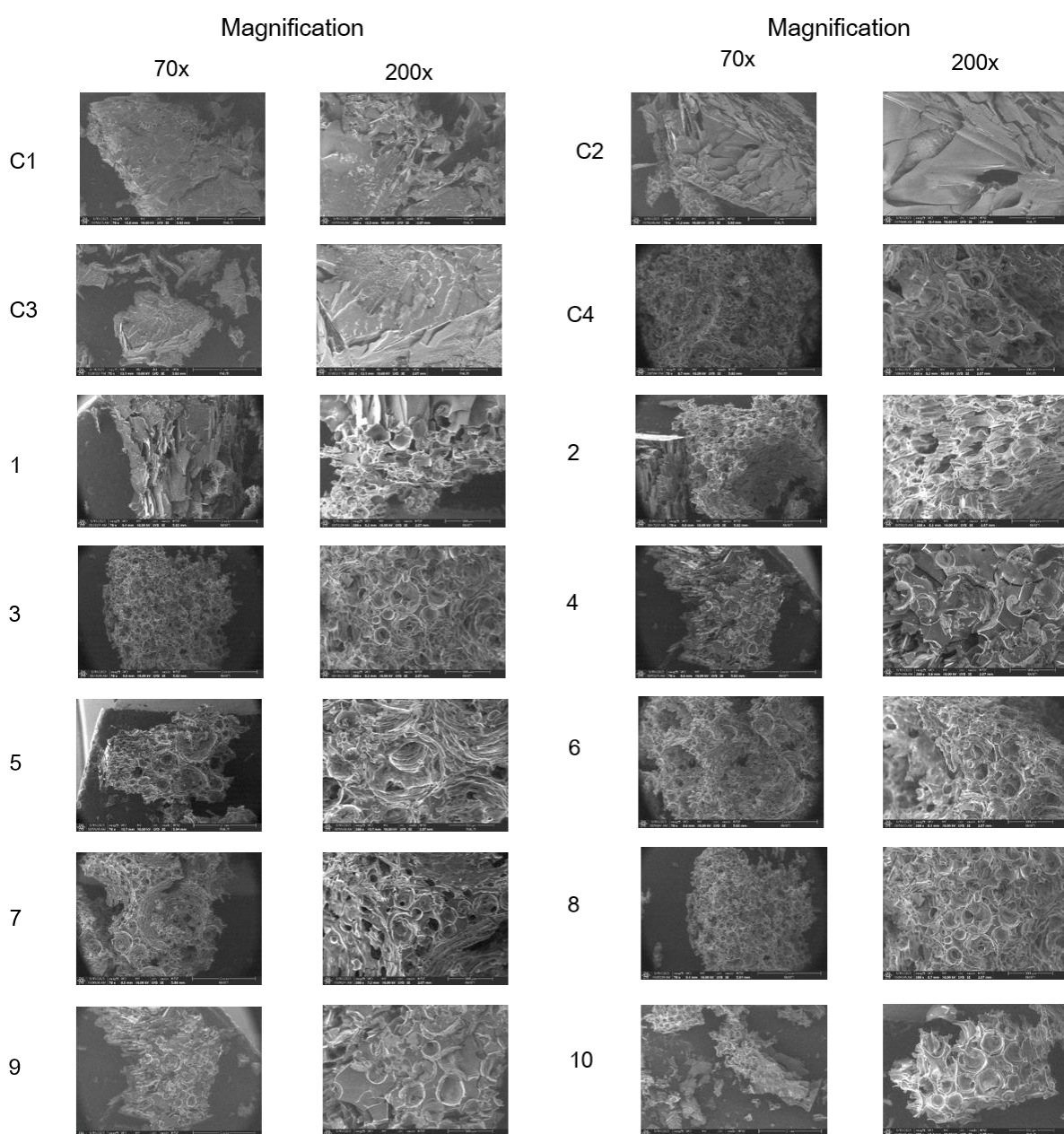


Figure 2 SEM images showing the surface structure and porosity of 14 samples with varying proportions of foaming agents at 70x and 200x magnification.

The experimental formulations presented a range of foam structures, from highly porous and interconnected matrices to dense, minimally foamed textures. Samples with a high proportion of EWP, particularly when combined with moderate amounts of WPI and low to mid-levels of MD, exhibited the most desirable foam properties. Sample 1, which included EWP at its highest ratio with supportive levels of WPI and MD, demonstrated a highly stable and porous foam with well-distributed, spherical pores. This highlights a synergistic interaction where WPI promotes foam expansion and EWP provides stabilization, while MD acts as a rheological modifier without inhibiting structure formation (Campbell and Mougeot, 1999). Similar to Sample 4, where EWP remained dominant despite higher MD content, resulting in well-maintained pore architecture. On the other hand, samples where MD was the dominant component, such as Samples 3, 7, and 8, showed denser structures with reduced porosity or evident pore collapse. This supports the notion that excessive MD impairs foam expansion by excessively increasing the viscosity of the continuous phase, which restricts air incorporation and foam elasticity (Ozcelik and Kulozik, 2023).

Comparative trends also suggest that a balanced mixture of all three agents, such as in Sample 5, produced stable foam structures with moderate pore size and uniformity. This formulation avoided the extremes of either over-stiffening (due to MD) or collapse (due to excessive protein content), offering a structurally coherent foam. Interestingly, when WPI was increased disproportionately, as seen in Sample 2, the structure showed signs of pore deformation and partial collapse, implying that although WPI enhances foam volume, it does not necessarily improve foam stability unless complemented by EWP. Similarly, in high-MD systems where EWP was present in moderate quantities (e.g., Sample 10), the presence of WPI appeared to mitigate structural degradation to a degree, although not as effectively as in EWP-rich formulations. Collectively, the data confirm that EWP plays a dominant role in foam stability and integrity, while WPI contributes to foamability and MD must be carefully regulated to avoid over-thickening the matrix (Raikos *et al.*, 2007).

4. Conclusion

This study demonstrates that the selection and ratio of foaming agents significantly influence foam stability and microstructural integrity in freeze-dried coffee production using the foam-mat method. SEM analysis confirmed that formulations with higher concentrations of egg white powder yielded well-structured, stable foams with uniform pore distribution. Maltodextrin and whey protein isolate contributed to structural integrity and viscosity modulation but were ineffective as standalone foaming agents. The highest foam stability was achieved in samples containing balanced amounts of all three agents, particularly where egg white powder exceeded 5%.

These findings underscore the synergistic role of protein-based foaming agents supported by carbohydrates in forming and stabilizing foam matrices during drying, thereby providing a critical foundation for optimizing the integrated foam-mat and freeze-drying techniques. This optimized approach presents a highly viable method for producing high-quality instant coffee while preserving aroma, solubility, and structure, offering significant benefits to community enterprises like Plang Yai by enabling value-added processing of locally grown coffee.

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Research Article

Effects of Avocado Puree as a Fat Replacer on the Quality Characteristics of Gluten-Free Brownies

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ABSTRACT

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Keywords:

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Avocado is categorized as a superfruit owing to its elevated concentration of monounsaturated fatty acids, which may help reduce LDL cholesterol. It is beneficial both for direct consumption and for use in nutritious food products. The aim of this research was to maximize the replacement of butter with avocado to produce a gluten-free brownie product with a lower lipid content than conventional products. The research studied the effects of three avocado ripeness levels (AR; 50%, 75%, and 100%) and butter-to-avocado puree ratios (Butter/AP; 50:50, 25:75, and 0:100) on the quality of gluten-free brownies, resulting in nine formulations. Sensory evaluation indicated that the formulation prepared with 100% avocado ripeness and a butter-to-avocado puree ratio of 25:75 achieved the highest overall liking score (7.72), classified as "like very much" on a 9-point hedonic scale ($p < 0.05$). The brownie height was 5.25 cm, and its redness value (a^*) was 8.33, yellowness value (b^*) was 8.13, and lightness value (L^*) was 15.18, with a specific volume of 1.49 cm³/g. Compared to the control brownie prepared with 100% butter (17.12 g/100 g) and without avocado puree, the developed brownie showed a 43.79% reduction in fat content and a 16.03% reduction in energy. The results demonstrate that replacing butter with avocado can enhance the nutritional profile of gluten-free brownies, offering benefits for individuals with health concerns and providing a suitable alternative for those with cardiovascular disease, obesity, or gluten intolerance.

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1. Introduction

Recently, the incidence of cardiovascular diseases (CVDs) has surged, posing a significant global public health challenge that affects nearly every country. Cardiovascular disease is one of the leading non-communicable diseases (NCDs) that is associated with various health conditions, including hypertension, stroke, diabetes, dyslipidemia, and obesity (Powell-Wiley *et al.*, 2021; Budreviciute *et al.*, 2020). According to the World Health Organization (WHO), CVDs are the highest number of deaths in NCDs groups, totaling 17.9 million deaths annually, and this number is expected to rise to 22.2 million by 2030 (Şahin and Ilgün, 2022). In Thailand, CVDs result in 70,000 deaths annually, which averages to 8 deaths per hour (Department of Disease Control, 2023). The causes

of CVDs are closely related to the consumption of foods high in sugar and fats, particularly saturated fats (Jessri *et al.*, 2023; Valk *et al.*, 2022). These fats tend to elevate low-density lipoprotein (LDL) cholesterol levels, which are commonly found in products with high butter or margarine content (Guggisberg *et al.*, 2022; Zhang *et al.*, 2021), especially in bakery products. Globally, all age groups widely consume brownies among the diverse range of bakery products (Mulyati *et al.*, 2019). However, these products usually have high amounts of saturated fat from butter and wheat flour, making them potentially inappropriate for people susceptible to cardiovascular diseases (CVDs) or individuals with gluten sensitivity. In 100 grams of brownies, the primary components are butter, sugar, flour, chocolate, and eggs, yielding 575

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kilocalories, 7.44 grams of protein, 56.18 grams of carbohydrates, and 35.61 grams of fat, with 63.82% of the fat being saturated fatty acids (SFA) (Martínez *et al.*, 2025). This high concentration of SFA primarily originates from butter. Due to the high fat content in brownies, numerous researchers have attempted to create recipes that are more nutritionally beneficial.

The primary objective is to substitute the two major components: flour and fat. Diverse flours have been utilized as substitutes for wheat flour, which contains the allergic gluten protein responsible for Celiac Disease (Cabanillas, 2020; Strońska *et al.*, 2021). Presently, gluten-free brownie goods have been produced by substituting wheat flour with other flours, including black rice (Sumonsiri *et al.*, 2022), kidney beans (Yadav *et al.*, 2021), orange sweet potato (Selvakumaran *et al.*, 2019), and sweet potato (Dameswary *et al.*, 2023). The second step is to decrease the fat content of butter in the recipe or replace it with vegetable oil. A study investigated the effect of replacing margarine with rice bran oil organogel emulsions in chocolate brownies (Manakla *et al.*, 2020) and replacing butter with cold-pressed nut oils (pistachio, walnut, and almond) in brownies (Martínez *et al.*, 2025). Moreover, flaxseed and okra gum have been used as fat replacements in the production of cakes (El-Sayed *et al.*, 2014). In addition to vegetable oils, there are initiatives to use avocados, regarded as a high-unsaturated-fat fruit and part of the superfood group (Ohlau *et al.*, 2023; Arumugam *et al.*, 2021), to replace fats or oils in baked items. This is due to its texture, which resembles butter or cream, and its high unsaturated fatty acid content (Hu, 2021; Rizkiyah *et al.*, 2022). Avocados contain 71% monounsaturated fatty acids (MUFA), 13% polyunsaturated fatty acids (PUFA), and 16% saturated fatty acids (SFA) (Flores *et al.*, 2019; USDA, 2011), which can improve good cholesterol (HDL-Cholesterol) and reduce bad cholesterol (LDL-Cholesterol) (Faizah *et al.*, 2024). This minimizes the accumulation of blood lipids and reduces the risk of stroke, heart disease, and atherosclerosis (Okobi *et al.*, 2023). Previously, researchers have used avocado flesh instead of butter, margarine, or shortening, which contain a large amount of trans fats in baked products. For example, avocado can replace 50% of the trans fats in cake cream (Phungbunhan *et al.*, 2021), 35% in oatmeal cookies (Wekwete and Navder, 2008), and up to 32.5% in muffins (Baniya, 2022). However, replacing avocados with more fat in many baked goods will result in lower general acceptance due to the limited bitter taste. When avocado is heated, it will taste bitter and darken due to the browning reaction that occurs during thermal treatment (Degenhardt and Hofmann, 2010; Eteng *et al.*, 2020; Eteng *et al.*, 2020).

Therefore, to reduce these limitations, the researchers have the idea of using avocado to replace butter in brownies, which contain chocolate with acceptable bitterness for

consumers. It is expected that avocado can be substituted in higher proportions than other products. This aligns with the development of chocolate custard filling products that can use avocado to replace fat entirely (Dholvitayakhun *et al.*, 2025). Additionally, the use of domestically produced red jasmine rice flour as a substitute for wheat flour enhances nutritional value and offers an option for gluten-intolerant consumers in gluten-free brownie products, while also promoting the expansion of the avocado food product market.

2. Materials and Methods

Main materials used in this research for the preparation of gluten-free brownies (GFB) were avocado (PP08 varieties, sourced from Phop Phra District, Tak Province, Thailand), harvested during the 2023 growing season, and other food-grade ingredients (Moonfarms® red jasmine rice flour (Thailand), Super Find® corn starch (Thailand), eggs, granulated sugar, dark chocolate, butter, xanthan gum, baking powder, and salt) were purchased from the local market (Tak, Thailand).

2.1 Preparation of avocado puree

Thai avocados (PP08 varieties) were matured in a room at ambient temperatures ($28 \pm 2^\circ\text{C}$) before use, and there were three ripeness levels for the experiment: starting with 50% ripeness (5 days of ripening) because if the ripeness exceeds this, the texture will not be smooth when blended. The skin will have a greenish-purple color, and the flesh will be yellowish-green, soft, and bland. The 75% ripeness level (7 days of ripening) will have a purple skin, yellow flesh, very soft texture, and bland taste. The 100% ripeness level (9 days of ripening) exhibited a dark skin, brownish flesh, mushy texture, and a bland taste, as shown in Table 1. All avocados were washed with water and cut into two parts with a kitchen knife. Then, the flesh was taken and cut into big chunks. Next, the avocado flesh was mashed using a domestic blender to obtain avocado puree and kept in polyethylene bags at -20°C until use.

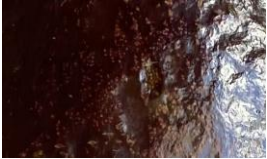
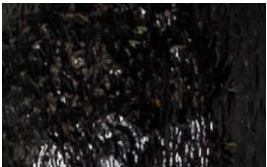
2.2 Preparation of gluten-free brownies

The procedure for preparing gluten-free brownies (GFB) using red jasmine rice flour was based on Mahasaengsawan (2018), with modifications to the formulation involving three avocado ripeness levels (AR: 50%, 75%, and 100%) and three butter-to-avocado puree ratios (Butter/AP: 50:50, 25:75, and 0:100), resulting in nine GFB treatments. All ingredients were prepared and weighed according to the formulation shown in Table 2. All formulations except avocado and butter were the same amount for each ratio. Red jasmine rice flour, xanthan gum, and salt were sieved during preparation to prevent lumps when they were added into the batter. Next, eggs, vanilla extract, and white granulated sugar were mixed in a bowl using a hand mixer at a slow speed for two minutes until the sugar melted. Then, add the melted butter or avocado and

chocolate to the beaten egg mixture. In the mixing bowl, slowly add the mixed red jasmine rice flour after combining them together and mixing to combine. Lastly, bake at 180°C for 40

minutes. When finished, the GFB were then cooled and wrapped in food-grade zip-lock polyethylene plastic bags prior to further analysis.

Table 1 Visual appearance and descriptive characteristics of avocado fruit and puree at different ripeness levels (0%, 25%, 50%, 75%, and 100%) used in this study.

Day	ripeness level (%)	External appearance	Internal appearance	Description
1	0			Dark green peel; firm texture with a bitter and astringent taste; light green flesh.
3	25			Dark green peel; firm texture with a bitter and astringent taste; greenish-yellow flesh.
5	50			Greenish-purple peel; soft texture with a mild, fatty taste; yellowish flesh.
7	75			Purple peel; softer texture than day 5 with a mild, fatty taste; yellow flesh.
9	100			Dark black peel; very soft to mushy texture with a mild, fatty taste; brownish flesh.

Note: All photographs presented in this table were taken by the authors.

2.3 Color determination

The color of the brownies was measured using a chromaticity instrument (Hunter, MiniScan EZ 4500L Spectrophotometer, USA) under illuminant D65 with a 10° standard observer. The color values were measured using a CIE L^* a^* b^* scale in 4 random zones of 4 different baked brownies (3 × 3 × 3 cm) that were randomly selected, and the means were recorded as L^* (whiteness/darkness), a^* (redness/greenness), and b^* (yellowness/blueness).

2.4 Determination of the specific volume and height of brownies

The specific volumes (cm³/g) of brownies were measured by using the seeds displacement method (American Association of Cereal Chemists (AACC), 2000). Heights of the brownies were measured using a vernier caliper (Mitutoyo Corp., Japan). Height was measured from the highest point of the brownie to the bottom, and the photos were taken by

placing the cakes on a flat surface and placing a ruler vertically on each cake to show the height in centimeters.

2.5 Sensory evaluation

This study was approved by the Human Research Ethics Committee of [Rajamangala University of Technology Lanna], Thailand (Approval No. RMUTL-IRB 049/2021). All panelists participated voluntarily and provided informed consent prior to sensory evaluation. A hedonic test was used to determine the degree of overall liking for brownies by using the BIB unbalanced block design ($t = 9$, $k = 4$, $r = 8$, $b = 18$, $\lambda = 3$) in four replication, randomized trials. Seventy-two untrained panelists were given four random samples (2 cm x 2 cm) from nine treatments of brownies that had been held at room temperature for 24 hours. Each sample was coded with a 3-digit random number. The brownies were evaluated for acceptance of appearance, color, texture, flavor, and overall

acceptability based on a nine-point hedonic scale (1 = extremely dislike, 9 = extremely like). The next section will select the formula with the highest average liking score for testing.

2.6 Nutrient evaluation

Following the development and sensory evaluation of the products, the highest score was deemed acceptable. The brownie sample was analyzed for nutritional evaluation.

Moisture, crude protein, fat, and ash contents were determined using standard AOAC methods (AOAC, 2000), including oven-drying, Kjeldahl, Soxhlet extraction, and dry ashing, respectively. Carbohydrate content was calculated by difference. Energy value was determined by bomb calorimetry. Compare with basic GFB prepared with 100% butter (17.12 g/100 g) and without the addition of avocado puree.

Table 2 Formulations of gluten-free brownies (GFB) prepared using three avocado ripeness levels (AR) and three butter-to-avocado puree (Butter/AP) ratios.

Ingredients	50% AR			75% AR			100% AR		
	50:50	25:75	0:100	50:50	25:75	0:100	50:50	25:75	0:100
Butter	8.56	4.28	0	8.56	4.28	0	8.56	4.28	0
Avocado puree	8.56	12.84	17.12	8.56	12.84	17.12	8.56	12.84	17.12
Granulated sugar	17.12	17.12	17.12	17.12	17.12	17.12	17.12	17.12	17.12
Eggs	25.66	25.66	25.66	25.66	25.66	25.66	25.66	25.66	25.66
Dark chocolate	25.66	25.66	25.66	25.66	25.66	25.66	25.66	25.66	25.66
Red jasmine rice flour	6.42	6.42	6.42	6.42	6.42	6.42	6.42	6.42	6.42
Corn starch	6.42	6.42	6.42	6.42	6.42	6.42	6.42	6.42	6.42
Salt	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Vanilla extract	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Baking powder	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Xanthan gum	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Note: AR represents the avocado ripeness level (50%, 75%, and 100%). Butter/AP indicates the ratio of butter to avocado puree used in the formulation.

2.7 Statistical analysis

The completely randomized design or CRD was applied to create the different formulations of brownies for the physicochemical properties study. The randomized complete block design (RCBD) was applied for sensory evaluation. Three replications were performed for each sample. The mean values recorded for each test were compared using analysis of variance (ANOVA). Duncan's multiple range test (DMRT) was applied to indicate a significant difference at a 95% confidence level (using SPSS statistical software version 30, IBM Corp., New York, USA).

3. Results and Discussion

3.1 Effect of substitution level on color

Figure 1 and Table 3 show the physical characteristics of the results of color tests, respectively. The color of gluten-free brownies (GFB) prepared using avocado ripeness levels (AR) and butter-to-avocado puree ratios (AP) across nine formulations was evaluated. Red values (a^*) and yellow values (b^*) are statistically significant differences at the level of $p <$

0.05. Both the avocado content and the ripeness level exhibited an interactive effect on the lightness of the product. The formulation of the results showed that brightness (L^*), prepared with 100 AR and AP of 0:100, exhibited the highest brightness value of 17.18. As the avocado matures, its color intensity often decreases, leading to increased lightness (L^*) and reduced values of redness (a^*) and yellowness (b^*) (Thomya *et al.*, 2025). Furthermore, Han *et al.* (2023) revealed that ripening significantly affects the color characteristics of avocado flesh, L^* values increase while a^* and b^* values decrease as ripeness increases. The findings correspond with the results of this study, which found that brownies made with fully ripened avocado had increased lightness and reduced a^* and b^* values.

3.2 Effect of substitution level on specific volume and height of brownies

The specific volume and height of GFB formulated with avocado substitutions for butter across nine treatments were analyzed. The results revealed statistically significant differences at the 0.05 level ($p < 0.05$). Both avocado ripeness

(AR) and butter-to-avocado puree ratio (AP) exhibited interactive effects on the specific volume and height of the products. Brownies prepared with 100% AR and higher levels of butter substitution demonstrated increased specific volume and height, as presented in Table 3 and Figure 1. A higher specific volume was associated with a lighter and more aerated texture of the product, with values ranging from 1.11 to 1.67 across the nine formulations. These values were consistent with brownie height, which increased within the range of 3.14–5.32 cm, as shown in Figure 1. When the

amount of avocado used to replace fat increased, the specific volume of the cake tended to rise, which is consistent with the findings of El-Sayed (2019), who reported that muffins incorporated with avocado and cantaloupe puree exhibited significantly higher specific volume compared to the control sample. The specific volume of baked cake determines the quantity of air that can remain in the finished product. Higher gas retention and product expansion result in higher specific volume (Ain *et al.*, 2016).



Figure 1 Effect of avocado ripeness (AR) and butter-to-avocado puree ratio (AP) on the physical appearance of GFB.

Table 3 Effect of avocado ripeness (AR) and butter-to-avocado puree ratio (AP) on height, specific volumes, and color value of GFB.

AR level (%)	Butter/AP ratio	Parameter				
		L^*	a^*	b^*	Height (cm)	Specific volumes (cm^3/g)
50	50:50	12.42 ± 1.86^d	8.92 ± 0.43^b	9.23 ± 1.16^b	3.14 ± 0.05^d	1.11 ± 0.12^d
50	25:75	15.22 ± 1.38^b	8.88 ± 0.12^b	8.07 ± 1.56^c	3.39 ± 0.10^d	1.17 ± 0.04^d
50	0:100	13.82 ± 0.60^c	8.64 ± 0.26^b	8.90 ± 0.65^b	3.80 ± 0.05^c	1.18 ± 0.06^d
75	50:50	13.41 ± 0.47^c	9.02 ± 0.32^b	8.94 ± 0.32^b	4.64 ± 0.17^c	1.18 ± 0.04^d
75	25:75	16.42 ± 1.28^a	8.70 ± 0.76^b	9.34 ± 1.00^b	4.77 ± 0.18^c	1.21 ± 0.08^d
75	0:100	16.47 ± 0.41^a	9.31 ± 0.70^a	9.65 ± 0.76^a	4.90 ± 0.06^b	1.49 ± 0.14^b
100	50:50	13.18 ± 0.27^d	8.53 ± 0.54^b	8.09 ± 1.10^c	5.05 ± 0.19^b	1.33 ± 0.10^c
100	25:75	15.18 ± 1.04^b	8.33 ± 0.35^c	8.13 ± 0.57^c	5.25 ± 0.05^{ab}	1.49 ± 0.14^b
100	0:100	17.18 ± 1.20^a	7.53 ± 0.42^c	7.64 ± 0.44^d	5.32 ± 0.10^a	1.67 ± 0.08^a

The numbers represent the mean $\pm$ standard deviation. Different letters in the same column for each attribute indicate significant differences ($p < 0.05$).

3.3 Sensory analysis of GFB

Table 4 contains the sensory evaluations of the final products. In the color and taste of all the GFB organoleptic properties that the panelists tested, no significant differences ($p > 0.05$) were observed in color and taste preference among all GFB formulations. The color scores ranged from 6.94 to 7.56, indicating ratings from “like slightly” to “like moderately,” while taste scores ranged from 6.53 to 7.44, corresponding to “like moderately” on a 9-point hedonic scale. Nevertheless, there were statistically significant differences in aroma, texture, and overall preference at the 0.05 level ($p < 0.05$). Aroma scores ranged from “like slightly” to “like moderately,” texture scores ranged from “like slightly” to “like very much,” while overall preference scores were mainly within the “like moderately” category on a 9-point hedonic scale (Table 4). The treatment with 100% AR and a butter-to-avocado puree ratio of 25:75 showed the highest overall preference score (Table 4). The overall liking will gradually increase as the level of ripening increases. This effect is because the ripening of

avocados is directly related to bitter taste. Through changes in phenolic compounds, ripening avocados for 8 days at a temperature of about 20°C increases fatty acids and makes them less bitter (Thomya *et al.*, 2025). Additionally, the heat generated during processing increases the bitterness of the taste (Degenhardt and Hofmann, 2010; Eteng *et al.*, 2020).

Brownies formulated with completely mature avocado (100% AR) and a moderate butter-to-avocado puree ratio (25:75) attained the highest acceptability ratings, indicating that an ideal equilibrium between hydration, lipid substitution, and flavor perception is essential for consumer inclination. This decline may be attributed to customers' perception of undesirable qualities, characterized by a moderately bitter taste and lingering bitter aftertaste, together with the aroma of avocado. Consequently, the GFB that replaced butter with avocado formula 8 was selected for the subsequent step in the experiment.

Table 4 Influence of AR and AP substitution on sensory attributes of GFB.

AR level (%)	Butter/AP ratio	Parameter				
		color ^{ns}	Aroma	Taste ^{ns}	Texture	Overall acceptability
50	50:50	7.38 ± 1.52	6.63 ± 2.15 ^c	6.53 ± 2.11	6.25 ± 2.37 ^b	6.69 ± 2.28 ^b
50	25:75	7.50 ± 1.02	7.25 ± 1.14 ^b	7.16 ± 1.37	6.84 ± 1.57 ^b	7.44 ± 1.33 ^{ab}
50	0:100	7.34 ± 1.26	6.62 ± 1.56 ^c	6.63 ± 1.96	6.50 ± 1.48 ^b	7.09 ± 1.44 ^b
75	50:50	7.19 ± 1.62	7.65 ± 1.31 ^a	7.44 ± 1.05	6.72 ± 1.69 ^b	7.50 ± 1.08 ^{ab}
75	25:75	7.16 ± 1.51	7.13 ± 1.50 ^b	7.13 ± 1.68	7.13 ± 1.52 ^b	7.44 ± 1.22 ^{ab}
75	0:100	6.94 ± 1.13	6.75 ± 1.41 ^c	6.50 ± 1.61	6.38 ± 1.74 ^b	7.06 ± 1.50 ^b
100	50:50	6.94 ± 1.78	6.66 ± 1.81 ^c	6.81 ± 1.73	6.53 ± 1.81 ^b	7.13 ± 1.58 ^b
100	25:75	7.56 ± 0.91	7.46 ± 1.27 ^b	7.41 ± 1.13	8.06 ± 1.43 ^a	7.72 ± 1.14 ^a
100	0:100	7.44 ± 1.27	6.19 ± 1.90 ^c	6.72 ± 2.00	6.63 ± 1.56 ^b	6.91 ± 1.49 ^b

The numbers represent the mean ± standard deviation. Different letters in the same column for each attribute indicate significant differences ($p < 0.05$).

Table 5 Calorific and nutritional value of GFB prepared with 100% AR and Butter/AP ratio of 25:75 (100 g).

Calorific and nutritional value	Control (100%butter)	GFB (100% AR, Butter/AP = 25:75)	Nutrient changes (%)
Protein (g)	6.20	5.05	- 18.55
Carbohydrate (g)	47.18	51.05	+ 8.20
Fat (g)	28.57	16.06	-43.79
Ash (g)	1.44	1.50	+4.17
Moisture (g)	16.61	26.34	+ 58.58
Energy (Kcal)	470.65	395.20	- 16.03

3.4 Nutrient evaluation of GFB

The nutritional analysis indicates that one serving (100 grams) of GFB prepared with an avocado ripeness level (AR) of 100% and a butter-to-avocado puree ratio (AP) of 25:75 contains 395.20 calories, 5.05 grams of protein, 51.05 grams of carbs, 16.06 grams of fat, 26.34 grams of moisture, and 1.50 grams of ash, as shown in Table 5. In contrast to a control brownie recipe, the GFB result shows decreased nutritional, protein, fat, and energy content by 18.55%, 43.79%, and 16.03%, respectively. In contrast, the carbohydrate, ash, and moisture content increased relative to the control brownie recipe. Avocado puree consists of greater quantities of carbs, ash, and moisture (10.5 g, 0.6 g, and 81.8 g/100 g, respectively) compared to butter (0 g, 85 g, and 15.7 g/100 g), which is usually used in normal brownies. This finding accords with Wongwaiwech *et al.* (2024), which showed that including avocado increased the energy, fat, and protein levels in Thai-style custard cake goods, while the fat and calorie content diminished in proportion to the butter substituted with avocado (Othman *et al.*, 2018; Baniya, 2022; Adeyeye *et al.*, 2023).

4. Conclusion

Gluten-free brownies prepared with 100% avocado ripeness and a butter-to-avocado puree ratio of 25:75 received the highest overall acceptability. The product contained protein, carbs, fat, ash, and moisture at 5.05%, 51.05%, 16.06%, 1.50%, and 26.34%, respectively, giving a total energy of 395.20 kcal per 100 grams. This formulation reduced fat content by 43.79% and caloric intake by 16.03% compared to the control formulation. The addition of avocado into the product relies not only on the quantity used but also on the state of preservation of the avocado to effectively replace the fat. To improve the real-world applicability of avocado-based gluten-free brownies, future work should emphasize storage stability assessments and consumer acceptance testing.

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Research Article

An Integrated Lean-Visual-Green (LVG) Model for Warehouse Layout Optimization and Carbon Footprint Reduction: A Case Study in the Food Products Industry

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ABSTRACT

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In modern industrial logistics, managing warehouses presents a key challenge-enhancing operational efficiency while minimizing environmental impact. However, existing studies on lean and green warehouse practices often address these dimensions separately, with limited integration into a unified framework applicable in real industrial contexts. This study proposes an integrated Lean-Visual-Green (LVG) model that combines waste reduction, visual control, and environmental impact assessment into a single analytical approach. Unlike conventional lean-green models, the LVG framework incorporates visual management to enhance operational clarity and support layout decision-making. A before-after comparative design was applied in a finished-goods warehouse in the food products industry with 81 stock-keeping units (SKUs). One year of historical data was analyzed to develop a Product Utilization Index (PUI), which was used for ABC classification and warehouse layout redesign. Following implementation, forklift travel distance decreased from 3,519,647.28 to 1,385,685.20 meters per year (-60.63%), with a corresponding reduction in CO₂ emissions from 35,372.49 to 13,926.11 kgCO₂ per year. The results demonstrated that the LVG model provides a practical and integrative approach for improving warehouse efficiency and reducing environmental impact through data-driven layout optimization.

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1. Introduction

In the context of escalating global environmental crises, sustainable warehouse and logistics management has become a strategic priority for organizations seeking to mitigate environmental impacts while maintaining operational efficiency. Warehouses, as a core component of logistics systems, consume significant amounts of energy and resources, often resulting in higher carbon footprints (CFO) compared to other logistics activities (Perotti and Colicchia, 2023; Luca *et al.*, 2025). Under the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 on industry and infrastructure, SDG 12 on responsible consumption and production, and SDG 13 on climate action, industries worldwide are being driven to adopt more sustainable practices in logistics and warehouse management. Numerous

studies have proposed technical innovations and modelling frameworks to assess warehouse sustainability. For instance, (Agyabeng-Mensah *et al.*, 2020) examined the relationship between green warehousing, social values, and economic performance, highlighting the role of ethics in logistics to support sustainability. Similarly, Nicoletti and Appolloni (2024) introduced the concept of green warehouse 5.0, which integrates smart technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and autonomous robotics into sustainable warehouse operations. Systematic literature reviews by Domagała (2022) and Kumar and Adil (2025) have also revealed research trends emphasizing renewable energy adoption, passive design strategies, and carbon emission reduction as key approaches to advancing sustainable warehousing.

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Advancements in warehouse technologies have continued to emerge, such as smart lighting systems that reduce electricity consumption in warehouses (Füchtenhans *et al.*, 2023), and PV–battery systems capable of efficiently controlling and storing renewable energy (Yasir *et al.*, 2024). Other developments include optimized routing and transportation system design aimed at lowering carbon dioxide (CO₂) emissions (Wang *et al.*, 2018; Shih-Che Lo, 2022). In addition, the logistics 4.0 paradigm, which emphasizes automation, has demonstrated environmental benefits for warehouses, particularly in reducing reliance on human resources and enhancing system control accuracy (Nantee and Sureeyatanapas, 2021). In this context, recent studies have increasingly emphasized the role of Industry 4.0 technologies in enhancing both operational performance and environmental outcomes, particularly through data-driven decision-making and real-time system integration (Sousa Jabbour *et al.*, 2018).

Nevertheless, despite these advances, several critical knowledge gaps remain. First, while existing models address energy efficiency and warehouse design, there is still a lack of integrated analytical frameworks capable of simultaneously improving environmental, economic, and operational performance under real-world constraints such as demand and supply uncertainty. This limitation has also been highlighted in prior studies on green logistics and operational research, which emphasize the need for integrated optimization approaches capable of addressing both cost efficiency and environmental impact simultaneously (Dekker *et al.*, 2012). For instance, Accorsi *et al.* (2017) proposed a multi-objective warehouse design model that minimizes costs and carbon footprint (CFO), yet it did not account for uncertainty factors. Similarly, Rajković *et al.* (2019) developed an Automated Storage and Retrieval System (AS/RS) model aimed at reducing CO₂ emissions, but the model did not sufficiently address investment considerations or demand variability. Kumar *et al.* (2022) examined the implications of carbon footprint (CFO) under fluctuating demand and supply conditions; however, their simulation failed to provide actionable policy guidelines or clear design strategies. Furthermore, while some studies have emphasized carbon reduction in specific sectors such as cold chains (Wang *et al.*, 2018), the food industry (Luca *et al.*, 2025), and transportation systems (Jerbi *et al.*, 2022), comprehensive evaluations of carbon reduction in warehouse operations remain limited, especially in terms of integrating smart technologies with ethical management practices. Although Jerbi *et al.* (2022) highlighted the positive influence of logistics 4.0 on warehouse sustainability, the broader organizational impacts derived from ethics and stakeholder engagement have yet to be thoroughly explored. Despite these findings, prior studies have demonstrated the benefits of lean-green integration, most approaches remain conceptually separated from practical warehouse layout design and lack explicit mechanisms for

improving operational visibility and decision-making in real industrial contexts. In particular, the role of visual management as a bridge between operational efficiency and environmental performance has not been sufficiently explored.

In parallel with technological developments, recent studies have emphasized the integration of lean and green approaches as complementary strategies for achieving operational efficiency alongside environmental sustainability. Lean principles primarily focus on eliminating operational waste and improving process flow efficiency, whereas green practices aim to reduce environmental impacts and resource consumption throughout logistics activities (Dües *et al.*, 2013). Prior research has demonstrated that lean practices can serve as an enabling mechanism for environmental improvement by reducing unnecessary movement, energy usage, and material waste within operational systems (Ferroq *et al.*, 2016). Furthermore, systematic reviews have highlighted that the integration of lean and green paradigms provides synergistic benefits by simultaneously enhancing productivity performance and environmental outcomes (Garza-Reyes, 2015). Additional studies have further strengthened this perspective by demonstrating that lean-green integration can be systematically implemented through structured frameworks that align process efficiency with environmental sustainability objectives (Zheng *et al.*, 2017). Despite these advances, applications integrating lean and green concepts within warehouse layout design and operational decision-making remain relatively limited, particularly in real industrial environments supported by empirical operational data. Moreover, existing studies tend to emphasize either process efficiency or environmental impact, with limited attention to how these dimensions can be operationally integrated through layout design and real-time warehouse control practices. This limitation highlights the need for a more comprehensive and practically applicable framework.

Another area that remains insufficiently explored is inventory management. Although ABC analysis techniques have been widely applied (Abdolazimi *et al.*, 2021a; Abdolazimi *et al.*, 2021b; Mashud *et al.*, 2022; Ray Silaen *et al.*, 2024), systematic investigations into their direct impact on the carbon footprint (CFO) are still lacking. Even the study by Mashud *et al.* (2022), which incorporated environmental considerations into inventory strategies, relied on deterministic models that may not accurately reflect real-world operational conditions. Emerging trends also point to the integration of blockchain technology into inventory management, aiming to enhance supply chain transparency and reduce carbon emissions (Priyan, 2024). At the same time, simulation frameworks for energy utilization and greenhouse gas (GHG) emission accounting are becoming increasingly common. For instance, Yaman (2024) proposed a structured approach to preparing GHG inventories and developing systematic measures for CFO mitigation. In addition, Life Cycle Assessment (LCA) has been widely recognized as a

standard methodological framework for evaluating environmental impacts across logistics systems, providing a more comprehensive basis for sustainability assessment (International Organization for Standardization, 2006). Other research focusing on organizational practices, such as sustainable logistics internships (De Assis *et al.*, 2024) and raw material inventory management in small and medium-sized enterprises (Vanessa and Helma, 2023), has also demonstrated the potential to lower carbon emissions through well-designed warehouse strategies. Furthermore, the application of Multi-Criteria Classification (MCC) models in conjunction with ABC analysis has gained attention as a more refined approach to inventory categorization (Kaabi, 2022).

The LVG Model will be applied to analyze, evaluate, and design warehouse systems capable of responding effectively to organizational constraints and real-world operating environments. Unlike traditional lean-green approaches, this study explicitly introduces “Visual” as a distinct and operationally grounded component that enhances transparency, supports decision-making, and reduces process ambiguity in warehouse layout and material handling systems. This integration provides a more holistic framework that connects process efficiency, operational control, and environmental performance within a single analytical structure. For instance, inventory classification using ABC analysis enables prioritization in storage and retrieval, while route analysis and forklift movement tracking within the warehouse identify bottlenecks and operational waste. The model also incorporates the calculation of environmental impacts by linking travel distance of material handling equipment to carbon dioxide (CO₂) emissions, alongside planning measures to reduce energy consumption and increase the share of renewable energy use. This approach not only supports efficiency and cost-reduction objectives but also aligns with environmental commitments and the United Nations Sustainable Development Goals, specifically SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). In addition, the proposed LVG model provides a structured integration mechanism that links operational decision-making with environmental performance through measurable indicators, such as travel distance and carbon emissions, thereby strengthening its conceptual contribution beyond a purely applied framework and reinforcing its potential for broader analytical application. Beyond addressing academic knowledge gaps, this research aspires to deliver both policy-level and practical industrial implications, ultimately contributing to the transition toward organizational or higher-level carbon neutrality (net zero).

To address these gaps, this study focuses on a real industrial case in the food products industry, where operational complexity, product variety, and demand variability present practical challenges for warehouse optimization. By employing

a data-driven and before–after comparative approach, the study aims to provide empirical evidence of how the LVG model can be applied to improve both operational efficiency and environmental performance under actual working conditions.

Therefore, to systematically examine the effectiveness of the proposed LVG model in addressing these operational and environmental challenges, this study establishes clear research objectives and testable hypotheses as presented below.

This study aims to develop and evaluate an integrated LVG model for improving warehouse operational efficiency while simultaneously reducing environmental impacts. The specific objectives of this research are as follows:

- (1) To develop an integrated warehouse management framework based on lean, visual, and green principles.
- (2) To evaluate the impact of warehouse layout redesign on operational efficiency, particularly in terms of material handling distance.
- (3) To assess the reduction of carbon dioxide (CO₂) emissions resulting from improved warehouse operations.

Based on the theoretical integration of lean and green operational principles, the following research hypotheses are proposed:

- H1: Implementation of the LVG model significantly reduces forklift travel distance in warehouse operations.
- H2: Reduction in travel distance leads to a proportional decrease in CO₂ emissions generated from material handling activities.
- H3: ABC-based warehouse layout redesign improves operational efficiency through optimized storage allocation and workflow clarity.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods employed in the development and implementation of the LVG model. Section 3 presents the results and discussion, focusing on operational efficiency improvement and environmental impact reduction. Finally, section 4 concludes the study and outlines implications and future research directions.

2. Materials and Methods

This study employed an applied research approach with the objective of developing a warehouse management framework that simultaneously enhances operational efficiency and reduces carbon dioxide (CO₂) emissions. The research began with an in-depth investigation of the internal management processes within the finished goods warehouse of Doi Kham Food Products Co., Ltd., focusing on product flow structures, order-picking behaviors, forklift movements, and systematic patterns of storage utilization.

The research process was designed under the LVG Model, an integrated framework that emphasizes efficient resource utilization (lean), clear communication and operational visibility (visual), and comprehensive consideration of environmental

impacts (green). This framework was employed as the basis for analyzing quantitative data such as product picking frequency, material handling distances, and carbon footprint calculations. The analysis was further linked with strategies including ABC classification for inventory prioritization, optimal storage allocation, and redesigned material flow routes to minimize waste and improve energy efficiency. Collectively, these measures were structured into a system-level improvement simulation, guided by the principles of operational feasibility and environmental sustainability. The methodology was executed through the following steps.

To ensure methodological rigor and reproducibility, the analysis was conducted using structured data processing and validation procedures. All datasets were verified for completeness and consistency prior to analysis, and calculations were performed using spreadsheet-based analytical tools (e.g., Microsoft excel) to support transparency and traceability. Reliability was ensured through cross-validation of calculated indicators such as travel distance and CO₂ emissions against operational records.

2.1 Data collection process

The finished goods warehouse of Doi Kham Food Products Co., Ltd. covers an area of approximately 1,000 square meters and is equipped with a racking system comprising six rows of four-tier shelves, providing a total capacity of 880 pallets. The warehouse operations begin with the receipt of products from the semi-finished goods warehouse, transported by diesel-powered forklifts, followed by inspection and storage on the racks. When orders are received from the central warehouse in

Bangkok, items are picked and recorded using the SAP business system.

For this study, one year of historical data (January 1, 2023 to December 31, 2023) was collected, covering 81 active stock-keeping units (SKUs). The selection of this one-year data collection period was intentionally designed to capture seasonal variations in product demand, order frequency, and warehouse activity patterns, thereby providing a more representative assessment of operational behavior under real-world conditions and reducing bias associated with short-term fluctuations. As summarized in Table 1, the total annual picking frequency (PF) was 32,948 transactions, with a total annual quantity (TAQ) of 7,785,843 units. The calculated Product Utilization Index (PUI) reached 3,227,570,505 units per year, while the total annual travel distance (TDY) for material handling amounted to 3,519,647.28 meters, resulting in carbon dioxide (CO₂) emissions of 35,372.49 kg CO₂ per year. High-movement items, such as 100% tomato juice (200 ml), were picked 736 times per year with a total volume of 197,398 units, generating a cumulative travel distance of 158,432.40 meters and annual emissions of 1,592.25 kgCO₂. In contrast, low-movement items, such as concentrated red guava juice (750 ml), were picked only 15 times per year with a total volume of 159,053 units, corresponding to a travel distance of 2,601.72 meters and annual emissions of 26.15 kgCO₂. These data formed the basis for ABC classification using Pareto principles, which was subsequently employed to redesign the warehouse layout for optimal efficiency.

Table 1 Annual summary of product dispatch frequency and volume in 2023.

No.	Product name	PF (times/year)	TAQ (units)	PUI (times × quantity)	TDY (meters)	CO ₂ /Y (kgCO ₂)
1	100% Tomato Juice 200 ml	736	197,398	145,284,928	158,432.40	1,592.25
2	100% Tomato Juice 750 ml	517	66,408	34,332,936	37,439.88	376.27
3	100% Tomato Juice 750 ml × 12 bottles	396	189,117	74,890,332	81,667.44	820.76
4	100% Honey Tangerine Juice 750 ml	587	150,922	88,591,214	96,608.28	970.91
5	100% Honey Tangerine Juice 250 ml	568	119,594	67,929,392	74,076.60	744.47
...	...	...	...	...	...	...
77	Concentrated Red Guava Juice 750 ml	15	159,053	2,385,795	2,601.72	26.15
78	Concentrated Watermelon Juice 250 ml	26	177,870	4,624,620	5,043.12	50.68
79	Concentrated Pink Guava Juice 750 ml	43	85,189	3,663,127	3,994.56	40.15
80	Plum and Mulberry Juice Blend 750 ml	739	30,272	22,371,008	24,395.52	245.17
81	Carrot and Guava Juice Blend 750 ml	747	156,802	117,131,094	127,730.76	1,283.69
Totals		32,948	7,785,843	3,227,570,505	3,519,647.28	35,372.49

Note: PF = Picking Frequency (times/year), TAQ = Total Annual Quantity (units), PUI = Product Utilization Index (times × quantity), TDY = Total Distance per Year (meters), CO₂/Y = Total CO₂ per Year

2.2 Analysis process and improvement approach using the LVG model

To address inefficiencies in space utilization and product movement within the finished goods warehouse, particularly concerning product placement, travel distance, and operational clarity, this research began with an analysis of actual warehouse processes. ABC analysis was applied in conjunction with real operational data to calculate the Product Utilization Index (PUI), derived from the product of picking frequency (PF) and total accumulated quantity (TAQ). This metric provided a more accurate prioritization of items compared to using either frequency or volume alone, as it reflected the actual utilization level of each product. The analysis results classified products into three groups: Group A, representing high-frequency, high-volume items that should be placed near receiving and dispatch areas to minimize travel distance and handling time; Group B, representing medium-importance items stored in accessible zones; and Group C, representing low-movement items that can be placed deeper within the warehouse.

Following classification, a new warehouse layout was developed based on prioritization derived from the PUI. Visual Management concepts were incorporated through a visual control system that assigned color codes to each product category: green for Group A (frequent access), yellow for Group B (moderate importance), and blue for Group C (infrequent use). These codes were implemented in both the warehouse layout and actual storage locations, enabling workers to identify and retrieve products quickly and accurately, reducing human error, minimizing training time for new staff, and eliminating unstructured storage congestion. Furthermore, the redesigned storage system reduced forklift travel distances and associated carbon dioxide (CO₂) emissions from material handling, thereby establishing a foundation for long-term sustainability.

Synthesizing these initiatives, the improvement framework was formalized under the LVG model, with the objective of providing a systematic and sustainable solution. The lean dimension emphasizes waste reduction and resource efficiency, the visual dimension supports operational clarity and traceability while reducing human error, and the green dimension focuses on mitigating environmental impacts, particularly CO₂ emissions. Importantly, the LVG Model highlights a data-driven design approach, replacing reliance on operator experience with empirically grounded decision-making. This ensures an efficient storage system that supports sustainable operations while fulfilling both logistics requirements and the organization's environmental commitments in the long term.

2.3 Environmental impact assessment of warehouse improvement

To evaluate the environmental impacts associated with warehouse operations, this study established the indicator of carbon dioxide (CO₂) emissions generated from forklift operations, as forklifts represent the primary equipment used for internal material handling. The measurement framework was

based on the total annual travel distance of forklifts, with emissions calculated using the Emission Factor (EF_m) standardized and certified by the Thailand Greenhouse Gas Management Organization (TGO) (Thaicarbonlabel, 2025), where the emission calculation is based on the assumption of a constant fuel consumption rate for diesel-powered forklifts under normal operating conditions. Factors such as equipment age, maintenance condition, operator behavior, idle time, and load variation were not explicitly considered in this study. While this simplification follows standard carbon footprint accounting practices, it may introduce minor deviations from actual operational emissions; however, the use of a consistent emission factor ensures comparability between pre- and post-improvement scenarios.

The purpose of this analysis was to compare CO₂ emissions before and after the warehouse improvement, while controlling for external variables such as workforce size, warehouse system configuration, information system, and floor space. This ensured that any observed differences accurately reflected the impact of implementing the LVG Model. The calculation of CO₂ emissions was derived from actual annual forklift travel distances, which were then linked to diesel fuel consumption through Equation (1) (Thaicarbonlabel, 2025), following the standard methodology for carbon footprint (CFO) assessment:

$$CO_2 \text{ Emissions (kg)} = D \times EF_m \quad (1)$$

Where: D = travel distance of material handling (meters), EF_m = emission factor per meter (kgCO₂/meter)

The value of EF_m was derived from the estimated diesel consumption of forklifts, which averages 3.75 liters per kilometer, or 0.00375 liters per meter. Multiplying this consumption rate by the diesel emission factor of 2.68 kgCO₂ per liter yields the emission factor per meter, as expressed in Equation (2) (Thaicarbonlabel, 2025).

$$EF_m = 0.00375 \times 2.68 = 0.01005 \text{ kgCO}_2/\text{meter} \quad (2)$$

The calculated values were subsequently compared between the pre- and post-warehouse layout improvement periods to quantitatively assess the reduction in CO₂ emissions. This reduction represents a key objective of green logistics embedded within the LVG Model framework.

2.4 Comparative analysis of research results

Following the implementation of warehouse improvements based on the LVG Model, empirical data were collected to compare pre- and post-improvement outcomes. The data collection was conducted continuously over a one-year period to enable a concrete and academically significant assessment of changes in operational performance. Throughout this process, external variables that could potentially influence the evaluation results, such as workforce size, warehouse management system,

information system, and available storage space, were controlled to remain constant. This ensured the reliability of the comparison and accurately reflected the impacts of applying the LVG model in warehouse improvement. The comparative evaluation was designed to cover a 12-month period, from February 1, 2024 to January 31, 2025, thereby allowing for a meaningful measurement of operational performance after the warehouse redesign under the LVG framework. As with the pre-improvement phase, external variables, including workforce size, warehouse system, available space, and information system, were strictly controlled to enhance the credibility of the results and provide a valid reflection of the LVG model's effectiveness in improving warehouse operations. In addition to descriptive comparison, the study acknowledges the importance of statistical validation in assessing the significance of observed improvements. Although the primary objective is to demonstrate practical industrial applicability, future extensions of this work may incorporate statistical hypothesis testing (e.g., paired *t*-test or non-parametric methods) and sensitivity analysis to further validate the robustness of the results. Furthermore, sensitivity analysis on emission factors could be conducted to evaluate the impact of variability in fuel consumption assumptions on CO₂ estimation.

3. Results and Discussion

This study collected and analyzed data before and after the warehouse improvement through the application of the LVG model, in order to systematically compare outcomes in terms of both operational efficiency and environmental impacts. The evaluation emphasized three main aspects: warehouse space utilization, reduction in product travel distance, and reduction of carbon dioxide (CO₂) emissions generated from forklift operations, which constitute the primary material handling activity in the organization's internal logistics system. The findings can be summarized into two main areas: (1) results of product classification and warehouse layout redesign under the LVG model, and (2) operational performance improvements related to environmental impact reduction, particularly the measurable and verifiable decrease in CO₂ emissions.

3.1 Product classification and layout redesign under the LVG model

By applying the LVG model, which integrates lean warehousing, visual management, and green logistics, the finished goods warehouse of Doi Kham Food Products Co., Ltd. implemented ABC classification based on the Product Utilization Index (PUI). The results were subsequently plotted in a Pareto chart (Figure 1) to analyze product priority levels and further categorized into Groups A, B, and C according to cumulative percentage (Cum. %) thresholds, as summarized in Table 2, which presents the outcomes of ABC classification.

Based on the historical data analysis using ABC classification and Pareto charting, with the Product Utilization

Index (PUI) serving as the grouping criterion, all 81 stock-keeping units (SKUs) were classified into three categories: Group A comprised 5 items (6.17%), Group B comprised 19 items (23.46%), and Group C comprised 57 items (70.37%). This classification accurately reflected the operational priorities and logistical impacts of each product, forming a critical basis for redesigning storage allocation in line with the LVG model, which effectively integrates lean warehousing, visual management, and green logistics.

Following this classification, a new warehouse layout was designed by considering product usage frequency, handling volume, and movement-related impacts, while utilizing a racking system with a total capacity of 880 pallets. The revised allocation assigned 288 pallets to Group A items, which represent high-movement and large-volume products, strategically placed near the entrance and receiving/dispatch points to minimize travel distance and handling time. Group B was allocated 424 pallets, positioned in zones that remain accessible but do not require proximity to entry points. Group C, consisting of low-movement and low-volume items, was assigned 156 pallets located in the innermost section of the warehouse. In total, 868 pallets, or 98.64% of available capacity, were allocated, leaving 12 pallets (1.36%) as reserve space to accommodate contingencies or future product introductions.

In addition, the principle of visual control was applied to enhance efficiency in product picking and verification. Color codes were assigned to designate storage zones for each product category: green for Group A, yellow for Group B, blue for Group C, and purple for reserve or unallocated spaces, as illustrated in Figure 2. This color-coding system, developed under the visual management approach, improved clarity and traceability in warehouse operations, reduced human error, shortened the training time required for new employees, and strengthened systematic product control. This improvement can be explained by the reduction of search time and decision uncertainty during picking operations, as visual cues enable workers to immediately identify storage zones without relying on memory or complex instructions. Consequently, operational flow becomes more streamlined, reducing unnecessary movement and handling inefficiencies, which directly contributes to shorter travel distances and improved overall warehouse efficiency. These findings not only demonstrate practical improvements in warehouse operations but also highlight the potential of the LVG model as a foundation for further analytical modelling and optimization in sustainable logistics systems.

The redesigned warehouse layout was subsequently implemented in the facility, with performance data collected over a one-year period (February 1, 2024 to January 31, 2025). The operational outcomes were analyzed and summarized in Table 3 to evaluate both warehouse operational efficiency and the measurable reduction of carbon dioxide (CO₂) emissions from internal logistics processes within the organization.

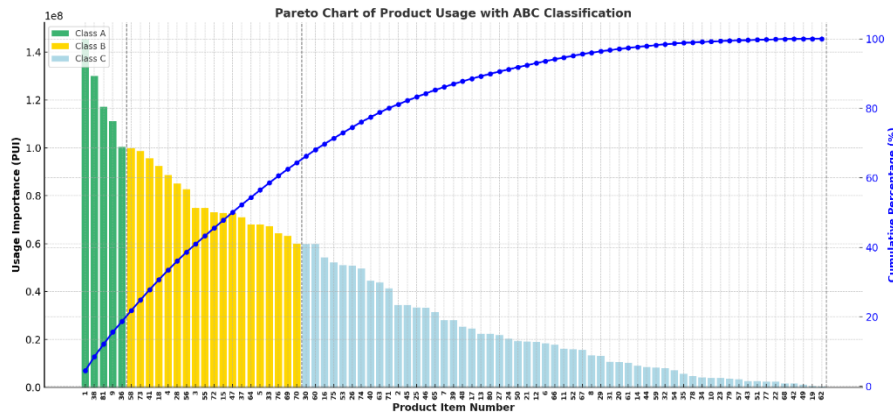


Figure 1 Pareto chart of product usage based on ABC classification.

Table 2 Product classification based on ABC analysis.

Item No	Product name	PF (times/year)	TAQ (units)	PUI (times × quantity)	%(f)	Cum. %	Class
1	Tomato Juice 100% 200 ml	736	197,398	145,284,928	4.50%	4.50%	A
38	Butterfly Pea Drink 700 ml	679	191,472	130,009,488	4.03%	8.53%	A
81	Carrot and Guava Juice 750 ml	747	156,802	117,131,094	3.63%	12.16%	A
9	Passion Fruit Juice 750 ml	556	199,724	111,046,544	3.44%	15.60%	A
36	Watermelon Juice 750 ml	768	130,618	100,314,624	3.11%	18.71%	A
58	Butterfly Pea with Honey Drink 250 ml	696	143,465	99,851,640	3.09%	21.80%	B
73	Mulberry Concentrate 750 ml	734	134,530	98,745,020	3.06%	24.86%	B
41	Carrot and Apple Juice 750 ml	653	146,571	95,710,863	2.97%	27.83%	B
18	Aromatic Coconut Water 750 ml	538	171,811	92,434,318	2.86%	30.69%	B
4	Mandarin Orange Juice 100% 750 ml	587	150,922	88,591,214	2.74%	33.43%	B
...	...	...	...	...	...	...	...
68	Coconut Concentrate 750 ml	30	56,255	1,687,650	0.05%	99.89%	C
42	Plum Concentrate 750 ml	376	4,290	1,613,040	0.05%	99.94%	C
49	Coconut Water with Nata de Coco 750 ml	40	27,777	1,111,080	0.03%	99.98%	C
19	Soy Milk 400 g x 12 bottles	64	8,125	520,000	0.02%	99.99%	C
62	White Guava Concentrate 750 ml	14	16,965	237,510	0.01%	100.00%	C
Totals		32,948	7,785,843	3,227,570,505	100%	-	-

Note: PF = Picking Frequency (times/year), TAQ = Total Annual Quantity (units), PUI = Product Utilization Index (times × quantity), %(f) = Percentage (%), Cum. % = Cumulative Percentage (%)

3.2 Operational efficiency improvement and carbon reduction through the LVG model

In this study, data from the year 2023 were compared with data collected after the warehouse improvement in 2024, while maintaining a constant number of 81 stock-keeping units (SKUs). Although the number of SKUs remained unchanged between the two periods, the total product volume differed significantly. To control for variability caused by external factors such as fluctuations in order volumes or other related influences, the researchers employed the average Product Utilization Index (PUI) to normalize the data prior to statistical analysis. This method reduced variability from external factors and ensured that the results accurately reflected the effectiveness of the warehouse layout redesign.

Furthermore, to enhance the robustness of the analysis and clearly demonstrate the impact of the improved storage system, the study reported both annual data and annualized averages in parallel. This approach increased the reliability of the findings and provided a comprehensive view of the operational and environmental improvements achieved. The detailed results are presented in Table 4.

From the data presented in Table 4, it was found that in 2024 the total annual product quantity (TAQ) reached 7,938,831 units, representing a 1.96% increase compared to 2023, which recorded 7,785,843 units. However, the number of picking transactions (PF) in 2024 decreased to 32,153, down from 32,948 transactions in 2023, reflecting a 2.41% reduction. This change resulted from an increase in the number of units per

picking transaction (per pallet), which, while still constrained by pallet storage capacity, allowed each picking operation to

transport larger volumes and consequently reduced the overall number of transactions.

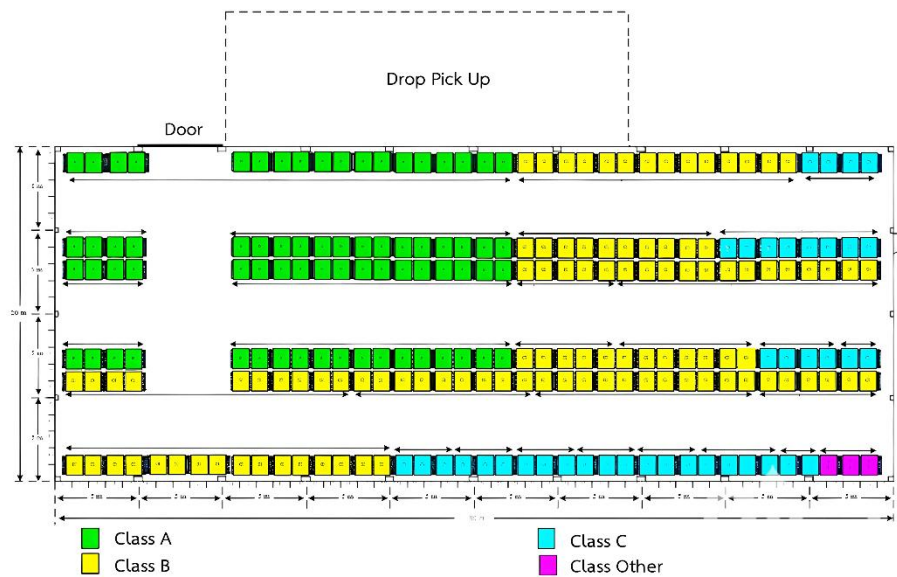


Figure 2 Warehouse layout based on ABC classification and visual control.

Table 3 Operational performance and CO₂ impact of warehouse activities by product group.

PIN	PF (times/year)	TAQ (units)	PUI (times × quantity)	Class	NPR	TDY (meters)	CO ₂ /Y (kgCO ₂)
1	715	213,602	152,725,430	A	65	62,374.84	626.87
38	649	186,460	121,012,540	A	63	55,816.66	560.96
81	741	152,015	112,643,115	A	51	50,287.60	505.39
9	541	210,688	113,982,208	A	66	47,675.34	479.14
36	743	129,143	95,953,249	A	43	43,067.87	432.83
58	690	157,101	108,399,690	B	22	42,869.06	430.83
73	746	130,469	97,329,874	B	21	42,393.98	426.06
41	625	151,956	94,972,500	B	22	41,091.32	412.97
18	534	184,623	98,588,682	B	27	39,684.63	398.83
4	571	136,468	77,923,228	B	24	38,034.68	382.25
...	...	...	...	...	...	...	...
68	30	58,085	1,742,550	C	2	724.53	7.28
42	367	4,640	1,702,880	C	1	692.50	6.96
49	39	25,927	1,011,153	C	1	477.02	4.79
19	62	8,619	534,378	C	1	223.23	2.24
62	13	17,151	222,963	C	1	101.95	1.02
Totals	32,153	7,938,831	3,205,504,281	-	712	1,385,685.20	13,926.11

Note: PIN = Product Item Number, PF = Picking Frequency (times/year), TAQ = Total Annual Quantity (units), PUI = Product Utilization Index (times × quantity), NPR = Number of Pallet Rotations per Year, TDY = Total Distance per Year (meters), CO₂/Y = Total CO₂ per Year

The Product Utilization Index (PUI) in 2024 was 3,205,504,281 units per year, a slight decrease of 0.68% from 3,227,570,505 units in 2023. This indicates that overall product utilization patterns remained relatively stable, though differences existed at the individual product group level.

The study revealed a significant reduction in total annual travel distance (TDY), which declined from 3,519,647.28 meters in 2023

to 1,385,685.20 meters in 2024, a 60.63% decrease. Similarly, the average distance per picking transaction (ADP) decreased from 8,490.38 meters to 3,526.90 meters, representing a 58.46% reduction. These reductions clearly demonstrate the effectiveness of the warehouse layout redesign under the LVG Model.

Correspondingly, carbon dioxide (CO₂) emissions followed the same trend. The total annual CO₂ emissions (CO₂/Y) declined

from 35,372.49 kgCO₂ in 2023 to 13,926.11 kgCO₂ in 2024, reflecting a 60.63% reduction directly linked to the decrease in travel distance. Likewise, CO₂ emissions per picking transaction

(CO₂/P) dropped from 85.33 kg CO₂ to 35.45 kg CO₂, a 58.46% reduction.

Table 4 Comparison of internal distance and CO₂ emissions before and after warehouse improvement.

Year	PF (times/year)	TAQ (units)	PUI (times × quantity)	TDY (meters)	ADP (meters)	CO ₂ /Y (kgCO ₂)	CO ₂ /P (kgCO ₂)
2023	32,948.00	7,785,843.00	3,227,570,505.00	3,519,647.28	8,490.38	35,372.49	85.33
2024	32,153.00	7,938,831.00	3,205,504,281.00	1,385,685.20	3,526.90	13,926.11	35.45
Difference	795.00	-152,988.00	22,066,224.00	2,133,962.08	4,963.48	21,446.38	49.88
% Change	-2.41%	1.96%	-0.68%	-60.63%	-58.46%	-60.63%	-58.46%

The results confirm a direct linear relationship between the reduction in travel distance (TDY) and CO₂ emissions. When comparing pre- and post-improvement conditions, the 60.63% reduction in travel distance corresponded exactly with the 60.63% reduction in CO₂ emissions. This outcome is attributable to the mathematical formulation of CO₂ emission calculations, which are directly proportional to travel distance and the emission factor (EF_m), a constant value defined by the Thailand Greenhouse Gas Management Organization (TGO) for diesel fuel consumption. Thus, when travel distance decreases, CO₂ emissions decrease proportionally. These findings demonstrate that the redesigned warehouse layout under the LVG model is highly effective in reducing material handling distances and significantly mitigating environmental impacts in a quantifiable manner. In addition to environmental benefits, the substantial reduction in travel distance also contributes to measurable improvements in labor productivity and equipment utilization efficiency. Shorter travel routes reduce idle time, improve cycle time per operation, and increase the effective use of forklift resources, thereby enhancing overall operational throughput. These operational improvements highlight the broader impact of the LVG model beyond environmental performance.

From an economic perspective, the significant reduction in travel distance (60.63%) directly contributes to lower fuel consumption and operational costs associated with material handling activities. Although this study does not explicitly quantify cost savings or return on investment (ROI), the proportional relationship between travel distance and fuel usage suggests a strong potential for cost reduction in long-term warehouse operations. This indicates that the LVG model can provide not only environmental benefits but also tangible economic advantages for warehouse management.

3.3 Discussion

The implementation of the LVG model demonstrated the potential of an integrated warehouse system design that can simultaneously enhance storage efficiency and reduce environmental impacts. The outcomes are presented in two major dimensions: (1) improving warehouse operational efficiency and (2) achieving measurable reductions in carbon

dioxide (CO₂) emissions. From a managerial perspective, the LVG model provides a structured approach that can be implemented incrementally. Warehouse managers can begin by analyzing product movement data, followed by ABC classification and visual zoning, before proceeding to layout redesign. This stepwise approach reduces implementation complexity and allows gradual adaptation within existing operational constraints.

In practice, this phased implementation approach is particularly beneficial in industrial environments where operational disruptions must be minimized. Managers can initiate pilot zones before full-scale deployment, allowing performance monitoring and gradual workforce adaptation.

Regarding operational efficiency, this study applied ABC classification using the Product Utilization Index (PUI) to prioritize items, thereby aligning product placement with utilization behavior and significantly reducing picking time. This approach is consistent with the findings of Abdolazimi *et al.* (2021a), Abdolazimi *et al.* (2021b), and Ray Silaen *et al.* (2024), who emphasized that ABC analysis remains a flexible tool and, when combined with real utilization data, enhances the accuracy of inventory management. Furthermore, the integration of visual management with lean principles improved clarity and traceability in warehouse operations, reduced human error, and shortened the training period for new employees. This supports the proposition of Nantee and Sureeyatanapas (2021), who noted that automation and visual control tools play a vital role in reducing labor dependence and increasing control accuracy, particularly under the logistics 4.0 paradigm. Similarly, Kumar and Adil (2025) highlighted that intelligent warehouse technologies should adopt adaptive structures capable of responding flexibly to fluctuating order volumes, a requirement addressed by the LVG model in this study through the systematic classification of products into A, B, and C categories.

More importantly, the observed efficiency gains can be explained through a reduction in operational complexity and cognitive load during picking activities. The use of visual control mechanisms, such as color-coded zoning, enables faster recognition, minimizes search time, and reduces decision

uncertainty among operators. This causal mechanism highlights that the contribution of the “Visual” component extends beyond communication, acting as an operational enabler that directly influences process efficiency.

With respect to CO₂ reduction, the results showed that the redesigned warehouse layout reduced forklift travel distance by over 60%, leading to a corresponding decrease in annual CO₂ emissions from 35,372.49 kgCO₂ to 13,926.11 kgCO₂, or 60.63%. This trend indicates that more efficient product placement inherently minimizes unnecessary movement and energy consumption within logistics operations. Similar findings were reported by Accorsi *et al.* (2017), Rajković *et al.* (2019), and Luca *et al.* (2025), who established a strong relationship between spatial efficiency and carbon footprint reduction in warehouse systems, especially in automated and complex environments. In addition, Shih-Che Lo (2022) and Wang *et al.* (2018) confirmed that optimized routing and data-driven analyses of equipment movement significantly reduce CO₂ emissions. Complementary perspectives from Domagała (2022) and Fächtenhans *et al.* (2023) further demonstrated that even moderate changes, such as upgrading lighting systems or reconfiguring storage structures, can cut CO₂ emissions by several thousand kilograms annually, underscoring the systemic power of targeted interventions without requiring large-scale investments.

In addition to environmental benefits, the reduction in travel distance also implies improvements in labor productivity and equipment utilization efficiency. Shorter travel routes reduce idle time, increase cycle efficiency, and enhance the overall throughput of material handling operations.

From an economic standpoint, the reduction in travel distance is directly associated with lower fuel consumption and operational costs. Although this study does not explicitly quantify cost savings or ROI, the proportional relationship between distance reduction and fuel usage indicates strong potential for long-term economic benefits in warehouse operations.

Compared to prior literature, this study is distinctive in its use of real operational data to redesign warehouse systems, differing from earlier works that relied primarily on deterministic models without accounting for seasonal fluctuations or environmental variables (Kumar *et al.*, 2022; Priyan, 2024). Moreover, the LVG model presents opportunities for extension into other systems such as cross-docking, blockchain-enabled inventory management, and cold chain logistics, all of which demand both operational efficiency and environmental sustainability.

Furthermore, unlike previous studies that primarily focus on either operational optimization or environmental performance independently, this study demonstrates how both dimensions can be simultaneously achieved through an integrated and data-driven framework, thereby strengthening the practical and analytical contribution of the LVG model.

From a broader operational perspective, the findings suggest that the LVG model possesses a degree of generalizability to

warehouse environments that share similar operational characteristics, particularly medium-scale facilities relying on manual or semi-automated material handling systems. The integration of ABC-based storage prioritization, visual control mechanisms, and distance-based environmental assessment can be adapted to warehouses where product movement patterns and storage allocation decisions significantly influence operational performance. In such contexts, the model provides a practical framework for aligning efficiency improvement with environmental objectives without requiring substantial infrastructure investment.

However, the applicability of the LVG model may be influenced by several operational conditions. Warehouses operating fully automated Auto-mated Storage and Retrieval Systems (AS/RS), highly dynamic real-time allocation systems, or facilities with extremely high SKU variability may require further modification of the model parameters and decision rules. In addition, differences in energy sources, equipment types, and organizational policies may affect the magnitude of environmental benefits achieved, suggesting that performance outcomes should be interpreted in relation to local operational contexts.

In practical implementation, several challenges may arise, including resistance to layout changes from operational staff, the need for retraining to adapt to visual control systems, and temporary performance fluctuations during the transition phase. These challenges can be mitigated through phased implementation, staff involvement, and continuous monitoring of operational performance.

These considerations indicate that while the LVG model offers a transferable conceptual and analytical framework, its implementation should be supported by context-specific data analysis and operational assessment. Future research may therefore extend the model by incorporating digital monitoring technologies, adaptive optimization algorithms, or multi-site comparative studies to further validate its scalability and robustness across diverse industrial sectors.

In addition, future studies may incorporate statistical hypothesis testing and sensitivity analysis to further strengthen the robustness and generalizability of the findings. Taken together, the findings of this study provide empirical support for the proposed research objectives and hypotheses. The significant reduction in forklift travel distance confirms hypothesis H1, while the proportional decrease in CO₂ emissions supports hypothesis H2. Furthermore, improvements in operational efficiency resulting from ABC-based layout redesign validate hypothesis H3. These results collectively demonstrate that the LVG model effectively integrates operational efficiency enhancement with environmental impact reduction under real warehouse conditions.

4. Conclusion

This research introduced the integrated LVG model as a sustainable approach to finished goods warehouse management. The model combines lean principles to enhance

space utilization, minimize waste, and reduce unnecessary product movement; visual principles to establish clarity, transparency, and traceability while reducing operational errors; and green principles to mitigate environmental impacts from logistics activities through systematic evaluation of CO₂ emissions. By applying this model through ABC classification and visual management in the case study of Doi Kham Food Products Co., Ltd., the results demonstrated clear effectiveness. The total travel distance for material handling was reduced by 60.63%, from 3,519,647.28 meters per year to 1,385,685.20 meters per year. This directly translated into an equivalent reduction in CO₂ emissions, from 35,372.49 kgCO₂ per year to 13,926.11 kg CO₂ per year. These findings highlight that the LVG model can simultaneously enhance warehouse operational efficiency and support environmentally sustainable practices.

Beyond operational and environmental benefits, the LVG model aligns closely with the United Nations Sustainable Development Goals (SDGs). Specifically, it supports SDG 9 (industry, innovation, and infrastructure) by applying data-driven and innovative warehouse management techniques; SDG 12 (responsible consumption and production) through tangible reductions in storage and handling waste; and SDG 13 (climate action) by reducing CO₂ emissions from warehouse and logistics operations. Thus, the LVG model provides an important pathway for industrial organizations to adopt environmentally responsible practices and contribute to carbon reduction goals at organizational, societal, and national levels. Despite these contributions, several limitations of this study should be acknowledged. First, the research is based on a single case study within the food products industry, which may limit the generalizability of the findings to other industrial contexts. Second, the analysis relies on a one-year dataset, which, although sufficient to capture seasonal variations, may not fully represent long-term operational dynamics. Third, the environmental impact assessment is based on a deterministic emission model assuming constant fuel consumption, which does not account for operational variability such as equipment condition, operator behavior, or load differences.

Furthermore, the applicability of the LVG Model may depend on specific operational conditions, such as warehouse size, level of automation, and product variety. Highly automated systems or warehouses with dynamic real-time allocation may require adaptation of the model structure and decision parameters.

Looking forward, the LVG model can be further developed and adapted to warehouses in other industries with similar constraints, thereby expanding its role in enhancing efficiency and environmental sustainability on a broader scale. Future studies should also explore the integration of digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain with the LVG model to improve accuracy and effectiveness in product and data management.

Moreover, extending the assessment to include economic and social dimensions will elevate the value of this research by generating broader policy and industry-level impacts in pursuit of sustainable development. Furthermore, this study contributes to the development of an operationally grounded framework that can be extended toward statistical validation, simulation-based optimization, and broader theoretical generalization in future research. In addition, future research may incorporate statistical validation methods and sensitivity analysis to enhance the robustness and theoretical rigor of the LVG framework, as well as multi-case or cross-industry studies to further validate its scalability and applicability.

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Research Article

Land Use Changes after the Construction of the Xesalalong Reservoir: A Case Study of Three Villages in Thapangthong District, Savannakhet Province, Lao PDR

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ABSTRACT

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This study analyzed land use changes in three villages: Thongpang, Maiphosi, and Kouthi in Thapangthong District, Savannakhet Province, Lao PDR, following the construction of the Xesalalong Reservoir. Land use was classified into six categories: agricultural land (paddy fields and other agricultural land), water area, forest land, built-up land, roads, and cultural land, using Google Earth imagery combined with GIS analysis and field surveys. The total study area covered 6,653 ha. Between 2014 and 2024, agricultural land expanded substantially by 947.94 ha (+14.25%), driven primarily by paddy field expansion (+875.51 ha, +13.16%), which was the dominant form of land use change. Water area grew by 200.02 ha (+3.01%), built-up land by 40.36 ha (+0.61%), and cultural land by 7.74 ha (+0.12%). In contrast, forest land declined substantially by 1,193.65 ha (-17.94%), while roads decreased slightly by 2.41 ha (-0.04%). The overall classification accuracy was 81.5% with a Kappa coefficient of 0.76. The annual change rate indicated agricultural land expansion at +1.42% per year, contrasted with forest loss at -1.79% per year. These results demonstrate that reservoir construction and water management facilitated agricultural expansion, particularly paddy cultivation, while reducing forest cover. The findings highlight trade-offs between human land use and natural ecosystems and provide spatial evidence to support sustainable land and water management planning in rural Lao communities.

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1. Introduction

Land use reflects the relationship between human activities and ecosystems, particularly in rural areas where communities rely on agriculture and natural resources (Lambin *et al.*, 2001; Turner *et al.*, 2007). Land use changes are often influenced by economic, social, and infrastructural factors, such as water development projects, which can alter cropping patterns and expand cultivated areas (Hett *et al.*, 2012; Kamwi *et al.*, 2020). Therefore, studying land use changes is important for development planning, resource management, and sustainable land use (Loures, 2019; Gaur and Singh, 2023).

The study area includes three villages: Thongpang, Maiphosi, and Kouthi in Thapangthong District, Savannakhet Province, Lao PDR. These villages are adjacent and have

similar land use patterns. Originally, the communities mainly practiced subsistence agriculture using rainwater and natural water sources for cultivation. In 2014, the Xesalalong Reservoir was constructed near the communities, and water from the reservoir began to be used for agriculture around 2015 (China Daily, 2015; Lao News Agency, 2017).

The three villages were selected due to their geographical, lifestyle, and land use connections. Including all three villages allows for broader data coverage, enabling clearer and more comprehensive analysis of land use change patterns. Previous studies in the area focused on district-level land use change, emphasizing forest reduction and surrounding areas (Douangphachanh *et al.*, 2022). However, there remains a gap in understanding how village-level land use has changed in

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response to the Xesalong Reservoir, particularly with regard to the spatial patterns and rates of agricultural expansion versus forest loss at the local community scale. This study addresses this gap by analyzing land use changes between 2014 and 2024 in the three villages to examine spatial patterns and support local resource management, using Google Earth imagery as an accessible, high-resolution data source that effectively reflects land changes (Sheppard and Cizek, 2009; Yu and Gong, 2012). The results will provide insight into land use trends in rural Lao communities and support local development planning, water resource management, and sustainable land use.

2. Materials and Methods

This study is quantitative research combining secondary data from Google Earth imagery with field surveys to analyze land use changes in three villages: Thongpang, Maiphosi, and

Kouthi in Thapangthong District, Savannakhet Province, Lao PDR, located near the Xesalong Reservoir.

2.1 Study area

The study area includes Thongpang, Maiphosi, and Kouthi villages in Thapangthong District, Savannakhet Province, Lao PDR, situated near the Xesalong Reservoir, which was constructed in 2014 and started supplying water for agricultural use in 2015. The area ranges from 15°57'N to 16°04'N latitude and 105°46'E to 105°52'E longitude, covering a total of 6,653 ha. The three villages share similar geographic features, soil types, and environmental conditions. Their primary livelihood is rainfed agriculture, and local economic activities are closely tied to natural resources, making the area suitable for comparative analysis of land use changes following reservoir construction. As shown in Figure 1, the study area covers the three villages.

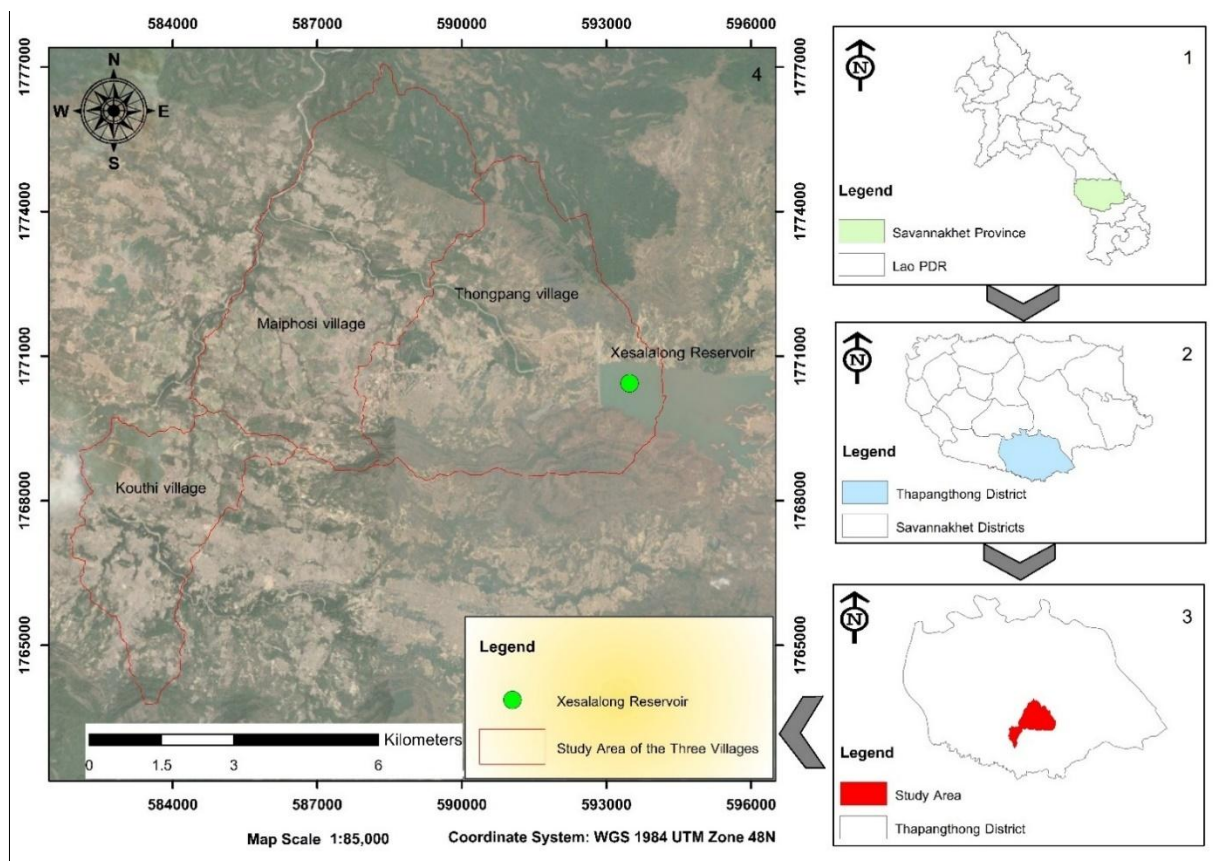


Figure 1 The study area covering the three villages.

2.2 Data collection

Google Earth Imagery: High-resolution Google Earth images from November 2014 (before reservoir utilization) and November 2024 (10 years after reservoir utilization) were used. November was selected because it represents the post-rainy season when agricultural land is fully utilized and cloud-free conditions are more frequent, ensuring clear imagery and comparability between years. Prior to analysis, the images were visually inspected for cloud cover, geometric distortion, and color consistency. Only cloud-free images with comparable color

balance and spatial resolution were selected for both time periods to minimize interpretation errors.

Field Surveys: Ground truth data were collected in 2024 to validate land use classification, including agricultural land, water area, forest land, built-up land, roads, and cultural land. GPS coordinates of sample points were recorded to support the accuracy assessment.

GIS Analysis: The imagery was georeferenced and re-projected to UTM WGS 1984 Zone 48N to align with actual coordinates. Land use boundaries were delineated through on-

screen visual interpretation and manual digitization in ArcGIS, using color, texture, shape, and pattern as the primary identification criteria. A minimum mapping unit of approximately 0.1 ha was applied to avoid excessive fragmentation of small features. In areas where land use types were ambiguous or transitional (e.g., forest-agricultural boundaries), field verification data and local knowledge were used to assign the most appropriate classification. Digitized areas were calculated in hectares. Land use change detection between 2014 and 2024 was carried out in terms of both absolute area and percentage. Change detection maps were then produced to illustrate spatial distribution patterns across the three villages.

2.3 Land use classification

Land use was classified into six main categories according to the Lao PDR National Land Law (National Assembly of Lao PDR, 2019):

- 1) Agricultural land: subdivided into paddy fields and other agricultural land, such as upland crops, cassava plantations, and pasture.
- 2) Water area: including reservoirs, rivers, and other water bodies.
- 3) Forest land: encompassing natural forest, secondary forest, and areas covered by trees.
- 4) Built-up land: including residential, commercial, and other constructed areas.
- 5) Roads: including main and secondary roads within the villages.
- 6) Cultural land: used for religious, traditional, or heritage purposes.

2.4 Accuracy assessment

To evaluate the accuracy of land use classification, 200 sample points were randomly selected across all six categories. A confusion matrix compared Google Earth classifications with field survey data. Overall Accuracy and Kappa coefficient were calculated. The classification achieved an Overall Accuracy of 81.5% and a Kappa coefficient of 0.76, which is considered acceptable for analyzing land use changes at this scale (Congalton and Green, 2019). Potential sources of classification error included seasonal variation in vegetation appearance, mixed pixels in transitional zones between forest and agricultural land, and differences in image quality between the two time periods. These limitations were mitigated through field verification and cross-referencing with local land use records.

2.5 Annual change rate

The annual change rate for each land use type was calculated using the formula:

$$\text{Annual Rate (\%/year)} = \frac{\text{Changes\%}}{\text{Number of Year}} \quad (1)$$

Where Change (%) is the percentage of land use change between 2014 and 2024, calculated as the difference in area divided by the total study area and multiplied by 100, and Number of Years = 10 (i.e., the period from 2014 to 2024). This formula assumes a linear rate of change over the study period and allows for standardized comparison of the speed and direction of change for each land use category, such as the expansion of agricultural land and the reduction of forest land.

3. Results and Discussion

3.1 Overall land use change in three villages

Comparison of land use before and after the utilization of the Xesalong Reservoir revealed a total change of 2,392.12 ha, accounting for 35.96%. Agricultural land increased by 947.94 ha (+14.25%), of which paddy fields contributed 875.51 ha (+13.16%) and other agricultural land (including upland crops, cassava plantations, and pastures) increased by 72.43 ha (+1.09%). Water area expanded by 200.02 ha (+3.01%), built-up land increased by 40.36 ha (+0.61%), and cultural land increased by 7.74 ha (+0.12%). In contrast, forest land decreased by 1,193.65 ha (-17.94%), and roads declined slightly by 2.41 ha (-0.04%).

Accuracy assessment indicated an Overall Accuracy of approximately 81.5% and a Kappa coefficient of 0.76, which is considered acceptable to good. The highest classification accuracy was observed for agricultural land and paddy fields, while forest and built-up land were moderately accurate but still sufficient for land use change analysis.

The annual change rate showed that overall agricultural land expanded at an average of +1.42% per year, particularly paddy fields at +1.31% per year. Other agricultural land and water area increased slightly at +0.10% and +0.30% per year, respectively. In contrast, forest land declined significantly at an average rate of -1.79% per year, indicating a clear trend of agricultural expansion, especially paddy cultivation, alongside continuous forest reduction. Table 1 summarizes the overall land use change in the three villages between 2014 and 2024, while Figure 2 presents the spatial distribution of land use change over the study period.

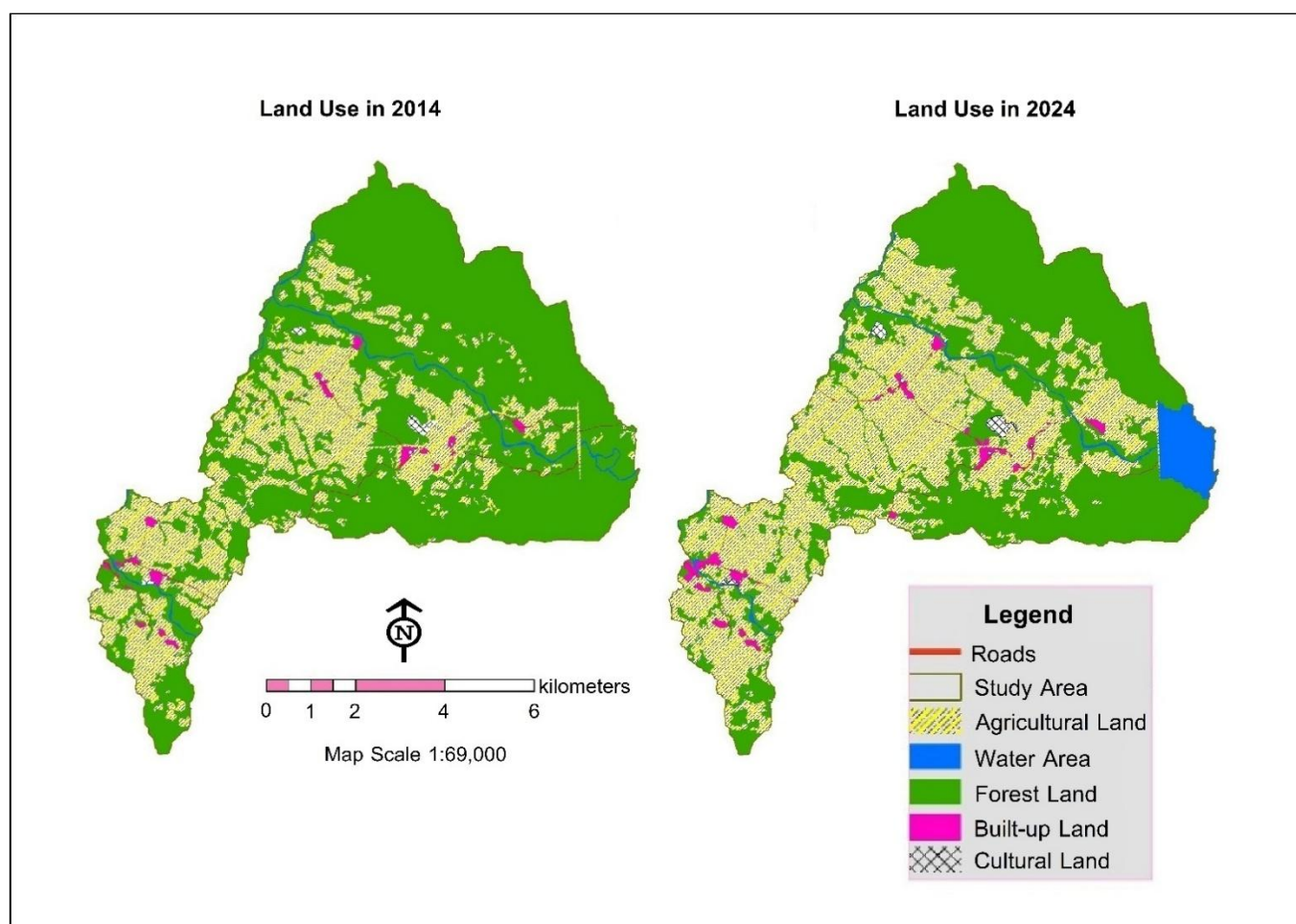
3.2 Land use change in individual villages

3.2.1 Thongpang village

The total land use change was 1,016.06 ha (37.62%). Agricultural land increased by 295.56 ha (+10.94%), of which paddy fields expanded by 282.41 ha (+10.46%) and other agricultural land increased by 13.15 ha (+0.49%). Water area increased by 197.83 ha (+7.33%), built-up land by 11.98 ha (+0.44%), and cultural land by 2.66 ha (+0.10%). Forest land showed the largest decrease of 504.97 ha (-18.70%), and roads declined slightly by 3.06 ha (-0.11%). Table 2 shows land use change in Thongpang village between 2014 and 2024.

Table 1 Summary of land use change in the three villages between 2014 and 2024.

No.	Type of land	2014 Area (ha)	2014 (%)	2024 Area (ha)	2024 (%)	Change area (ha)	Change (%)
1	Agricultural land	2,088.10	31.39	3,036.04	45.63	+947.94	+14.25
1.1	Paddy fields	2,056.16	30.91	2,931.67	44.07	+875.51	+13.16
1.2	Other agricultural land	31.94	0.48	104.37	1.57	+72.43	+1.09
2	Water area	65.58	0.99	265.60	3.99	+200.02	+3.01
3	Forest land	4,392.32	66.02	3,198.67	48.08	-1,193.65	-17.94
4	Built-up land	60.18	0.90	100.54	1.51	+40.36	+0.61
5	Roads	23.73	0.36	21.32	0.32	-2.41	-0.04
6	Cultural land	23.09	0.35	30.83	0.46	+7.74	+0.12
Total		6,653.00	100.00	6,653.00	100.00	2,392.12	35.96

**Figure 2** Land use change map of the three villages between 2014 and 2024.

3.2.2 Maiphosi village

The total land use change was 960.92 ha (36.08%). Agricultural land increased the most, by 467.94 ha (+17.57%), of which paddy fields increased by 447.86 ha (+16.82%) and other agricultural land by 20.08 ha (+0.75%). Built-up land increased by 7.60 ha (+0.29%), cultural land by 4.33 ha (+0.16%), roads by 0.31 ha (+0.01%), and water area by 0.28

ha (+0.01%). Forest land decreased the most, by 480.46 ha (-18.04%). Table 3 presents land use change in Maiphosi village between 2014 and 2024.

3.2.3 Kouthi village

The total land use change was 416.44 ha (32.30%). Agricultural land increased by 184.44 ha (+14.30%), including paddy fields (+145.24 ha, +11.26%) and other agricultural land

(+39.20 ha, +3.04%). Built-up land increased by 20.78 ha (+1.61%), reflecting residential expansion as the community grew in response to improved agricultural productivity. Water area increased slightly by 1.91 ha (+0.15%), as Kouthi Village is located farther from the main reservoir compared to Thongpang Village. Cultural land increased by 0.75 ha

(+0.06%), and roads by 0.34 ha (+0.03%), indicating modest infrastructure development. Forest land declined by 208.22 ha (-16.15%), primarily due to conversion to paddy fields and other agricultural uses driven by increased water availability from the reservoir. Table 4 shows land use change in Kouthi village between 2014 and 2024.

Table 2 Land use change in Thongpang village between 2014 and 2024.

No.	Type of land	2014 Area (ha)	2014 (%)	2024 Area (ha)	2024 (%)	Change area (ha)	Change (%)
1	Agricultural land	439.14	16.26	734.70	27.21	+295.56	+10.94
1.1	Paddy fields	436.84	16.18	719.25	26.63	+282.41	+10.46
1.2	Other agricultural land	2.30	0.09	15.45	0.57	+13.15	+0.49
2	Water area	27.79	1.03	225.62	8.35	+197.83	+7.33
3	Forest land	2,185.64	80.93	1,680.67	62.23	-504.97	-18.70
4	Built-up land	20.18	0.75	32.16	1.19	+11.98	+0.44
5	Roads	12.08	0.45	9.02	0.33	-3.06	-0.11
6	Cultural land	15.72	0.58	18.38	0.68	+2.66	+0.10
Total		2,700.55	100.00	2,700.55	100.00	1,016.06	37.62

Table 3 Land use change in Maiphosi village between 2014 and 2024.

No.	Type of land	2014 Area (ha)	2014 (%)	2024 Area (ha)	2024 (%)	Change area (ha)	Change (%)
1	Agricultural land	935.48	35.13	1403.42	52.70	+467.94	+17.57
1.1	Paddy fields	919.57	34.53	1367.43	51.35	+447.86	+16.82
1.2	Other agricultural land	15.91	0.60	35.99	1.35	+20.08	+0.75
2	Water area	25	0.94	25.28	0.95	+0.28	+0.01
3	Forest land	1,678.94	63.05	1,198.48	45.01	-480.46	-18.04
4	Built-up land	12.48	0.47	20.08	0.75	+7.60	+0.29
5	Roads	6	0.23	6.31	0.24	+0.31	+0.01
6	Cultural land	4.97	0.19	9.3	0.35	+4.33	+0.16
Total		2,662.87	100.00	2,662.87	100.00	960.92	36.08

Table 4 Land use change in Kouthi village between 2014 and 2024.

No.	Type of land	2014 Area (ha)	2014 (%)	2024 Area (ha)	2024 (%)	Change area (ha)	Change (%)
1	Agricultural land	713.48	55.33	897.92	69.63	+184.44	+14.30
1.1	Paddy fields	699.75	54.26	844.99	65.52	+145.24	+11.26
1.2	Other agricultural land	13.73	1.06	52.93	4.10	+39.20	+3.04
2	Water area	12.79	0.99	14.70	1.14	+1.91	+0.15
3	Forest land	527.74	40.92	319.52	24.78	-208.22	-16.15
4	Built-up land	27.52	2.13	48.30	3.75	+20.78	+1.61
5	Roads	5.65	0.44	5.99	0.46	+0.34	+0.03
6	Cultural land	2.40	0.19	3.15	0.24	+0.75	+0.06
Total		1,289.58	100.00	1,289.58	100.00	416.44	32.30

3.3 Discussion

In the comparison of land use change characteristics among the three villages, a consistent trend was observed. Agricultural land increased significantly in all villages, particularly paddy fields, which were the main driver of agricultural expansion. Simultaneously, forest land decreased the most across all villages, reflecting the direct impact of land use restructuring following the operation of the Xesalong Reservoir. In addition, water areas, built-up land, and cultural land showed slight increases in all villages, indicating community adaptation and increased utilization of land for human activities.

However, each village exhibited distinct characteristics. Maiphosi Village showed the highest increase in agricultural land, both in terms of area and proportion, whereas Thongpang Village experienced the greatest loss of forest land and the most substantial increase in water area. Notably, Thongpang was the only village where road areas decreased. In contrast, Kouthi Village, despite showing the lowest overall land use change, had a higher proportional increase in other agricultural land and built-up land compared to the other villages. Overall, land use changes in the three villages followed similar main trends but also reflected variations according to local context and resource utilization in each community.

The land use patterns of the three villages prior to the operation of the Xesalong Reservoir in 2014 are consistent with Chaikaew (2019), who studied land use structures in the Klong Kui Reservoir area in the same year. Chaikaew reported that forest land occupied the largest proportion (54.8%), followed by agricultural land (36.98%) and water areas (2.59%), with paddy fields being the dominant type of agricultural land (11.05%), while upland crops, cassava, and grasslands together accounted for 25.93%. However, these findings differ from those of Sribunkhum *et al.* (2021), who analysed land use in the Lam Dom Yai sub-watershed in 2014 and found that agricultural land had the highest proportion (72.86%), followed by forest land (16.74%), built-up areas (4.95%), miscellaneous land (3.43%), and water areas (2.01%). These differences likely reflect variations in socioeconomic conditions, which influence land use patterns, particularly the proportion of agricultural land closely related to community livelihoods and the role of agriculture in sustaining local life.

After the operation of the Xesalong Reservoir in 2024, land use patterns of the three villages were similar to those reported by Agumagu *et al.* (2025), who analysed land use and land cover in the Niger Delta, Nigeria, in the same year. They found that forest land occupied the largest proportion (50.5%), divided into tropical forest (27.6%) and mangrove forest (22.9%), followed by agricultural land (29.07%), built-up land (18.5%), and water areas (1.9%). Although the proportions differ, both cases indicate that forest and agricultural lands continue to dominate land use. Similarly, Faksomboon *et al.* (2022) reported that in the Pong Nam Ron sub-watershed, Kamphaeng Phet

Province in 2024, forest land accounted for 91.23%, followed by agricultural land (7.89%), built-up land (0.37%), water areas (0.32%), and miscellaneous land (0.10%), highlighting the continued importance of forest and agricultural lands despite differences in geographical and socioeconomic contexts.

The study of land use changes in the three villages between 2014 and 2024 revealed that agricultural land increased more than any other land type, with a total increase of 947.94 ha (+14.25%), particularly paddy fields, which increased by 875.51 ha (+13.16%). This trend was driven by the construction and operation of the Xesalong Reservoir, which provided sufficient water for double-cropping of rice (wet and dry seasons), enabling local communities to expand agricultural production to meet both consumption and market demands. Meanwhile, forest land decreased the most, losing 1,193.65 ha (-17.94%), mainly due to the conversion of forest areas to agricultural land, especially paddy fields and gardens, as well as partial conversion to the reservoir area, resulting in a clear reduction in forest cover.

These findings are consistent with previous studies. Toemton (2021), who analysed the Royal Initiative Project at Doi Bae Lae Highland Agriculture Development Station, Chiang Mai (2013–2020), reported a 34.62% increase in agricultural land, particularly paddy fields (+42.39%), while other agricultural lands decreased by 7.77% and built-up areas increased by 8.42%. Similarly, Ibrahim *et al.* (2025) found in the Black Belt region of Alabama, USA, that conversion from forest to agricultural land affected rainfall, temperature, and ecosystems, requiring adaptation in agriculture and environment. Zhang (2023) also noted that such land use changes impact biodiversity and natural resource utilization, reflecting potential effects in the study area.

However, some studies show contrasting trends. For example, Rakuasa and Achmadi (2024) reported that in Slawi Subdistrict, Tegal Regency (2014–2024), agricultural land decreased by 9.03%, while built-up areas increased by 9.21%. Toemton (2021) also observed that although paddy fields increased, other agricultural lands and water areas decreased significantly, differing from the Xesalong study area, where the reservoir supported agricultural expansion, leading to increases in water and other agricultural lands.

These comparisons illustrate that land use changes vary according to geographic, economic, water management policy, and community livelihood contexts. While some trends, such as the expansion of paddy fields, may be similar, overall land use change is strongly influenced by local factors.

4. Conclusion

Between 2014 and 2024, the total land use change in the three villages near Xesalong Reservoir reached 2,392.12 ha (35.96%) of 6,653 ha. Agricultural land increased by 947.94 ha (14.25%), mainly due to paddy fields expansion (+875.51 ha,

13.16%), corresponding to an annual change rate of +1.42% per year for agricultural land and +1.31% per year for paddy fields. Forest land decreased by 1,193.65 ha (-17.94%), with an annual decrease rate of -1.79% per year. Water areas, built-up land, roads, and cultural land changed at lower rates (+0.30%, +0.06%, -0.004%, and +0.01% per year, respectively). These results highlight the role of water management in promoting agricultural expansion while leading to forest loss. These land use change patterns are strongly influenced by local geography, socioeconomics, and community livelihoods.

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Research Article

A Solar Powered Ultrasonic Water Level Monitoring System with IoT Type for Small-Scale Agricultural Water Management

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ABSTRACT

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This research aims to develop and evaluate the performance of an ultrasonic water level meter prototype by applying solar power and an IoT network communication system to support the management of small water resources in community-level agricultural areas. The prototype is designed to be low-cost to implement non-contact measurements and to be able to transmit real-time data to a central server and display results on a mobile application. There are 5 units that have been installed in agricultural areas in lower northeastern Thailand to create a network of water databases reflecting the situation from multiple sources simultaneously. Laboratory testing results showed an average measurement error of 1.36%, which was within acceptable limits while field testing with five agencies, totaling 20 times, indicated an average success rate of 90.2%, with the water level measurement accuracy at 92.5%, ease of installation and practical use at 100%, and data transmission continuity and power durability at 88.3%. These results confirm the potential of combining low-cost sensor technologies, renewable energy, and IoT to create a collaborative water management network prototype across multiple water bodies, and this prototype is practical and field-ready.

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1. Introduction

Local water management is critical for the agriculture sector because it is Thailand's major water consumer, accounting for around 70% of overall water consumption (Thai National Committee on Irrigation and Drainage, 2024). Most rural areas rely on small water sources and reserves for off-season cultivation. These sources not only serve as storage to meet water demands during the dry season but also serve as a crucial mechanism for maintaining continuous agricultural production, which impacts food security and farmers' incomes in the region, particularly in the Northeast, the country's largest agricultural region (National Statistical Office, 2024). The region has been

reported to be continuously at a high risk of drought (Chatklang *et al.*, 2024). This causes the area to be highly vulnerable to climate fluctuations. Recent drought index research indicates that the trend of consecutive dry days is increasing in the Northeast (Oliveira-Júnior *et al.*, 2025). Consequently, it has a direct influence on field crop productivity and the availability of reserve water supplies. Furthermore, an examination of water usage efficiency in Thailand revealed that it has fallen by more than 21% in recent years while the level of water stress has risen from 9.68% to 13.8% in numerous river basins (Theprasit *et al.*, 2025). This indicates greater pressure on the water system in the cultivation area.

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Despite the importance of water management, remote areas continue to face structural and practical limitations. Limited personnel are available, while water sources are numerous and widely dispersed. This causes the impossibility of continuously and consistently monitoring water levels at all sources. Moreover, daily field visits are nearly impossible, leading to individual water users utilizing water as needed without coordinated planning. Furthermore, there is no centralized database that clearly reflects the water level situation in each area and how much water remains. These problems lead to unbalanced water usage, the risk of water shortages before the end of the growing season, and the possibility of inequitable in water distribution to various stakeholders. The previous research has attempted to apply IoT technology and information systems to support water management. It has been found that measurement accuracy and support for predictive analysis could be increased. However, most of the research still has been focused on development in the context of large-scale irrigation systems or industrial applications rather than community-level agricultural areas (Mu and Antwi-Afari, 2023). Moreover, some research showed that the utilization of IoT in conjunction with data analytics could actually improve water management, yet it was limited to the individual plot level and did not cover linking data from multiple water sources to a central system (Ngamsin *et al.*, 2024). Furthermore, research on flood monitoring systems using low-cost sensors has highlighted the potential of IoT technology in the field, but it has focused solely on warning of floods and has not evolved to support collaborative water allocation in agricultural areas (Choosumrong *et al.*, 2025). In addition to the work that applies IoT to directly measure water levels, several recent studies have applied GIS and remote sensing technologies to support water management, such as drought-risk area assessment, reservoir condition analysis, and spatial mapping (Kumar *et al.*, 2024; Rabie *et al.*, 2025). This offers an in-depth overview of the watershed, although the main limitation is that it is unable to evaluate water levels in minor community water sources in real time. It relies on satellite imagery with a relatively long data collection period, making it unsuitable for daily, local decision-making. Meanwhile, research is underway on the application of AI to forecast water levels or analyze risks (Azad *et al.*, 2025; Panta *et al.*, 2025). Despite its potential for in-depth data analysis, it relies on data from existing monitoring stations, causing it to be inapplicable to areas without basic water level monitoring systems. A review of research reveals that there is no multi-point water-level network that transmits data to a central server that is low-power and suitable for rural contexts where electricity and internet are lacking. Furthermore, there is no system that is able to be applied to support integrated, multi-source water management at the community level. Therefore, despite research demonstrating progress in the use of IoT and intelligent systems for water management, there has been no development of a prototype

multi-point water level monitoring network connected to a central system to serve as a centralized database for simultaneous water management from multiple water sources in rural areas. This is a key gap that this research aims to address and further develop.

To address the aforementioned issue, this research aims (1) to develop a prototype ultrasonic water level meter that is able to measure water levels without contact and transmit data via an IoT network to a central server in real time, with display results via a mobile phone application to enable users to monitor water level situations from multiple sources in the same system; and (2) to test the prototype's performance at both the laboratory and field levels. The 5 prototypes were installed in agricultural areas in the lower northeastern region to evaluate their accuracy, data transmission stability, and suitability for practical use. The resulting data had the potential to support community and local government decision-making, including collaborative water management across multiple water sources.

2. Materials and Methods

2.1 Population and samples

The population of this research was community-level agricultural water resource management personnel who were the target users of the prototype system. The sample consisted of 5 field officers from 5 provinces: Surin, Buriram, Sisaket, Roi Et, and Kalasin. The population was specifically selected based on the criteria that participants were required to be officers of agencies directly involved in water level monitoring, water resource management, and water management in the area, with more than 5 years of experience in this field to ensure that participants understood the actual working process and were able to evaluate the efficiency of the prototype system.

2.2 Design of research instruments

In this study, the research instruments were developed in two main parts: The first was the design and development of an ultrasonic sensor-based water level measuring device, and the second was the development of a usability assessment form for field officers. The details of the procedures are described as follows.

2.2.1 Design and development of an ultrasonic sensor based water level measuring device

This research referenced the embedded system design methodology (Marwedel, 2011) framework as the main framework for prototype development. However, some steps were modified and expanded to be consistent with the context of rural agricultural areas with limitations in communication signals, electricity, and variable field environments. Specifically, steps included the survey of actual site conditions, energy-oriented design for solar cell systems, adaptation of the architecture to support multiple networks, and testing of the

system under real weather conditions. Details of the process in each step are presented in the following subsections.

1) Determination of requirements: Field visits with local government officials revealed that one field officer was responsible for multiple agricultural water sources that were dispersed and far apart. This physical survey to obtain real-time water level data found its limitations of time, distance, and budget. This resulted in farmers lacking information on water usage situations without coordinating plans and being unaware of trends in water level decline, leading to problems of water running out before plants reach their full growth stage and inadequate water use. To address this issue, the system's functional requirements were defined as (1) continuously measuring water levels in the field by applying a non-contact method; (2) transmitting real-time or semi-real-time data to the cloud via a rurally accessible communication network (3G/4G); and 3) displaying and alerting via a mobile application to support operational decision-making by officials and water users.

2) Components of the system included a 40-watt solar panel and a 12V 15Ah battery for power and backup, a charging control system, and electrical protection circuits for enhanced safety, a voltage converter circuit to power the NodeMCU ESP8266 microcontroller, which served as the sensor processor and control unit, a 3G/4G router module for mobile network data communication, and an HC-SR04 ultrasonic sensor for non-contact water level measurement. According to the equipment specifications, the system had a total power consumption of approximately 3–4 watts in continuous operation, which was equivalent to approximately 72–96 Wh per day. A 40-watt solar panel can produce approximately 160–200 Wh per day under average sunlight conditions of 4–5 hours per day. A 12V 15Ah battery had an energy capacity of approximately 180 Wh, which, according to rough calculations, was able to support the system operation for approximately 36–48 hours in the absence of sunlight. This numerical analysis was implemented to support the selection of solar panel and battery sizes for rural applications.

3) Prototype development and functional testing: Once the system components were as specified, the entire device was assembled into a prototype water level meter, starting with the installation of an electrical circuit between the solar panels, charge controller, and battery to test its ability to supply continuous power. Afterwards, the voltage converter circuit was connected to the NodeMCU ESP8266 board and the HC-SR04 ultrasonic sensor to control the distance measurement and convert the value to water level. The circuit connection is shown in Figure 1. Programming was carried out with Arduino IDE by developing a set of commands for reading values from sensors. This showed the performance of preliminary processing and sending data via HTTP request to the Ubuntu server, which was installed to act as a cloud server, communicating via a 3G/4G router module to support work in areas without a LAN network

and displaying the results via mobile applications. The system architecture is shown in Figure 2.

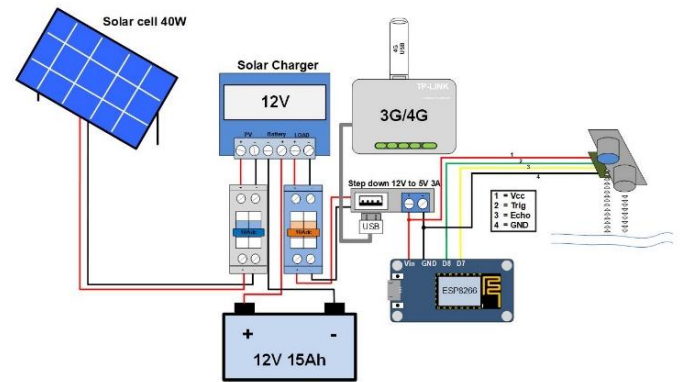


Figure 1 Circuit architecture.



Figure 2 Overall system architecture.

The system accuracy test was performed in a laboratory, which applied a 20-liter water tank with a water level scale marked on the tank wall in centimeters as a ground truth. The water level was then controlled by adding and releasing it in stages, with a level change range of every 5 centimeters, totaling at least 15 measurement points in each cycle. Afterwards, the experiment was repeated 3 times to obtain reliable values. After adding or releasing water at each water level point, a 10-15 second delay was set to allow the water surface to settle before recording the experimental equipment's readings. The system was set to read values continuously every 1 second for 30 seconds per water level. The acquired data was subsequently applied to generate an average value that represented the actual measured water level. The values read from the device were compared with the standard values from the water tank scale, and the error value was calculated according to Equation (1). This step was tested by 3 experts who have knowledge of embedded systems and data communication.

$$\text{Error (\%)} = \frac{|\text{Measured} - \text{Actual}|}{\text{Actual}} \times 100 \quad (1)$$

4) Improvement and validation: After the prototype passed laboratory testing, the water level meter was installed and tested in 5 provinces before being handed over to officials for field system readiness inspection. Following that, it was necessary to transfer knowledge and teach the field staff how to operate the machine in detail, which included checking the equipment's status, reading values through the application, and performing basic maintenance. The installation location map is displayed in Figure 3.

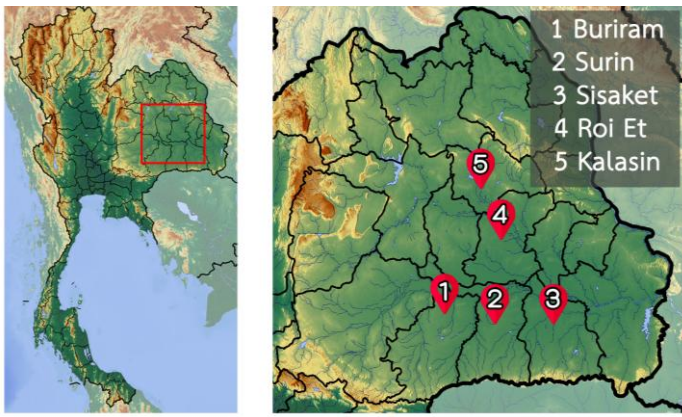


Figure 3 Water level sensor installation map.

2.2.2 Design and validation of the evaluation questionnaire for field officers: The test was designed to reflect the system's performance in terms of water level measurement accuracy, data transmission stability, ease of installation and usage, and suitability for usage in real field conditions. The test format applied field testing methodologies, defining specific test items such as calibration measurements, results presentation on applications, and continuous operation with solar power. The test results were recorded in a pass/fail format to avoid subjective evaluations and to obtain factual information about the system's operation. The test was reviewed by 3 experts in the field of computer technology with over 10 years of experience to check the content validity and appropriateness of the test items (IOC) before being used with field personnel.

2.3 Data collection

After the installation of the equipment, the performance was continuously monitored for a period of one month. The system was set to transmit water level data and timestamps to a central server at fixed intervals every day, while also recording the power system operation status and data transmission. Field personnel performed inspections 7 times a week. This test consisted of monitoring the actual water level at the water source, comparing the values with the data displayed on the application, verifying the solar panel power stability, and assessing the availability of equipment at each location. The evaluation variables included (1) the measured water level, (2) the data transmission status, and (3) the power system status. The evaluation criteria were established as the functional criteria of the system, including the continuity of data transmission, daily availability, and the accuracy of the values displayed on the system compared to field inspections. After the test period, 5 operators completed an online questionnaire to evaluate the ease of installation, usage, and suitability of the system in the actual field.

2.4 Data analysis

Data analysis was performed by utilizing descriptive statistics to summarize the test results from 5 field operators who continuously evaluated the prototype system 4 times (total

of 20 datasets) in quantitative terms by calculating the number of times the system could operate according to the criteria (frequency) and converting the results into percentage of success (percentage) in each evaluation item, which is calculated from Equation (2).

$$\text{Success Rate (\%)} = \frac{\text{Passed Tests}}{\text{Total Tests}} \times 100 \quad (2)$$

3. Results and Discussion

3.1 Laboratory test results for prototype water level meter

The accuracy results that are presented in this section are derived from the laboratory calibration process described in section 2.2.1, which involved testing the prototype in a controlled environment using a 20 L water tank with 15 water level measurement points and repeatable measurements for reliability. It found that the device was able to measure water level values close to the actual values from the standard scale, with an error value in the range of 0.2–4.0 % and an average error value of approximately 1.36 %. The experimental results indicated that the error tended to be higher at low water levels (e.g., 5 cm) and decreased with increasing water levels, with the error values being less than 2% at water levels of 20–50 cm, which was considered acceptable. The experimental results are shown in Table 1.

From Figure 4(a), the graph comparing the actual water level with the measured value indicates a clear linear relationship, where the measured value frequently remains near the reference line of the actual value almost throughout the measurement range. While Figure 4(b) demonstrates the percentage error plot at each point, it indicates the distribution pattern of error values, which, although they appear slightly higher during low water levels, when the water level increases, the error values become stable and remain low.

From the research results, it could be discussed that the accuracy of the developed ultrasonic water level meter reflected that the device was at a low average error value (approximately 1.36%), which was considered acceptable for prototype usage. Several worldwide studies pointed to the same tendency, notably in low-cost laboratory testing of devices with errors in the range of 1-5% (Ding *et al.*, 2025; Masoudimoghaddam *et al.*, 2024). It indicated that the developed instrument had performance consistent with academic standards. When considering the results at each point, it was found that the error tended to be higher at shallow water levels, especially in the range of 5 centimeters, where the maximum error value was up to 4%, which was a common result found in ultrasonic devices caused by entering the dead zone of the sensor and incomplete reflection of sound waves. This observation is consistent with the experimental results of Kim *et al.* (2024) and Pereira *et al.* (2022), who reported that the accuracy of ultrasonic measurements

decreased significantly when measurements were performed at low water levels. Furthermore, the research of Duangso *et al.* (2025) confirmed this observation by finding that the measurements in open channels increased errors in shallow water and intermittent flow. In terms of error-causing factors, it was possibly due to the variation of the speed of sound in air depending on temperature and humidity, which was possibly an important variable affecting the accuracy of the measurement,

including interference from air bubbles at the water surface and reflections from the walls of the water tank, which cause the signal to deviate from the true value (Yusupov *et al.*, 2023). In addition, the physical design of the device, including the sensor mounting angle, directly affected the quality of the wave reflection (Mydlarz *et al.*, 2024), requiring the use of multi-point calibration and temperature compensation to increase the stability of the measured values.

Table 1 Laboratory calibration and performance test results of the water level sensor.

Measurement Point	Actual Water Level (cm)	Measured Water Level (cm)	Error (cm)	Error (%)
1.	5	5.2	0.2	4.0
2.	10	9.8	-0.2	2.0
3.	15	15.3	0.3	2.0
4.	20	19.7	-0.3	1.5
5.	25	24.9	-0.1	0.4
6.	30	30.2	0.2	0.7
7.	35	35.5	0.5	1.4
8.	40	39.8	-0.2	0.5
9.	45	45.4	0.4	0.9
10.	50	50.1	0.1	0.2

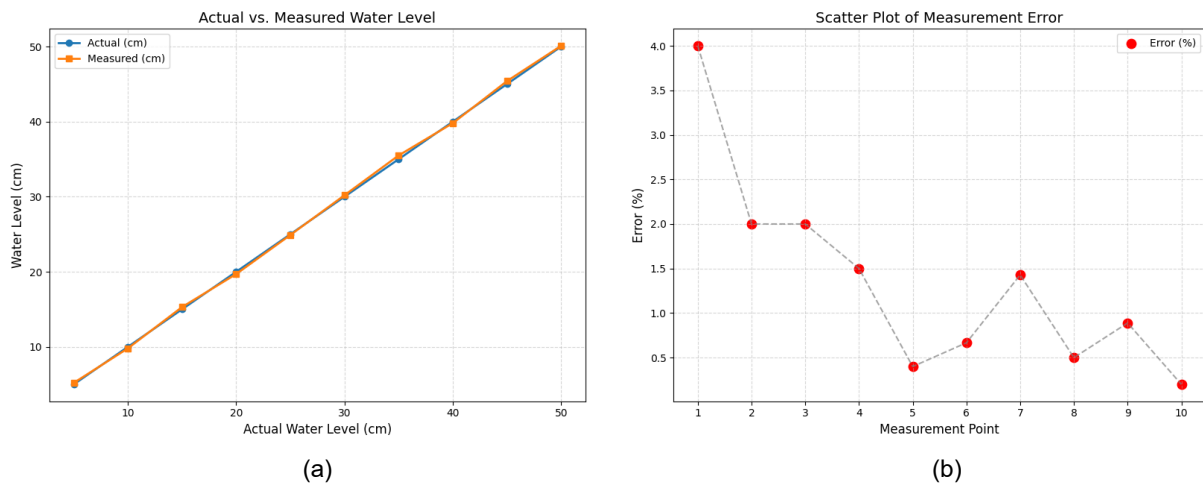


Figure 4 Laboratory calibration results: Actual vs. measured water levels.

In laboratory testing, the system was calibrated by comparing the readings to the actual values from a specified scale in a water tank as per the procedure in section 2.2.1, which gave an average error of 1.36%. However, the experiment was not designed to collect a large amount of data for generating a calibration curve or regression equation capable of reporting R^2 values and uncertainty analysis according to metric calibration standards. This research primarily focuses on evaluating the functional accuracy of the prototype at the laboratory and field level and thus applies the average of repeated measurements as a representative of the initial calibration results. This limitation is identified as part of the

research scope, and it is proposed to conduct metric calibration in future research in case a commercial system is developed.

Based on the experimental results and sensor characteristics, the overall measurement error was able to be explained through a factor analysis framework. It was found that changes in temperature and humidity, which affected the speed of sound waves in air, possibly caused errors in the range of approximately 0.1–0.3% according to the device specifications, while multipath reflections and sensor dead zones were important factors that increased the errors, especially in shallow water, which was consistent with the high errors found in the experiments. Water surface turbulence also causes instability in the reflected signal and may add additional errors. A sensor

mounting angle deviating from the perpendicular by 90 degrees caused the sound wave travel distance to be inaccurate and caused the measured value to deviate from the true value. All these factors were consistent with the average error of 1.36% found experimentally and were within the expected range for low-cost ultrasonic devices.

3.2 Field test results

Figure 5 shows the development results of a prototype water level meter installed in an agricultural area. The system consists of a solar panel for power supply and a control box containing a microcontroller circuit and a data communication module. It is linked to a mobile phone application to display the water level value in real time.



Figure 5 Field installation results.

The field test results with 5 agencies' personnel, 20 times per item (data recorded once per week for each person over a period of 1 month), found that the prototype water level meter was at an average success rate of 90.2%, with the most effective aspects being ease of installation and readiness of the device in real-world conditions, with a success rate of 95%. Subsequently, it was the accuracy of water level measurement compared to the water level pole with a success rate of 92.5%, while the continuity of data transmission and power durability was at an average success rate of 88.3%, indicating that the system effectively worked. The test details are shown in Table 2.

The field test results were able to be discussed, and the average success rate of 90.2% reflects the effectiveness of system design that focuses on suitability to the real context of agricultural areas. The ease of installation and practicality score of 100% is attributed to the design's simplified structure and modular approach, facilitating users to assemble and maintain. This is in line with the trend of developing field water measurement systems that focus on low-cost IoT and user-friendly design (James *et al.*, 2021). Meanwhile, the accuracy of water level measurement of 92.5% is explained by field calibration and design to reduce the interference of reflected signal by adjusting the installation angle to 90° to the water surface. This allows the sound wave reflection to be aligned with the receiver, which reduces the error from false echo, thus making the value obtained close to the measurement standard

(Gao *et al.*, 2021; Tawalbeh *et al.*, 2023). The data transmission continuity and power durability scores of 88.3% indicate limitations of relying on solar power during inclement weather conditions, especially on cloudy or rainy days. This finding is consistent with the report by Qian *et al.* (2023), who studied a wireless water quality monitoring system powered by solar panels and found that the intensity of the generated electrical energy depends on solar radiation. When sunlight decreases or during cloudy days, the system's performance declines, requiring the use of backup battery management to maintain continuous operation. However, the developed system could continue to operate with backup power, which is in line with technical proposals to increase the reliability of environmental IoT networks (Ajibola and Ogbolumani, 2024). Overall, the success of this field test is not solely due to the sensor's accuracy but also to the system's integrated design of power, communication, and ease of use.

In field tests, the system was configured to transmit data once a day to accommodate power constraints and signal instability in rural areas. This resulted in insufficiently detailed time-series logs for calculating network metrics such as RSSI, latency, and packet loss, or statistical values such as mean, standard deviation, and scatter. Evaluation of system stability and communication quality was therefore performed using functional performance checks, including daily transmission success, system availability, and events where the system was unable to transmit due to signal or power factors. This approach is consistent with the nature of IoT prototype testing in rural areas, which focuses on verifying real-world performance rather than collecting in-depth network statistics, which is in line with research by Zubaidah *et al.* (2025), where system evaluation also relied on functional indicators like transmission success and operational continuity rather than detailed network-level metrics.

Field testing results revealed that the main causes of data loss were both network and power factors. In rural areas, unstable mobile network signals led to intermittent dropouts and data packet loss. This is consistent with findings from field IoT research that indicated weak signals and limited telecommunications infrastructure were key factors in data loss in sensor systems. Additionally, during the rainy season, when rainfall lasted for up to 7 days, solar panel power generation dropped significantly to the point where it was insufficient to charge the batteries, causing the system to temporarily stop transmitting data before resuming operation when sufficient sunlight was available the next day. The data during this period were recorded based on observations between the research team and field personnel. This limitation highlights the requirement for more efficient energy management systems, such as applying high-capacity batteries or hybrid wind power systems, or adjusting the transmission interval based on remaining power levels, as well as increasing the number of cell

towers or using communication modules that support frequency bands suitable for rural areas, to enhance network stability and reduce future transmission losses.

Table 2 Field performance test results of the water level sensor (20 trials).

No	Evaluation Item	Pass (Times)	Fail (Times)	Success Rate (%)
Aspect 1: Accuracy of water level measurement				
1.	The system display corresponds to the staff gauge (error not exceeding ± 1 cm or $\pm 2\%$).	19	1	95.0
2.	Repeated measurements (3 times) yield similar results (standard deviation ≤ 0.5 cm).	18	2	90.0
Total		37	3	92.5
Aspect 2: Data transmission continuity and power durability				
3.	The system records data at least once daily for 30 consecutive days.	17	3	85.0
4.	The system records data $\geq 95\%$ of the total weekly time.	18	2	90.0
5.	No data gaps exceeding one day.	18	2	90
Total		53	7	88.3
Aspect 3: Power Durability				
6.	The system operates continuously every night (verified by morning data transmissions).	17	3	85.0
7.	The system maintains data transmission $\geq 90\%$ during consecutive cloudy or rainy days.	18	2	90.0
8.	The system operates for at least 24 hours without sunlight (e.g., during continuous rainfall).	18	2	90.0
Total		53	7	88.3
Aspect 4: Ease of installation and practicality				
9.	The device can be fully installed according to the manual within ≤ 60 minutes.	5	0	100.0
10.	The sensor head remains in proper condition with no obstructions or abnormal water disturbances during readings, verified weekly.	19	1	95.0
Total		24	1	96.0
All 10 Evaluation Items		167	18	90.2

4. Conclusion

This research successfully develops a prototype ultrasonic water level measurement system that combines solar power, non-contact measurement, and real-time data communication via an IoT infrastructure. The novelty of this work lies in the system's design to operate in a multi-point network, which has the ability to link water level data from multiple water sources to a central server simultaneously, even in rural areas lacking electrical infrastructure and stable internet signals. In addition, the system is also designed to be low-power and capable of continuous data transmission under remote agricultural conditions. Laboratory calibration and field sensor deployment verified the prototype's accuracy, achieving an accuracy of 92.5

percent. The system's IoT architecture enables continuous data transmission with an average success rate of 88.3 percent. From the installation of 5 prototype locations in the lower northeastern region, data from all locations was linked to a central system, creating a prototype water level data network for integrated water management at the community level. This network is usable to provide a real-time overview of water situations in multiple areas and support planning for water transfers between water sources when a particular area has insufficient water.

According to input from field users, the system promotes interagency collaboration, lessens the workload associated with field water level monitoring, and offers dependable daily data.

Users still point out issues with field equipment deterioration, though, and they demand the system be able to self-monitor and notify users when equipment malfunctions. This is an important direction for future development, including the application of artificial intelligence technology to analyze water level data, such as water level forecasting to assess water volume trends and shortage risks. The detection of abnormal signals in the devices and predictive energy management enable the system to adjust the operating mode, adjust the data transmission cycle, or increase the energy storage according to the sunlight and weather conditions. After the field test is completed, this research will be applied to a group of farmers in an agricultural area, and the implementation details will be presented in a future article.

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Research Article

Performance Enhancement of PVT-Porous Dryer under Humid Tropical Conditions

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ABSTRACT

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Drying remains one of the most energy-intensive processes in agriculture and food industries, accounting for significant energy costs and often compromising product quality under humid tropical conditions. This research investigates a photovoltaic–thermal (PVT) porous dryer designed to enhance drying efficiency and energy performance for kaffir lime leaves. The system integrates a 150 W photovoltaic panel with a double-pass solar collector and porous materials onto the absorber of three porosities (0.96, 0.97, and 0.98). Experiments were conducted under tropical conditions, with measurements of temperature distribution, moisture ratio (MR), drying rate (DR), and specific energy consumption (SEC). Data analysis employed two-way ANOVA and Tukey's HSD tests to evaluate statistical significance. Results indicated that drying occurred predominantly in the falling-rate period governed by internal diffusion. The incorporation of porous absorbers improved drying kinetics, reducing MR by 20–32% and increasing DR by 45–50% compared to the situation without porous material. Energy analysis revealed a 30–34% reduction in SEC, with the lowest value of 20.22 MJ/kg achieved at 0.96 porosity, corresponding to a 33.3% improvement. Statistical validation confirmed significant effects of airflow velocity ($p < 0.05$) and porosity ($p < 0.01$), identifying 0.96 as the optimal balance between air resistance and thermal contact. In conclusion, the PVT-porous dryer demonstrates strong potential as a sustainable and energy-efficient drying technology for herbal and agricultural products. Its ability to enhance drying rates while lowering energy consumption makes it particularly suitable for tropical regions where solar energy is abundant yet variable.

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1. Introduction

Drying represents a critical unit operation across various industries, including food processing, agriculture, and herbal product manufacturing. Its primary function is to reduce the moisture content of materials, thereby extending storage life, ensuring product stability, and preserving nutritional, functional, and sensory attributes (Kumar *et al.*, 2020). Beyond quality preservation, drying plays a central role in ensuring microbial safety and maintaining market competitiveness. However, it remains one of the most energy-intensive processes, accounting for approximately 10–25% of total industrial energy

consumption (Mujumdar, 2015; Tsotsas and Mujumdar, 2022). Consequently, advances in drying technologies are essential not only for enhancing process efficiency and improving product quality but also for addressing broader energy and environmental challenges. Nevertheless, drying is widely recognized as highly energy-intensive, requiring substantial energy input to achieve effective moisture removal. In many industrial sectors, drying accounts for approximately 10–25% of total energy consumption, underscoring its significant contribution to operational costs and environmental impacts. Consequently, improving the energy efficiency of drying systems is crucial not only for reducing production expenses but also for

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advancing sustainable industrial practices. Solar energy constitutes an abundant, renewable, and environmentally sustainable resource that is inherently inexhaustible and freely available. In light of escalating global challenges associated with climate change, largely attributable to the combustion of fossil fuels, alongside the rising costs of conventional energy, the transition toward solar energy has become increasingly imperative (Azis *et al.*, 2024; Senthil *et al.*, 2021). Solar energy, acknowledged as a clean, abundant, and renewable resource, presents a sustainable alternative for drying applications. However, its practical utilization is often constrained by inherent seasonal fluctuations and weather-dependent variations in solar radiation intensity. These limitations can result in inconsistent drying performance, particularly in humid tropical climates, thereby necessitating the development of integrated systems, such as photovoltaic–thermal (PVT) collectors, porous absorber materials, and phase change energy storage, to stabilize energy supply, enhance thermal efficiency, and ensure reliable drying outcomes. Solar dryers, by comparison, provide a more sustainable and cost-effective solution, particularly for agricultural materials (Rajarajeswari *et al.*, 2018; Teeboonma and Boonthum, 2019). Consequently, solar dryers have emerged as a cost-effective and environmentally sustainable alternative to conventional drying methods. Nevertheless, their efficiency remains relatively limited, as system performance is strongly influenced by the intermittency of solar radiation, particularly under unfavorable weather conditions. These inherent constraints highlight the need to incorporate performance-enhancing strategies, such as PVT integration for waste heat recovery, porous materials that incorporate an absorber for improved heat transfer, and thermal storage to stabilize energy availability, thereby ensuring consistent and efficient drying outcomes. Over the years, numerous researchers have investigated various strategies to enhance the efficiency of solar dryers. For instance, they designed and evaluated the performance of an innovative indirect free-convection solar dryer (Al-Jethelah *et al.*, 2021). Their results demonstrated substantial enhancements in drying performance, with thermal efficiency surpassing that of conventional systems by 68%, 39%, 49%, and 85%, respectively. Comprehensively investigated a double-pass hybrid PVT system for drying applications through theoretical modelling and experimental validation (Jadallah *et al.*, 2020). The system achieved outlet temperatures of up to 63°C and a peak overall efficiency of 85%, with maximum electrical and thermal outputs of 50.57 W and 389.37 W, respectively, at a flow rate of 0.031 kg/s. Their findings underscore the potential of PVT systems to enhance drying performance by leveraging both thermal and electrical outputs, while highlighting the importance of integrated waste-heat recovery for improved efficiency. Additionally, incorporating porous materials into solar collector absorber plates has been shown to enhance thermal efficiency and significantly stabilize

air temperatures, even during periods of low solar radiation (Nima *et al.*, 2020; Murali *et al.*, 2020). Various studies have shown that combining porous materials with advanced solar panels can improve drying efficiency and energy efficiency, including investigating the effects of porous materials on flow resistance and temperature distribution in passive solar air heaters using experimental and numerical analyses (Kumar and Premachandran, 2020). Their study showed porous material significantly altered flow structure by reducing recirculation zones and improving flow uniformity; air temperature increased due to enhanced convective heat transfer; and the heat transfer coefficient and outlet air temperature improved compared to the non-porous configuration. While their findings offer valuable design insights, the combined application of PV waste heat recovery and porous materials in solar dryers remains underexplored. Examined the design and energy efficiency of solar dryers, identifying limitations in energy savings and cost-effectiveness (Mohana *et al.*, 2020). Their study emphasized the economic and social benefits of solar drying while noting that broader adoption remains constrained by several operational and developmental challenges. Highlighted that hybrid solar drying technologies, particularly PVT-porous systems and heat pump integration, improve efficiency and suitability for delicate products, while the utilization of biomass reduces costs (Jha and Tripathy, 2021). However, design refinements and enhanced hygiene standards remain necessary for optimization. A qualitative investigation into technological advancements in solar dryer design (Kamarulzaman *et al.*, 2021). Their findings indicated that solar dryers are efficient, environmentally sustainable, and characterized by low carbon emissions, with payback periods ranging from 0.5 to 4.6 years. Despite notable cost and energy savings, further design improvements are necessary to optimize performance. Furthermore, integrating heat-accumulating materials has been shown to improve system performance further. Hybrid PV-T solar collector using amorphous type of solar cells for solar dryer (Tarigan, 2020). Experimental results demonstrated its dual capability to generate heat and electricity, achieving air temperatures of 35–50°C and electrical outputs of 4–25 W under solar irradiance of 300–1000 W/m². The integrated generation of heat and power significantly enhanced overall drying efficiency. PVT-porous solar dryers integrating PVT systems achieve higher efficiency through combined heat and electricity generation, though at higher construction costs (Mirzaei *et al.*, 2022). Incorporating heat-storage materials further improved drying performance, uniformity, and environmental sustainability. Integration of porous materials enhances thermal retention and controlled heat release, while waste heat recovery improves absorber efficiency. These modifications in PVT-porous dryers significantly increase energy and exergy efficiencies, stabilize temperature profiles, and reduce performance fluctuations,

thereby advancing system reliability under variable solar conditions.

This study addresses the research gap by experimentally assessing the performance of a photovoltaic–thermal (PVT) porous dryer that couples solar energy utilization with waste heat recovery from a PV panel while integrating porous materials onto the absorber to enhance heat transfer. Conducted under humid tropical conditions in Thailand, the investigation demonstrates the system's potential for improving drying efficiency and energy recovery in solar-assisted drying applications.

2. Materials and Methods

2.1 Experimental setup

The PVT-porous dryer employed in this research is a passive system that incorporates a 150-watt solar panel with cooling fins on its backside, referred to as a PVT system. The panel is mounted atop the drying chamber, is constructed from steel sheets and insulated, and has dimensions of 1 m x 1 m x 1 m and contains 3 trays. An air duct connects the PVT system to a double-pass solar collector panel (DPSC) measuring 0.75 m in width, 1.85 m in length, and 0.25 m in height. The absorber plate within the solar collector is made from a 1.5 mm-thick steel sheet. The PVT, solar collector panel, and fan are connected via an air duct to deliver hot air into the drying chamber at its lower side wall. An 80 W forward-curved centrifugal fan is installed, and the airflow rate is modulated using a damper.

The porous material was placed onto the absorber plate, which was fabricated from perforated steel sheets with a thickness of 1.2 mm, 2 PPI, hole diameters of 10 mm, and a pitch of 3 mm. These perforated steel sheets were precisely cut and assembled into hollow, rectangular enclosures measuring 100 mm in width by 90 mm in height. Steel meshes were placed within hollow rectangular enclosures to determine porosity values of 0.98, 0.97, and 0.96. Figures 1, 2, and 3 illustrate the schematic diagram, a photograph of the PVT-porous dryer, and the structure of porous material. The porosity was systematically adjusted by varying the number of stacked steel mesh sheets, yielding porosity values of 0.98, 0.97, and 0.96 for 10, 18, and 22 mesh layers, respectively.

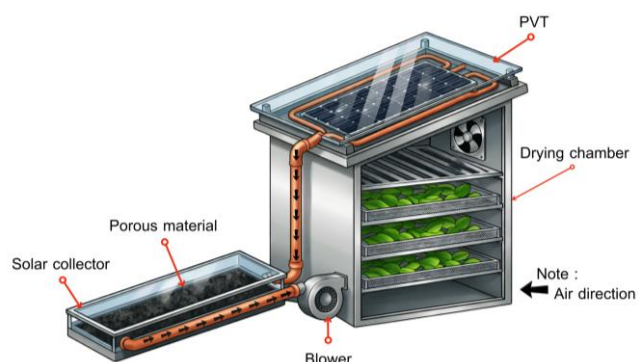


Figure 1 Schematic diagram of the PVT-porous dryer.



Figure 2 Photograph of the PVT-porous dryer.

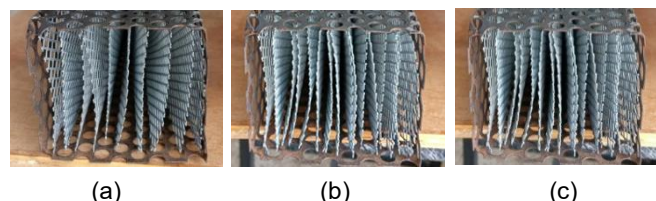


Figure 3 Porous material structure: (a) 0.98 porosity; (b) 0.97 porosity; (c) 0.96 porosity.

The porosity of the porous material was determined by weighing a representative sample, converting its mass to the corresponding solid volume using the steel density, and calculating the ratio of the solid volume to the total available volume above the heat collector plate.

The experiments were conducted under tropical weather conditions in Thailand on 9th June and 27th July 2025, from 9:00 a.m. to 4:00 p.m. Kaffir lime leaves were used as the drying sample, with an initial weight of 200 g per trial and a moisture content of 170% d.b. Using fresh whole kaffir lime leaves, select leaves that are of similar size and age. In solar drying of kaffir lime leaves, the moisture ratio (MR) is employed as an indicator of moisture content, with values maintained below 0.5. The AOAC (2019) standard was used to determine the product's moisture content (AOAC International, 2019). The selected air velocity represents the lowest feasible airflow that ensures proper solar dryer performance without excessive fan energy consumption. The hot air velocity inside the PVT-porous dryer was measured using a hot-wire anemometer with a range of 0 to 20 m/s, a tolerance of ± 0.03 m/s ($\pm 5\%$), and a resolution of 0.1 m/s. Temperature data were recorded using K-type thermocouples connected to a data logger with an accuracy of $\pm 1^\circ\text{C}$. The weight of the dried product was measured using a load cell capable of handling 1–20 kg with an accuracy of ± 0.1 g and a digital scale with a maximum capacity of 500 g and a resolution of 0.1 g. Figure 4 illustrates the measurement points utilized during the experiments.

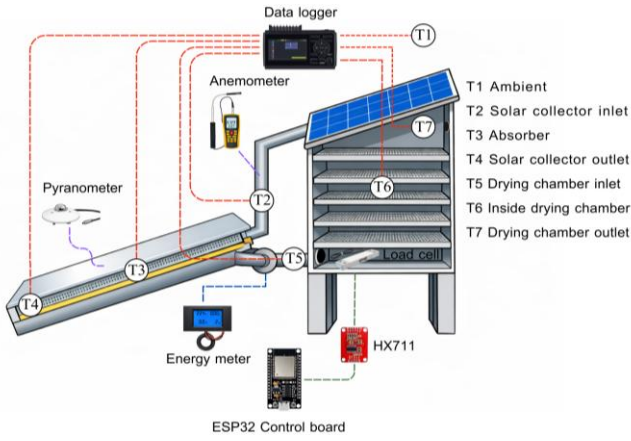


Figure 4 Measurement points utilized during the experiments.

2.2 Analysis

Porosity is calculated as the proportion of void volume relative to the total volume of a material. It represents a critical parameter for characterizing fluid retention and flow behavior in porous material, as expressed in Equation (1) (Bear, 1972).

$$\mathcal{E} = \frac{V_p}{V_t} = 1 - \frac{V_s}{V_t} \quad (1)$$

where $\mathcal{E}$ is porosity, V_p is the volume of the pore (m^3), V_t is the total volume (m^3), and V_s is the volume of the solid (m^3).

The moisture ratio (MR) is commonly used to approximate moisture content, assuming the equilibrium moisture content is negligible. It is calculated by comparing the moisture content at a given time with the initial moisture content, as expressed in Equation (2).

$$MR = \frac{M_t}{M_{in}} \quad (2)$$

where MR is the moisture ratio, M_{in} is the initial moisture content, and M_t is the moisture content at each time interval.

The dry weight was determined by preparing a representative sample and drying it in a hot-air oven at 103°C for 72 hours, in accordance with AOAC (2019) standards. These values were subsequently applied to calculate the moisture content at each interval using Equation (3) (AOAC, 2019).

$$MC = \frac{w - d}{d} \quad (3)$$

where MC is dry basis moisture content at each time interval (D.B.), w is wet weight of product at each time interval (g), and d is dry weight of product (g).

The drying rate quantifies the rate of moisture removal per unit time and serves as a fundamental indicator of mass transfer efficiency in drying processes. In solar drying systems, it reflects the combined effects of heat and mass transfer mechanisms, and is mathematically defined in Equation (4) (Mujumdar, 2015).

$$DR = \frac{\Delta w}{\Delta t} \quad (4)$$

where DR is drying rate (g/h), Δw is mass of evaporated water (g), and Δt is time interval (h).

Specific energy consumption (SEC) represents the energy required to remove a unit mass of moisture from the material and is determined using Equation (5) (Fudholi *et al.*, 2010). This parameter is widely employed to evaluate the energy efficiency of drying systems, as lower SEC values indicate more efficient utilization of input energy.

$$SEC = \frac{3.6E}{w_i - w_f} \quad (5)$$

where SEC is specific energy consumption (MJ/kg), E is power of fan motor (W), w_i is wet weight before drying (kg), and w_f is wet weight after drying (kg).

Measurement uncertainties were evaluated for key parameters, including air temperature, velocity, solar irradiance, and mass. The associated uncertainties were $\pm 1.0^\circ\text{C}$ for K-type thermocouples, $\pm 5\%$ for the hot-wire anemometer, $\pm 5\%$ for the solar radiation meter, and ± 1 g for the scale. A summary of the individual uncertainties is presented in Table 1. The overall combined uncertainty was calculated using the root-sum-of-squares (RSS) method (JCGM, 2008).

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta M}{M}\right)^2} \quad (6)$$

where R is the calculated result, T , I , V , and M are measured parameters (air temperature, solar irradiance, velocity, mass), and Δ is the respective uncertainties.

Table 1 Individual uncertainties for each measured parameter.

Parameter	Device	Uncertainty
Temperature	K-type Thermocouple	$\pm 1^\circ\text{C}$
Air velocity	Hot Wire Anemometer	$\pm 5\%$
Solar radiation	Solar radiation meter	$\pm 5\%$
Scale	Digital scale and load cell	± 0.1 g

The total uncertainty of the calculated parameters, including drying rate and specific energy consumption, was assessed using error propagation methods in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM). The combined uncertainty was $\pm 7\%$.

3. Results and Discussion

An experimental investigation conducted without porous materials at air velocities of 0.07, 0.09, and 0.10 m/s revealed notable variations in solar radiation and temperature profiles

within the dryer. Solar radiation ranged from 371 to 1,001 W/m², with an average of 776 W/m². The drying chamber temperature ranged from 36°C to 45°C, with an average of 41°C while the inlet air temperature ranged from 36°C to 46°C, with an average of 42°C. The absorber plate temperature fluctuated between 49°C and 66°C, with an average of 57°C. Ambient temperatures ranged from 29°C to 35°C, with an average of 32°C, and the solar collector inlet temperature ranged from 32°C to 36°C, with an average of 34°C. These results (as shown in Figures 5, 6, and 7) provide essential insights into the thermal behavior and energy dynamics of the PVT-porous dryer under varying air velocities.

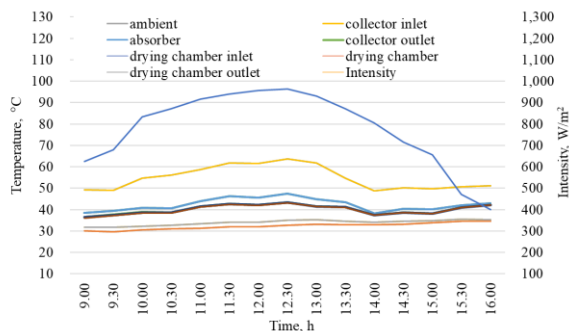


Figure 5 Temperature profile in the dryer without porous material at 0.07 m/s.

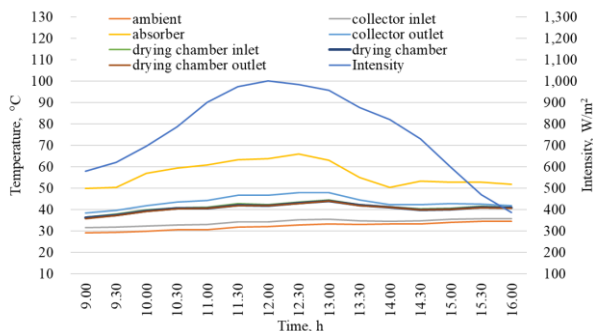


Figure 6 Temperature profile in the dryer without porous material at 0.09 m/s.

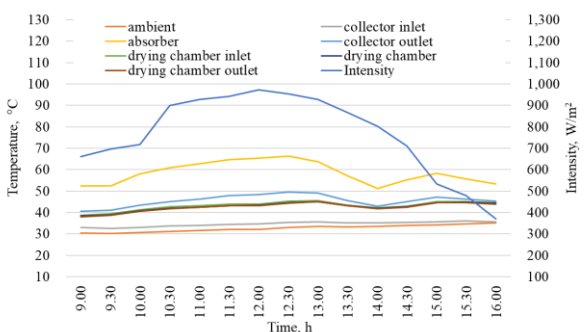


Figure 7 Temperature profile in the dryer without porous material at 0.10 m/s.

The experimental analysis of the solar dryer system incorporating 0.98 porosity porous materials on the absorber plate at air velocities of 0.07, 0.09, and 0.10 m/s demonstrated significant enhancements in thermal performance. Solar radiation values ranged from 332 to 1,015 W/m², with an

average of 763 W/m². The drying chamber temperature ranged from 38°C to 47°C, with an average of 41°C, while the inlet air temperature to the chamber ranged from 38°C to 47°C, with a mean of 41°C. The temperature on the absorber plate fluctuated between 47°C and 66°C, with an average of 55°C. Ambient temperatures ranged from 30°C to 34°C, with an average of 33°C. The inlet temperature to the solar collector ranged from 32°C to 37°C, with an average of 34°C. These results are illustrated in Figures 8, 9, and 10.

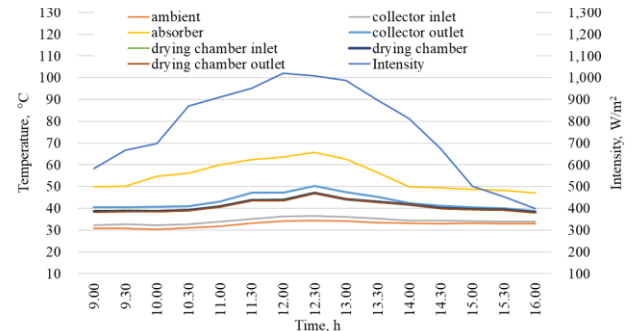


Figure 8 Temperature profile in dryer with 0.98 porosity porous at 0.07 m/s.

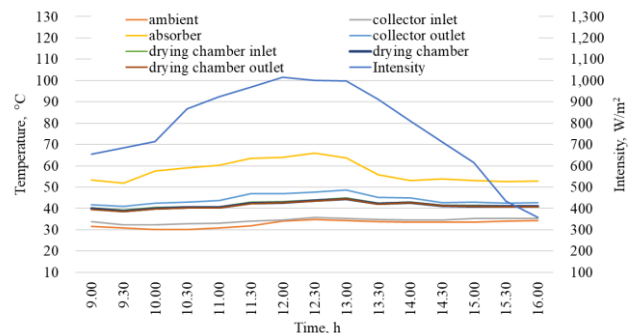


Figure 9 Temperature profile in dryer with 0.98 porosity porous at 0.09 m/s.

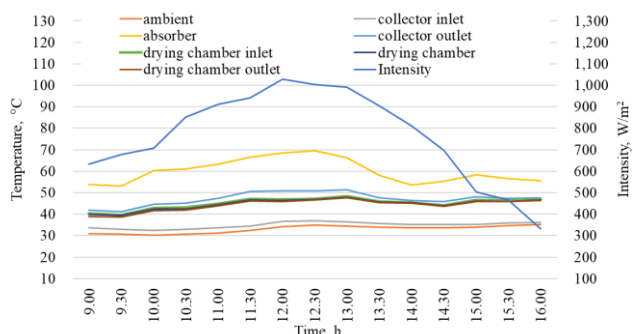


Figure 10 Temperature profile in dryer with 0.98 porosity porous at 0.10 m/s.

The experimental analysis of the solar dryer system incorporating 0.97 porosity porous materials on the absorber plate at air velocities of 0.07, 0.09, and 0.10 m/s demonstrated significant enhancements in thermal performance. Solar radiation values ranged from 411 to 1,022 W/m², with an average of 779 W/m². The drying chamber temperature ranged from 37°C to 50°C, with an average of 44°C, while the inlet air temperature to the chamber ranged from 38°C to 51°C, with a

mean of 45°C. The temperature on the absorber plate fluctuated between 50°C and 68°C, with an average of 59°C. Ambient temperatures ranged from 31°C to 33°C, with an average of 32°C. The inlet temperature to the solar collector ranged from 32°C to 57°C, with an average of 34°C. These results are shown in Figures 11, 12, and 13.

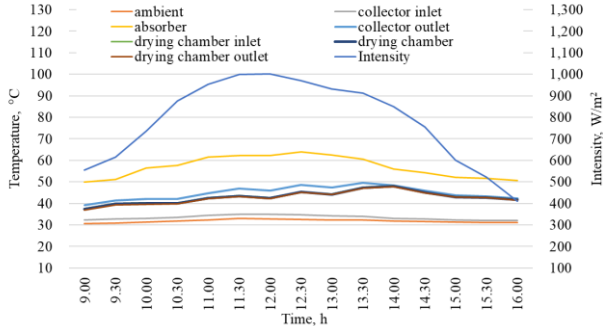


Figure 11 Temperature profile in dryer with 0.97 porosity porous at 0.07 m/s.

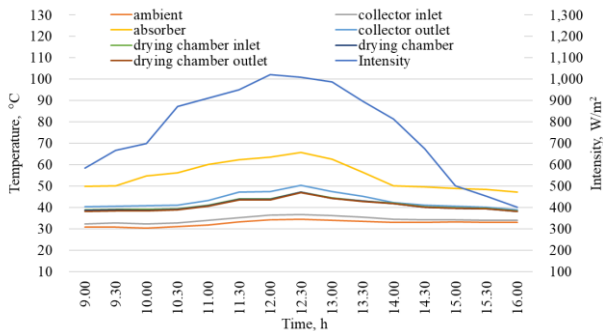


Figure 12 Temperature profile in dryer with 0.97 porosity porous at 0.09 m/s.

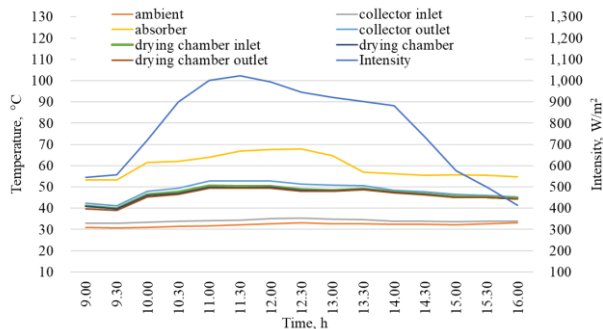


Figure 13 Temperature profile in dryer with 0.97 porosity porous at 0.10 m/s.

The experimental analysis of the solar dryer system incorporating 0.96 porosity porous materials on the absorber plate at air velocities of 0.07, 0.09, and 0.10 m/s demonstrated significant enhancements in thermal performance. Solar radiation values ranged from 357 to 1,008 W/m², with an average of 768 W/m². The drying chamber temperature ranged from 38°C to 55°C, with an average of 45°C while the inlet air temperature to the chamber ranged from 39°C to 55°C, with a mean of 45°C. The temperature on the absorber plate fluctuated between 50°C and 68°C, with an average of 59°C. Ambient temperatures ranged from 30°C to 33°C, with an average of

32°C. The inlet temperature to the solar collector ranged from 31°C to 35°C, with an average of 34°C. These results are shown in Figures 14, 15, and 16.

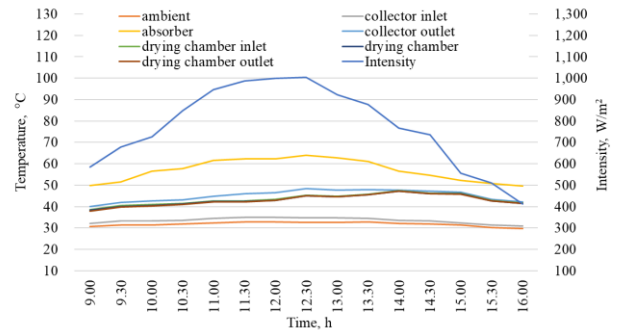


Figure 14 Temperature profile in dryer with 0.96 porosity porous at 0.07 m/s.

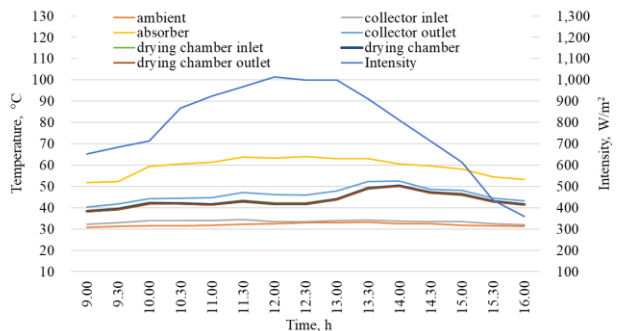


Figure 15 Temperature profile in dryer with 0.96 porosity porous at 0.09 m/s.

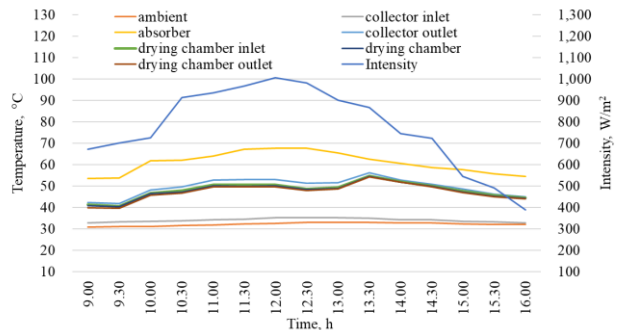


Figure 16 Temperature profile in dryer with 0.96 porosity porous at 0.10 m/s.

Figure 17 shows the variation of moisture ratio (MR) with drying time for kaffir lime leaves at air velocities of 0.07, 0.09, and 0.10 m/s without and with porous materials (0.96, 0.97, and 0.98). Figure 18 shows kaffir lime leaves after drying. In all cases, MR decreased continuously during the 420 min drying period, confirming that drying was dominated by the falling-rate stage controlled by internal diffusion. Incorporating porous materials enhanced drying efficiency, with final MR values of 0.15–0.20 compared to 0.22–0.25 without porous material, representing a 20–32% improvement. The 0.96 porosity consistently yielded the lowest MR values, suggesting an optimal balance between air resistance and thermal contact. Drying constants (k) derived from the exponential model

increased by 10–20% with porous absorbers, peaking at 0.96. A reduction in porosity facilitates a more uniform distribution of thermal energy across the heat transfer area and intensifies airflow turbulence, thereby enhancing convective heat transfer and improving mass transfer and overall drying performance compared with higher-porosity configurations. Two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porosity ($p < 0.01$) while Tukey's HSD validated differences across porosity levels. These results corroborate earlier findings (Das *et al.*, 2020; Messai *et al.*, 2022) and advance understanding by confirming the optimization of porosity, with 0.96 identified as the most effective configuration.

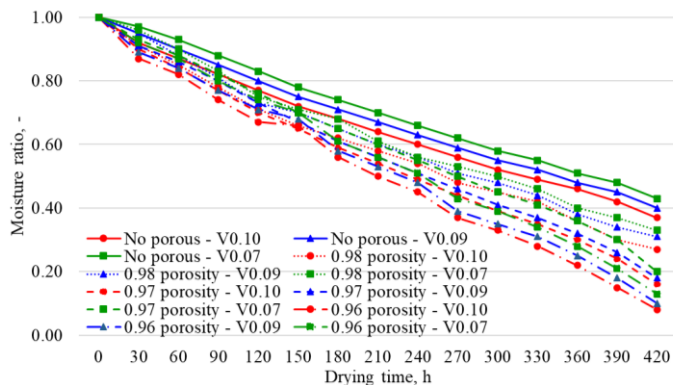


Figure 17 Moisture ratio in each experiment with and without porous material.



Figure 18 Dried kaffir lime leaves.

Figure 19 shows the drying rate of kaffir lime leaves at air velocities of 0.07, 0.09, and 0.10 m/s without and with porous materials (0.96, 0.97, and 0.98). Without porous material, drying rates increased from 6.86 g/h at 0.07 m/s to 7.71 g/h at 0.10 m/s, reflecting a modest 12% improvement. By contrast, incorporating porous material onto the absorber plate significantly enhanced performance, yielding 9.86–11.57 g/h, equivalent to a 45–50% improvement. Among the porous cases, a porosity of 0.96 consistently yielded the highest drying rates, indicating an optimal porosity threshold that balances air resistance and heat transfer. Two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porosity ($p < 0.01$), while Tukey's HSD test verified significant differences across groups. These results are consistent with earlier reports that porous media improve thermal performance and drying efficiency (Mirzaei *et al.*, 2022; Safri *et al.*, 2020; Coban *et al.*,

2021). The present study advances knowledge by identifying 0.96 porosity as the most effective configuration.

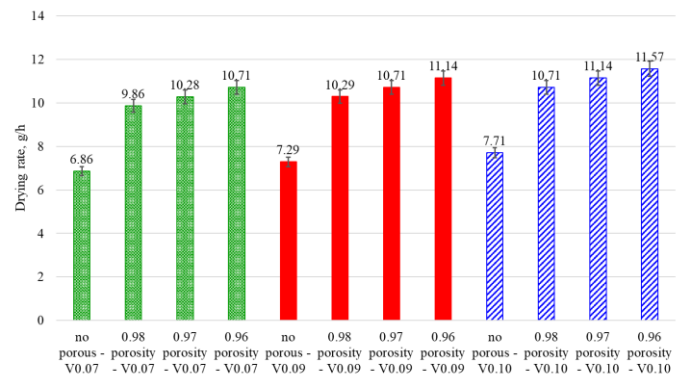


Figure 19 Drying rate in each experiment.

Figure 20 illustrates the specific energy consumption (SEC) of kaffir lime leaves under air velocities of 0.07, 0.09, and 0.10 m/s without and with porous materials (0.96, 0.97, and 0.98 porosity). Without porousness, SEC decreased from 34.13 MJ/kg at 0.07 m/s to 30.33 MJ/kg at 0.10 m/s, representing about an 11% improvement with velocity. In contrast, incorporating porous materials significantly reduced the SEC to 20.22–23.74 MJ/kg, corresponding to approximately 30–34% energy savings compared with the value without porous materials. The relative improvement with the maximum reduction was observed at 0.10 m/s for a porosity of 0.96 (33.3%). Among porous levels, 0.96 consistently achieved the lowest SEC, suggesting an optimal porosity that balances turbulence enhancement with effective heat transfer. Two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porosity ($p < 0.01$), with Tukey's HSD test verifying statistical differences across configurations. The reduced sensitivity of SEC to air in porous configurations indicates improved thermal stability. These results align with earlier reports (Mohammad *et al.*, 2025), while the present study advances understanding by identifying 0.96 porosity as the most energy-efficient configuration.

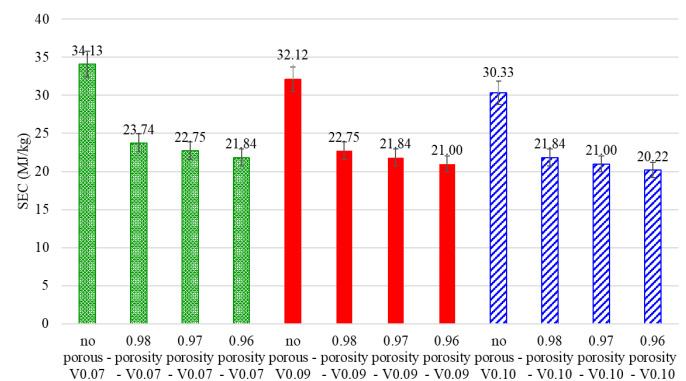


Figure 20 Specific energy consumption in each experiment.

4. Conclusion

This study experimentally demonstrated that a photovoltaic–thermal (PVT) dryer integrating porous materials onto the absorbers significantly improves drying performance and energy efficiency for kaffir lime leaves under humid tropical conditions. The results confirmed that drying was dominated by the falling-rate period, governed by internal diffusion. The use of porous materials reduced final moisture ratios by approximately 20–32% and enhanced drying rates by 45–50% compared to the case without porous materials. Specific energy consumption decreased by 30–34%, with the lowest value achieved at a porosity of 0.96, corresponding to a 33.3% reduction. Statistical analysis confirmed that both air velocity and porosity exerted significant effects, with 0.96 representing the optimal balance between air resistance and thermal contact. These findings establish the PVT-porous dryer as a sustainable and energy-efficient alternative for agricultural drying applications. Future studies should address scalability, economic feasibility, and performance under diverse climatic conditions.

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Research Article

Effects of *Azolla microphylla* and Effective Microorganisms on Rice Production in Cement Pots for Small-Scale Farming

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ABSTRACT

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Azolla is a nitrogen-fixing aquatic fern that can potentially reduce the use of synthetic nitrogen fertilizer in rice production, while effective microorganisms (EM) are widely promoted to enhance crop growth. This study evaluated the effects of *Azolla microphylla* and EM on rice production in 1-m- diameter cement pots under chemical fertilizer (CF) and chicken manure (CM) fertilization systems. Two experiments were conducted using glutinous rice cultivar 'Sakhon Nakhon' in Loei Province, Thailand. Treatments included *A. microphylla* grown before transplanting (BA) or after transplanting (A), with or without EM application. Results showed that *A. microphylla* grown in BA significantly increased tiller number, plant height, and panicle number in both CF and CM experiments. Grain weight/hill and yield/pot tended to be highest in treatments with *A. microphylla* grown BA, although differences were not always statistically significant. One crop of *A. microphylla* grown A and two crops grown BA reduced the requirement for chemical nitrogen fertilizer. EM application to the water showed no positive effects on rice growth or yield. These results indicate that integrating *A. microphylla*, particularly when grown prior to transplanting, is a practical and beneficial strategy for small-scale rice production in cement pots, whereas EM application under these conditions is not recommended.

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1. Introduction

Rice is a vital crop for global food security. The conventional production system of rice relies on paddy fields. In addition to conventional paddy fields, small-scale and household rice production systems have gained interest, particularly in limited-space environments, where alternative rice-growing systems such as container or cement pot cultivation are increasingly practiced.

Enormous efforts have been put to find procedures to enhance rice production while reducing production cost. Replacing synthetic fertilizer may be a good procedure to reduce the costs of rice production. *Azolla* is a genus of floating water fern that has the ability to accumulate substantial amounts of fixed nitrogen. *Azolla* contains nitrogen as high as 4-6% of its dry matter (Marzouk *et al.*, 2023). This

makes *Azolla* suitable as a biofertilizer for rice as both crops grow in flooded natural environments (Bhuvaneshwari and Singh, 2015). *Azolla* can also reduce ammonia volatilization, improve nitrogen use efficiency (de Macale and Vlek, 2004; Yao *et al.*, 2018; Yang *et al.*, 2021), accumulate phosphorus, potassium, and minerals from the water so the plants can take them when it decomposes (Arora and Singh, 2003; Bhuvaneshwari and Singh, 2015). In addition, *Azolla* has the ability in weed suppression, improve soil organic matter, improve the efficiency of inorganic fertilizer, and maintain soil pH, contributing to greater grain yield of rice (Thapa and Poudel, 2021). *Azolla* can be incorporated into the soil during the soil preparation process before rice transplantation or grown as an intercrop with rice (Adhikari *et al.*, 2021).

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Numerous species of *Azolla* have been used as biofertilizers for rice, including *A. pinnata*, *A. filiculoides*, and *A. microphylla* (Ventura and Watanabe, 1993; Bhuvaneshwari and Singh, 2015; Adhikary and Shrestha, 2018; Razavipour *et al.*, 2018; Setiawati *et al.*, 2020; Khair *et al.*, 2021). However, most previous studies on *Azolla* application in rice have been conducted under field or paddy conditions, while limited information is available on the performance of *A. microphylla* in container-based or cement pot rice production systems. In Thailand, *A. microphylla* is the species used for agricultural purposes as the Department of Agriculture, Ministry of Agriculture and Cooperatives has promoted the species among Thai farmers for several years (Suraphonphinit *et al.*, 2023). *A. microphylla* is the species having the highest biomass production and ability to fix nitrogen among *A. filiculoides*, *A. mexicana*, *A. microphylla*, *A. pinnata*, *A. rubra* and *A. caroliniana* (Arora and Singh, 2003).

Effective microorganisms (EM) are a mixed culture of microorganisms isolated from fertile soil that are beneficial for crop production (Olle and Williams, 2013). EM consist of photosynthetic bacteria, lactic acid bacteria, yeast, and actinomycetes (Higa and Parr, 1994). Numerous studies have been conducted to find out the efficiency of EM for various purposes such as plant growth, development, and yield (Renseigné, 2006; Megali *et al.*, 2014; Meng *et al.*, 2018; Domenico, 2019; Pszczółkowski *et al.*, 2023), disease control (El-Hadidy and El-Ati, 2014; Alshammari *et al.*, 2022), waste treatment (Namsivayam *et al.*, 2011; Lu *et al.*, 2019), waste decomposition (Kumar *et al.*, 2022; Amaral *et al.*, 2025), and reducing bad smell (Addeo *et al.*, 2023). Moreover, limited information is available on the effectiveness of EM when applied to flooded water in container-based rice systems, particularly in combination with *Azolla*, which may alter nutrient dynamics and microbial activity.

The benefits of EM for crop production derive from a substantial release of nutrients from organic matter mixed with EM, and increased photosynthesis and protein synthesis (Jusoh *et al.*, 2013; Olle and Williams, 2013). EM reduce the uses of chemical fertilizer and pesticides since EM helps improve soil structure and fertility, organic matter, and nutrient cycling (Abd El-Mageed *et al.*, 2020). However, both positive and non-positive impacts of EM on crop growth and yield have been reported. Mayer *et al.* (2010) conducted a 4-year field study to evaluate the effects of EM on crop yields under an organic system in Switzerland and found that EM had no positive effect on crop yield. Cui *et al.* (2021) reported positive effects of biochar and EM application on the growth of *Sesbania cannabina*. Talaat (2015) reported that EM reduced the negative effects of salt stress on common bean production by altering plant physiology, resulting in plant growth enhancement under stress condition.

Cement pots have been used in Thailand to grow some plants, including terrestrial plants such as lime and rice, and aquatic plants such as *Azolla*, *Wolffia*, and water lilies. The pot height is fixed at 0.5 m, but the pot diameter varies. The pots diameter 0.8 m and 1 m are popular among growers and researchers (Suriyakup *et al.*, 2007; Yamuangmorn *et al.*, 2020; Sanwong *et al.*, 2023). Some Thai farmers use these cement pots to grow rice for family consumption because it's more convenient and it can be used throughout the year. The transplanting method has been used for growing rice in the cement pots. Although cement pot rice cultivation is practiced by some Thai farmers for household consumption, scientific information on nutrient management and the use of biofertilizers such as *Azolla* and EM in this system is very limited. Therefore, evaluating suitable nutrient management strategies for cement pot rice production is necessary to improve the productivity and sustainability of this small-scale system.

Therefore, this study aimed to evaluate the effects of *A. microphylla* and effective microorganisms on rice growth and yield under chemical fertilizer (CF) and chicken manure (CM) fertilization in a 1-m diameter cement pot system. The results will provide scientific information for developing appropriate nutrient management strategies for small-scale rice production in container-based systems in Thailand.

2. Materials and Methods

2.1 Experimental design

Two experiments using different types of fertilizer: the CF experiment and the CM experiment, but similar treatments with *A. microphylla* and EM application were conducted (Figure 1). The two experiments were run at the same time from April to August 2020 at the Agricultural Training Center, Loei Rajabhat University, Loei Province, Thailand. Glutinous rice cultivar 'Sakon Nakhon' was grown in the two experiments. Completely Randomized Design (CRD) with five treatments and four replications was used in both experiments. Cement pots sized 1-m diameter (the actual diameter was approximately 92 cm) placed outdoor were used for this study. The soil ground in the open space was levelled before setting the cement pots for this study. The cement pots were filled with fertile soil below the top of the pot 15 cm. The soil was from a Para rubber tree plot in the Agricultural Training Center. The soil was clay loam with a pH of 7.26, organic matter 4.81%, total nitrogen 0.45%, total phosphate 0.10%, and total potassium 0.20% according to the soil test for this study. Rice seeds were activated for root emergence, and the pre-germinated seeds were sown in a 1-m diameter cement pot for seedlings. CM was applied in the seedling pot for seedling growth at seven days after sowing (DAS).



Figure 1 CF experiment and CM experiment (A) *A. microphylla* at nine DAG (days after growing); (B) *A. microphylla* at 22 DAG; (C) *A. microphylla* being incorporated into the soil at 28 DAG; (D) the soil after *A. microphylla* incorporated; (E) transplanted rice in the soil incorporated with *A. microphylla* at one DAT; (F) treatment CM of CM experiment at 56 DAS (28 DAT); (G) treatment CF2 + *A. microphylla* BA + EM of CF experiment at 56 DAS; (H) treatment CM + *A. microphylla* A of CM experiment at 56 DAS; (I) the two experiments at 60 DAS; (J) the two experiments at 112 DAS; (K) the two experiments at 123 DAS; and (L) treatment CF of CF experiment at 140 DAS.

Rice seedlings were transplanted at 28 DAS. Seven rice seedlings were transplanted in each cement pot with one seedling/hill where six hills were along the pot edge and one hill was in the middle of the pot. CF, CM, *A. microphylla* and EM were applied depending on the experimental conditions. Weeds were controlled by hand. Rice was harvested in both experiments at 142 DAS (114 days after transplanting, DAT).

2.2 CF experiment

There were five treatments for the CF experiment including: 1) CF1 (53.75 kg N/ha), 2) CF2 (39.375 kg N/ha) + *A. microphylla* BA, 3) CF2 (39.375 kg N/ha) + *A. microphylla* A, 4) CF2 (39.375 kg N/ha) + *A. microphylla* BA + EM, and 5) CF2 (39.375 kg N/ha) + *A. microphylla* A + EM. For treatment 1 CF1 at 53.75 kg N/ha: 16-16-8 fertilizer rated 156.25 kg/ha (25 kg N/ha) (10.39 g/pot) was applied at 5 DAT, and 46-0-0 fertilizer rated 62.5 kg/ha (28.75 kg N/ha) (4.16 g/pot) was applied at 39 DAT. The fertilizer uses in treatment CF 1 followed the recommendation for the rice cultivar 'Sakon Nakhon' which is

16-16-8 fertilizer rated 25 kg/rai and 46-0-0 fertilizer rated 10 kg/rai. For treatment 2-5 CF2 at 39.375 kg N/ha: 16-16-8 fertilizer rated 156.25 kg/ha (25 kg N/ha) (10.39 g/pot) was applied at 5 DAT, and 46-0-0 fertilizer rated 31.25 kg/ha (14.374 kg N/ha) (2.08 g/pot) was applied at 39 DAT. In the treatment CF2, 46-0-0 fertilizer was used in a half rate of the treatment CF1.

2.3 CM experiment

There were five treatments for the CM experiment including: 1) CM, 2) CM + EM, 3) CM + *A. microphylla* BA + EM, 4) CM + *A. microphylla* A, and 5) CM + *A. microphylla* A + EM. For the five treatments, CM rated 1,875 kg/ha (124.69 g/pot) and 1,250 kg/ha (83.13 g/pot) were applied at 5 DAT and 39 DAT, respectively.

2.4 *A. microphylla* application

For the treatment *A. microphylla* before transplanting, *A. microphylla* 200 g/pot was grown in the assigned pots for 28 days before rice transplanting. No fertilizer was applied for the

fern growth. Water was then regularly added to the pot for the fern growth. At transplanting date, *A. microphylla* was integrated into the soil before transplantation. For the treatment *A. microphylla* after transplanting, *A. microphylla* 66.5 g/pot was grown in the assigned pots along the rice plants at 3 DAT.

2.5 EM application

EM® used in this study was a branded product acquired from local market which consisted of photosynthetic bacteria, lactic acid bacteria, and yeast. EM was fermented and diluted before adding to the assigned pot. For EM preparation, 1 ml EM from the product was mixed with 1 g brown sugar and 1 l water and fermented for seven days. The EM solution 0.665 ml/pot (6.25 l/ha) was added to the water in the assigned pots three times at: 5 DAT, 39 DAT, and 64 DAT, respectively.

2.6 Data collection

Data recorded were 1) tiller number at 70 DAT, 2) plant height (cm) of the main plant at 114 DAT measured from the plant base to the collar of flag leaf, 3) panicle number at 114 DAT, 4) grains/panicle of the main plant at 114 DAT, 5) grain moisture (%) from three hills/pot, 6) grain weight/panicle (g) of the main plant at 14% moisture, 7) grain weight/hill (g) at 14% moisture, and 8) yield/pot (g) at 14% moisture. Seven hills/pot were measured for tiller number, plant height, panicle number, grains/panicle, grain weight/panicle, grain weight/hill, and yield/pot.

2.7 Statistical analysis

Data were analyzed using SAS OnDemand for Academics. Analyses of variance, and comparisons between group of treatments (orthogonal contrasts) were performed using PROC GLM. Homogeneity of variance were tested using PROC GLM. Fisher's least significant difference (LSD) was used to perform pairwise comparison of all treatments in the analysis of variance ($p = 0.05$). Coefficient of variation (CV) was obtained using PROC UNIVARIATE.

3. Results and Discussion

3.1 CF experiment

Significant differences for tiller number, plant height, and panicle number were observed among the five CF treatments (Table 1). There was no significant difference for grain number/panicle among the five treatments (Table 1). The two treatments having *A. microphylla* grown BA without and with EM application gave rice the highest tiller number, plant height, and panicle number among the five treatments.

Significant differences for grain moisture and grain weight/hill were observed among the five CF treatments (Table 2). There was no significant difference for grain weight/panicle and yield/pot among the five treatments (Table 2). The two treatments having *A. microphylla* grown BA without and with

EM application and the treatment having *A. microphylla* grown A with EM application gave the rice the highest grain moisture and grain weight/hill among the five treatments.

3.2 CM experiment

Significant differences for tiller number, plant height, and panicle number were observed among the five CM treatments (Table 3). There was no significant difference for grain number/panicle among the five treatments (Table 3). The treatment having *A. microphylla* grown BA with EM application gave rice the highest tiller number and panicle number among the five treatments. The treatment having *A. microphylla* grown BA with EM application and the treatment having *A. microphylla* grown A without EM application gave rice the highest plant height among the five treatments. The treatment having *A. microphylla* grown A without EM application was significantly greater than the treatment CM without EM application for plant height.

Significant differences for grain moisture, grain weight/hill, and yield/pot were observed among the five CM treatments (Table 4). There was no significant difference for grain weight/panicle among the five treatments (Table 4). The treatment having *A. microphylla* grown BA with EM application gave rice the highest grain moisture and grain weight/hill. The treatment having *A. microphylla* grown BA with EM application and the treatment having *A. microphylla* grown A without EM application gave rice the highest yield/pot.

3.3 Effects of *A. microphylla*

The treatment CF2 and *A. microphylla* grown A without or with EM applications was not significantly different from the treatment CF1 for all traits (Table 1 and 2). The treatment CM and *A. microphylla* grown A without or with EM applications tended to be greater than the treatment CM without or with EM applications for most traits although differences were not statistically significant (Table 3 and 4). The treatment CF2 and *A. microphylla* grown BA without or with EM application was greater than the treatment CF1 for tiller number, plant height, panicle number, grain moisture, and grain weight/hill (Table 1 and 2). The treatment CM with *A. microphylla* grown BA with EM application was greater than the treatment CM without or with EM applications for tiller number, plant height, panicle number, grain moisture, grain weight/hill, and yield/pot (Table 3 and 4). These suggested that two crops of *Azolla* accumulated nitrogen fertilizer in greater amounts than one crop of *Azolla*. The results also suggested that *A. microphylla* grown A might supply nitrogen fertilizer equal to or above 14.375 kg N/ha. Considering the treatment CF1 had 53.75 kg N/ha while the treatment CF2 and *A. microphylla* grown A had 39.375 kg N/ha, and yield/pot of the treatment CF2 with *A. microphylla* grown A without or with EM tended to be higher than the treatment CF1.

Table 1 CF experiment showing rice data for tiller number, plant height (cm), panicle number, and grain number/panicle of the five treatments.

Treatments	Tiller number	Plant height (cm)	Panicle number	Grain number/panicle
CF1	22.29 ^b	131.35 ^{bc}	19.86 ^b	215.52
CF2 + <i>A. microphylla</i> BA	27.93 ^a	137.11 ^a	24.32 ^a	198.93
CF2 + <i>A. microphylla</i> A	20.43 ^b	129.11 ^c	18.89 ^b	207.29
CF2 + <i>A. microphylla</i> BA + EM	26.07 ^a	134.19 ^{ab}	23.89 ^a	186.96
CF2 + <i>A. microphylla</i> A + EM	21.93 ^b	130.27 ^c	18.96 ^b	218.46
Mean	23.73	132.41	21.19	205.43
F-test	**	**	**	ns
CV. (%)	20.55	5.47	21.04	21.52
Contrast: Group of treatments				
CF1 vs CF2 + <i>A. microphylla</i> BA -/+ EM	**	*	**	-
CF1 vs CF2 + <i>A. microphylla</i> A -/+ EM	ns	ns	ns	-
CF2 + <i>A. microphylla</i> BA -/+ EM vs CF2 + <i>A. microphylla</i> A -/+ EM	**	**	**	-
CF2 + <i>A. microphylla</i> BA & A vs CF2 + <i>A. microphylla</i> BA & A + EM	ns	ns	ns	-

*, ** significant at the 0.05, and 0.01 probability level, respectively; ns not significant.

Means within the same column followed by the same letter are not significantly different at the 0.05 probability level.

Table 2 CF experiment showing rice data for grain moisture (%), grain weight/panicle (g), grain weight/hill (g), and yield/pot (g) of the five treatments.

Treatments	Grain moisture (%)	Grain weight/panicle (g)	Grain weight/hill (g)	Yield/pot (g)
CF1	14.71 ^c	6.16	102.68 ^b	718.76
CF2 + <i>A. microphylla</i> BA	19.18 ^a	5.69	122.41 ^a	856.89
CF2 + <i>A. microphylla</i> A	15.46 ^{bc}	6.07	107.49 ^b	752.40
CF2 + <i>A. microphylla</i> BA + EM	17.70 ^{ab}	5.46	121.68 ^a	851.78
CF2 + <i>A. microphylla</i> A + EM	17.06 ^{abc}	6.16	113.38 ^{ab}	793.64
Mean	16.82	5.91	113.53	794.69
F-test	**	ns	*	ns
CV. (%)	19.27	24.61	22.76	10.16
Contrast: Group of treatments				
CF1 vs CF2 + <i>A. microphylla</i> BA -/+ EM	**	-	**	-
CF1 vs CF2 + <i>A. microphylla</i> A -/+ EM	ns	-	ns	-
CF2 + <i>A. microphylla</i> BA -/+ EM vs CF2 + <i>A. microphylla</i> A -/+ EM	*	-	*	-
CF2 + <i>A. microphylla</i> BA & A vs CF2 + <i>A. microphylla</i> BA & A + EM	ns	-	ns	-

*, ** significant at the 0.05, and 0.01 probability level, respectively; ns not significant.

Means within the same column followed by the same letter are not significantly different at the 0.05 probability level.

However, the results that the fern grown A accumulated nitrogen at 14.375 kg N/ha disagreed with earlier studies that reported one crop of *Azolla* accumulated nitrogen fertilizer at 30 kg/ha (Kanareugsa *et al.*, 1984; Singh and Singh, 1986;

Bhuvaneshwari and Singh, 2015) or higher than 40 kg/ha (Yao *et al.*, 2018). The results also disagreed with previous studies that reported two crops of *Azolla* accumulated nitrogen fertilizer at 60 kg/ha (Kanareugsa *et al.*, 1984; Singh and Singh,

1986). Since this study was not designed to evaluate nitrogen accumulation by *Azolla*, thus, making comparison with other studies may be inappropriate at some points. However, it's apparent that *A. microphylla* growing with rice in cement pot cultivation system is beneficial to rice by providing nitrogen

fertilizer to the system. Rice production in cement pots can completely rely on organic fertilizer such as CM and biofertilizer such as *A. microphylla* to fertilize the system considering equivalent yield/pot in CM experiment and CF experiment.

Table 3 CM experiment showing rice data for tiller number, plant height (cm), panicle number, and grain number/panicle of the five treatments.

Treatments	Tiller number	Plant height (cm)	Panicle number	Grain number/panicle
CM	22.89 ^b	128.93 ^c	19.60 ^b	206.68
CM + EM	22.96 ^b	131.05 ^{bc}	19.21 ^b	206.43
CM + <i>A. microphylla</i> BA + EM	28.18 ^a	137.77 ^a	25.11 ^a	194.46
CM + <i>A. microphylla</i> A	21.57 ^{bc}	134.44 ^{ab}	19.36 ^b	216.89
CM + <i>A. microphylla</i> A + EM	20.64 ^c	129.59 ^c	18.46 ^b	210.39
Mean	23.25	132.36	20.35	206.97
F-test	**	**	**	ns
CV. (%)	20.48	5.80	22.24	18.63
Contrast: Group of treatments				
CM -/+ EM vs CM + <i>A. microphylla</i> BA + EM	**	**	**	-
CM -/+ EM vs CM + <i>A. microphylla</i> A -/+ EM	*	ns	ns	-
CM + <i>A. microphylla</i> BA + EM vs CM + <i>A. microphylla</i> A -/+ EM	**	**	**	-

*, ** significant at the 0.05, and 0.01 probability level, respectively; ns not significant.

Means within the same column followed by the same letter are not significantly different at the 0.05 probability level.

Table 4 CM experiment showing rice data for grain moisture (%), grain weight/panicle (g), grain weight/hill (g), and yield/pot (g) of the five treatments.

Treatments	Grain moisture (%)	Grain weight/panicle (g)	Grain weight/hill (g)	Yield/pot (g)
CM	15.43 ^b	5.98	105.77 ^b	740.40 ^b
CM + EM	15.35 ^b	6.05	106.56 ^b	745.95 ^b
CM + <i>A. microphylla</i> BA + EM	17.53 ^a	5.62	132.88 ^a	930.16 ^a
CM + <i>A. microphylla</i> A	15.48 ^b	6.49	117.54 ^b	822.76 ^{ab}
CM + <i>A. microphylla</i> A + EM	13.15 ^c	6.34	112.17 ^b	785.21 ^b
Mean	15.39	6.10	114.98	804.90
F-test	**	ns	**	*
CV. (%)	17.53	20.83	23.95	12.13
Contrast: Group of treatments				
CM -/+ EM vs CM + <i>A. microphylla</i> BA + EM	*	-	**	**
CM -/+ EM vs CM + <i>A. microphylla</i> A -/+ EM	ns	-	ns	ns
CM + <i>A. microphylla</i> BA + EM vs CM + <i>A. microphylla</i> A -/+ EM	**	-	**	*

*, ** significant at the 0.05, and 0.01 probability level, respectively; ns not significant.

Means within the same column followed by the same letter are not significantly different at the 0.05 probability level.

3.4 Effects of EM application

The treatment CF2 and *A. microphylla* grown A without EM application was not statistically different from the treatment CF2 and *A. microphylla* grown A with EM application for all

traits (Table 1 and 2). Similarly, the treatment CF2 and *A. microphylla* grown BA without EM application was not statistically different from the treatment CF2 and *A. microphylla* grown BA with EM application for all traits (Table 1 and 2).

The treatment CM without EM application was not statistically different from the treatment CM with EM application for all traits (Table 3 and 4). Similarly, the treatment CM and *A. microphylla* grown A without EM application was not statistically different from the treatment CM and *A. microphylla* grown A with EM application for most traits (Table 3 and 4). These suggested that EM applications had no positive effects on the rice plants for all traits in both experiments. These supports Komboonruang *et al.* (1995) which reported that rice yield did not increase in low organic matter soil (organic matter < 2.69%) mixed with EM, but the yield slightly increased in high organic matter soil (organic matter > 6.2) mixed with EM. However, the results contrasted to Myint (1996) which reported the increases in rice yield from the treatment of EM added to the soil having rice straw because EM accelerated rice straw decomposition and decreased soil nitrogen immobilization. The results also disagreed with Yanrong *et al.* (2006) that reported increases in rice grain yield when applied by EM and the increases were greater with increased year of growing. Again, the results from this study didn't support Saida and Mrema (2017) which reported the rice yield increased with application of farmyard manure treated with EM. There were differences in EM application methods used in this study and the other studies. EM solution was added to the water in the pots in this study while different methods of EM application were used in the other studies: EM solution was added directly to the soil (Komboonruang *et al.*, 1995), EM solution was added directly to the soil, and sprayed on the soil and rice plants (Myint, 1996), EM solution was inoculated into Bokashi as fertilizer and added to irrigation water (Yanrong *et al.*, 2006), and EM solution was inoculated into cattle manure as fertilizer (Saida and Mrema, 2017). Results from this study revealed that EM had no impact on the rice growth when added to the water in cement pots where the rice grown. But EM had positive effects on the rice plants when mixed with the soil or organic fertilizer or sprayed on the plants in paddy fields as reported in the other studies. Pests of *A. microphylla* found in this study were caterpillar while pests of rice were not found in this study.

4. Conclusion

One crop of *A. microphylla* grown A, and two crops of *A. microphylla* grown BA reduced the use of chemical nitrogen fertilizer for rice cultivation in 1-m- diameter cement pot in this study. Applying EM to the rice plants by adding it to the water in cement pots had no positive effect on the rice plants. The results suggest that growing *A. microphylla* along rice plants, particularly before rice transplanting, is a practical and useful procedure for small-scale rice farming in cement pots, while EM application to water is not recommended. Growing *A. microphylla* before transplanting in this study didn't require fertilizers because the soil was fertile. In addition, rice production in cement pots could rely on CM and *A. microphylla*

for fertilization. This suggests that organic agriculture may be applied to rice production in cement pots for small-scale farming. However, more knowledge of rice production in cement pots for small-scale farming is necessary, such as fertilization, establishment methods, and watering.

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Research Article

Production and Quality Evaluation of Dried Banana Stem Flavored with Miang-Kham Sauce

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ABSTRACT

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The production and quality evaluation of dried banana stem (BS) flavored with Miang-kham sauce (MS) were investigated. This research was focusing on three aspects. Firstly, conduct an evaluation of the effect of herbal ingredients on the quality of MS. Four treatments were studied, including 1) Control-MS, 2) Nutmeg-MS, 3) Ginger-MS, and 4) Nutmeg/Ginger-MS. It was found that nutmeg and ginger contributed to the color quality by significantly ($p < 0.05$) decreasing the brightness (L^*) value, redness (a^*) value, and yellowness (b^*) values. Additionally, the type of herb was found to have significant influence on the preference of the panelists. The highest sensory evaluation score was recorded for Ginger-MS: "Like Very Much" in color (8.00) and "Liking Extremely" in other characteristics, aroma (8.23), taste (8.73), texture (8.63), and overall acceptability (8.70). Second, find a suitable preparation method of BS. Acid immersion (acetic acid solvent) co-operated with the steaming or boiling method was chosen for the designation of seven different treatments. Results showed that the steaming or boiling method had significantly ($p < 0.05$) lower color (brightness (L^*), redness (a^*), and yellowness (b^*)) and Whiteness Index than the combination method. The 1.0% w/w acetic acid immersion co-operated with the steaming method (1.0AIS) and was the appropriate treatment. Finally, determine the appropriate concentration of MS on dried BS quality in the drying process, hot air dryer at 65°C. Using four different Ginger-MS concentration: 0%, 20.00%, 25.00%, and 33.33%. The result presented that 33.33% Ginger-MS was the optimal concentration, with the dried BS yielding 23.60%. Dried-Ginger-MS-BS had a moisture content and water activity that did not exceed the standard limit specified in Thai Community Product Standard "Dried Fruit and Vegetable" 136/2015. The liking mean score of sensory acceptability was described as "Like Extremely" in all characteristics. The investigation from this research provided a guideline for the potential to produce the BS flavored with MS for a healthy dried food product high in dietary fiber. Nevertheless, further research should investigate strategies for appropriate packaging method and product shelf life.

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1. Introduction

Drying is a type of food preservation based on the principle of removing water from food. In the past, the common sunlight method was to evaporate water from food. Later, with the development of science, various techniques of dry food processing were developed, such as using the evaporation principle with a solar oven, an electric oven, microwave ovens,

spray dryers, and using the vacuum principle with the freeze-drying method. Each method has different advantages and disadvantages, but the products will be in the same quality: lightweight and convenient to store and transport. Hot air drying is a widely used method because the equipment and maintenance are low cost. Upholsin (2010) reported that blanching fresh pandan leaves at 90°C for 3 min and drying at

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50°C for 6 h is the most appropriate. Tabklang *et al.* (2021) reported the optimal drying condition for pickled santol is 60°C for 8 h.

The banana stalk is the pseudo-stem of the banana tree, an herbaceous plant that grows well in all regions of Thailand. It is commonly consumed and used as an ingredient in savory dishes such as spicy curry with coconut milk and sour curry. Yasaswini *et al.* (2021) reported the nutritional composition of banana pseudo-stem flour from the inner tender core. The moisture content was 7.46%, protein 6.72%, fat 2.86%, ash 28.91%, carbohydrate 39.17%, crude fiber 14.86%, and total phenol 172.27 mg of GAE/100 g. Banana pseudo-stems are rich in dietary fiber, which helps to treat constipation and weight loss. They are also rich in antioxidants, antimicrobial, antitumor, antiallergic, and antiurolithiatic properties, which helps to fight against various diseases and keep the human body healthy.

Miang-kham is an ancient Thai food. It is found in the royal composition "Kap He Chom Khrueang Wang or Poem praising snake set" by King Rama VI, Thailand (Na-Songkhla, n.d.). In 2014, the Department of Cultural Promotion, Ministry of Culture, announced the registration of "Miang-kham" as a national cultural heritage (Sanamchandra Palace Library, 2018). This food has been popular until today because it has a unique herbal composition of side dishes with MS. The definition is provided in the Thai Community Product Standards 671/2004. "Miang-kham sauce" means a product made by simmering sugar with water and adding spices such as galangal, ginger, and shallots. It may be mixed with glucose syrup or corn syrup, dried shrimp, roasted coconut, fish sauce, grilled or roasted shrimp paste or not until it has the right thickness (Thai Industrial Standards Institute, 2004). There has been research to develop Miang-kham flavored products. Deepanya (2013) reported on the development of Miang-kham Khao Luem Pua products with a ratio of 1 part Miang-kham ingredients to 1 part MS. The Miang-kham components are comprised of puffed rice, 1 part; roasted peanuts, 1 part; dried shrimps, 0.25 parts; dried betel leaves, 0.05 parts; and roasted coconut, 1 part. Banthat *et al.* (2023) reported the development of a healthy Miang-kham stick product. The formulated product comprised dry ingredients,

including soy protein (12.84%), roasted coconut (11.85%), puffed rice (14.81%), cashew nuts (9.75%), dried betel leaves (0.50%), and garden chili (0.25%). The liquid phase consisted of MS prepared with ginger (1.44%), galangal (1.92%), lemongrass (1.60%), shallots (6.89%), vegetarian shrimp paste (3.21%), coconut sugar (16.35%), isomalt (5.77%), vegetarian soy sauce (3.21%), Indian gooseberry juice (4.81%), glucose syrup (3.21%), and lime juice (1.60%). However, in the commercial market, the only industrial product with Miang-kham flavor was potato chips. Therefore, it was an interesting research issue to apply Miang-kham flavor to another product different from the above data. In this research, we focused on the application of MS to BS, available locally and commonly used as an ingredient in various food menus, to obtain the Miang-kham flavored dried food product.

The objectives of this study were to investigate the production of dried BS flavored with MS, focusing on three aspects: (1) conducting an evaluation of the effect of herbal ingredients on the quality of MS, (2) finding a suitable preparation method of BS, and (3) determining the appropriate concentration of MS on dried BS quality in the drying process.

2. Materials and Methods

2.1 Effect of herbal ingredients on the quality of MS

The experiment was conducted using Completely Randomized Design (CRD), with the MS formula as a factor of the experimental treatments, totaling four experimental treatments. Each experimental treatment contained the basic ingredients of the Control-MS formula as follows: coconut sugar (57.51%), fish sauce (23.57%), dried shrimp (7.42%), shrimp paste (3.16%), galangal (2.78%), lemongrass (2.78%), and shallots (2.78%) adapted from Wongnai (2018). The treatments were as following Table 1.

The preparation steps of MS in all treatments can be illustrated as shown in Figure 1 and Figure 2. In the treatment with herb addition, ginger or nutmeg was cleaned, cut, and added into the mixture of the cut galangal, lemongrass and shallots. MS from all treatments were analyzed for quality.

Table 1 Experimental treatments of MS formula.

Treatment		Description of MS formula
1	Control-MS	Control-MS
2	Nutmeg-MS	Nutmeg (4%w/w) in control-MS
3	Ginger-MS	Ginger (4%w/w) in control-MS
4	Nutmeg/Ginger-MS	Nutmeg (4%w/w) and ginger (4%w/w) in control-MS

2.2 Effect of the preparation methods on the quality of BS

In this study, BS of Kluai namwa (*Musa sapientum* Linn) were used by selecting the 3rd-6th layer next to the core of BS. They were washed with clean water and cut into pieces

measuring 3x6 cm. The experimental design was CRD. The BS preparation method was the factor of the experimental treatments. There were seven experimental treatments, as in the following Table 2.

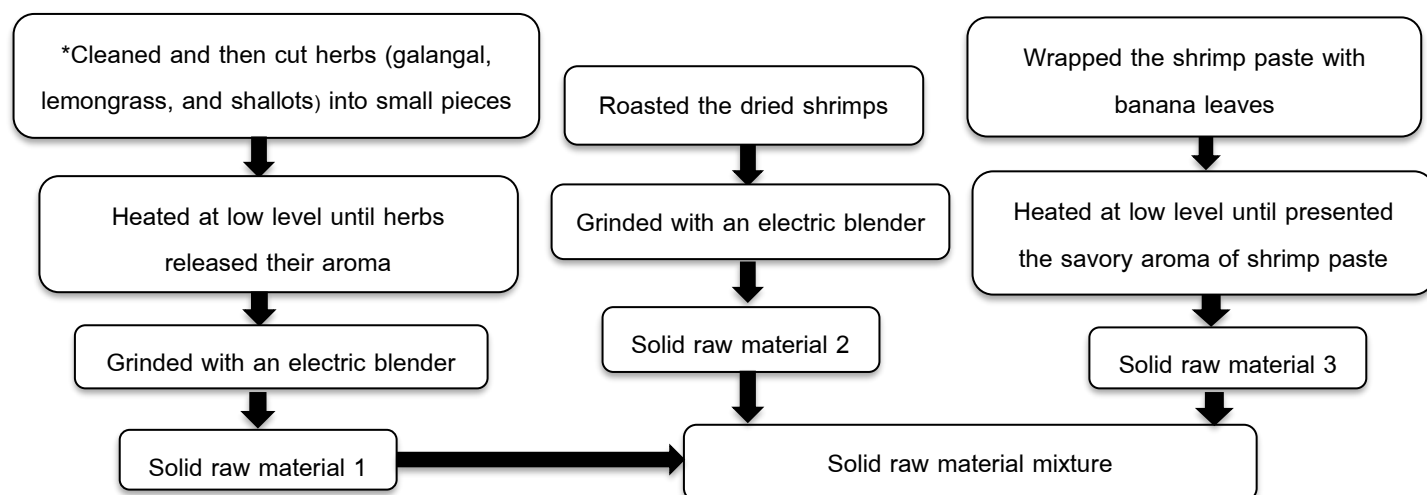


Figure 1 Flow chart of solid raw material preparation in Miang-kham sauce process in treatment 1: *Treatment 2, 3, and 4, the ginger or nutmeg was mixed in this step.

Source: Kongphan,2018.

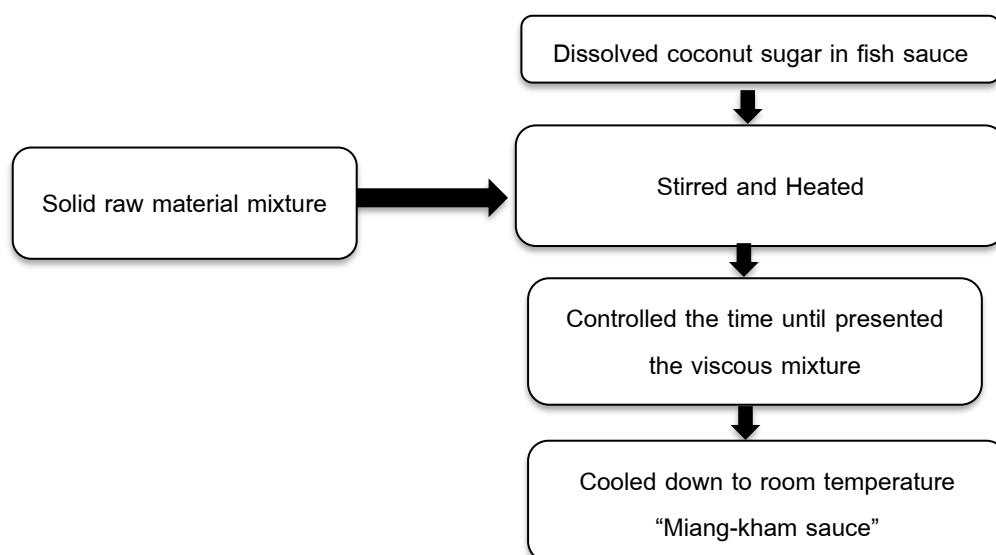


Figure 2 Flow chart of Miang-kham sauce process.

Source: Kongphan,2018.

Table 2 Experimental treatments of BS preparation.

Treatment		Description of BS preparation
1	F-BS	Fresh BS
2	S-BS	BS steamed 15 min
3	B-BS	BS boiled 15 min
4	0.5AIS-BS	BS immersed in 0.5% w/w acetic acid solvent 30 min and steamed 15 min
5	1.0AIS-BS	BS immersed in 1.0% w/w acetic acid solvent 30 min and steamed 15 min
6	0.5AIB-BS	BS immersed in 0.5% w/w acetic acid solvent 30 min and boiled 15 min
7	1.0AIB-BS	BS immersed in 1.0% w/w acetic acid solvent 30 min and boiled 15 min

2.3 Effect of the different concentrations of MS on dried BS quality in the drying process

The experimental design was CRD. The concentrations of Ginger-MS were the factor of the experimental treatment. The Ginger-MS was diluted with water by weight. There were four experimental treatments, as in the following Table 3.

1.0 AIS-BS were boiled for 30 min in different concentrations of Ginger-MS. Then, the surface of boiled BS was washed with water. Afterward, all treated BS were placed in a hot air dryer

and heated at 65°C. During heating, samples were taken at intervals to monitor changes in the moisture content with an infrared moisture analyzer (SARTORIUS MA37-1, Goettingen, Germany). Sample heating was ended when the moisture content was < 10.0%. The standard limit specified for moisture content was 12% in Thai Community Product Standard “Dried Fruit and Vegetable” 136/2015. The quality of finished products was analyzed.

Table 3 Experimental treatments of the Ginger-MS concentration.

Treatment		Description of the ginger-MS concentration
1	NGinger-MS	None-ginger-MS
2	20Ginger-MS	Ginger-MS 20.00% concentration (Ratio of ginger-MS to water 1: 4 w/w)
3	25Ginger-MS	Ginger-MS 25.00% concentration (Ratio of ginger-MS to water 1: 3 w/w)
4	33Ginger-MS	Ginger-MS 33.33% concentration (Ratio of ginger-MS to water 1: 2 w/w)

2.4 Quality analysis

2.4.1 Color measurement

The color of the samples was evaluated with a colorimeter (UltraScan VIS, HunterLab, Virginia, United States of America) and recorded in the CIE $L^* a^* b^*$ system. The instrument was calibrated with a white standard plate and illuminant D65. The brightness (L^*) value (light-dark spectrum) ranges from 0 (darkness) to 100 (brightness), the a^* value (green-red spectrum) ranges from green (-) to red (+) and the b^* value (blue-yellow spectrum) ranges from blue (-) to yellow (+). The value of the total color difference (ΔE) was calculated by using the following Equation (1) (Ruttarattanamongkol *et al.*, 2016) where L_o^* , a_o^* , and b_o^* are the control values (dried NGinger-MS-BS). The summary of ΔE values with their associated level of human perception was as follows: <1 = not perceptible by human eyes, 1-2 = perceptible through close observation, 3-10 = perceptible at a glance, 11-49 = colors are more similar than opposite, and 100 = colors are exact opposites (Minaker *et al.*, 2021).

$$\Delta E_{ab} = \sqrt{(L^* - L_o^*)^2 + (a^* - a_o^*)^2 + (b^* - b_o^*)^2} \quad (1)$$

2.4.2 Whiteness index (WI)

The whiteness index is an optical index used to qualitatively evaluate the “whiteness” of a material. The whiteness index was calculated according to Equation (2) (Li and Lee, 1996).

$$WI = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \quad (2)$$

2.4.3 Proximate composition

The moisture content was determined using the air oven method of AOAC Method 934.01 (AOAC, 2000). The AOAC Method 960.52 (AOAC, 2000) was used for crude protein using Kjeldahl equipment (BUCHI, Zurich, Switzerland). Ash

content of the samples was determined by the dry ashing method according to AOAC method 923.03 (AOAC, 2000). Crude fat was determined using an automated Soxhlet method (VELP SCIENTIFICA, Usmate, Italy) according to AOAC Method 963.15 (AOAC, 2000). The AACC Method 32-05.01 (AACC, 1999) was used for crude fiber using a fiber analyzer (VELP SCIENTIFICA, Usmate, Italy). Water activity was measured with a water activity analyzer (AquaLab, Washington, United States of America).

2.4.4 Sensory evaluation

The evaluation was conducted by the selected thirty panelists (the 4th-year undergraduate students of the Department of Food Innovation and Management, Faculty of Agro-Industry, Rajamangala University of Technology Srivijaya). All panelists were accustomed to consuming the ancient Thai dish Miang-kham. Panelists had directed to rinse their mouths with water in between evaluations for more accurate results. The characteristics of the samples were evaluated for color, aroma, taste, texture and overall acceptability using a 9-point hedonic scale, with 1 and 9 representing the least score (dislike extremely) and the highest score (like extremely), respectively (Anprung, 2008).

2.4.5 Statistical analysis

Completely Randomized Design (CRD) was used for physical and chemical quality analysis. The obtained data were analyzed statistically in terms of mean, standard deviation, and variance (Analysis of Variance; ANOVA). The difference in mean values between groups was analyzed using Duncan's multiple range test at 95% ($p < 0.05$) level of significance (Saiyos and Saiyos, 2001).

Randomized Complete Block Design (RCBD) was used for sensory quality analysis. The obtained data were analyzed statistically in terms of mean and standard deviation. The mean

of the liking score was described as follows: 8.12-9.00 (like extremely), 7.23-8.11 (like very much), 6.34-7.22 (like moderately), 5.45-6.33 (like slightly), 4.56-5.54 (neither like nor dislike), 3.67-4.55 (dislike slightly), 2.78-3.66 (dislike moderately), 1.89-2.77 (dislike very much), and 1.00-1.88 (dislike extremely) (Moreno and Solar, 2022).

3. Results and Discussion

3.1 Effect of herbal ingredients on the quality of MS

The results indicated there was a significance ($p < 0.05$) effect of the herbal ingredients, ginger and nutmeg, on the color value (brightness (L^*), redness (a^*), and yellowness (b^*)) of MS (Table 4). The brightness (L^*) value decreases significantly ($p < 0.05$) in all herbal treatments compared to Control-MS. The brightness (L^*) values of Control-MS > Ginger-MS > Nutmeg/Ginger-MS > Nutmeg-MS were 16.99 > 15.28 > 14.54 > 14.17, respectively. Both ginger and nutmeg are cellulose-rich structures, which increased solidity and reduced brightness. The positive a^* value represents redness, with a higher redness (a^*) value indicating greater browning as reported by Chansri and Kongkham (2022) in fresh sliced eggplant. The results of this study showed that Control-MS (12.42) had a significantly higher redness (a^*) value than the other groups. There was no significant ($p > 0.05$) difference in redness (a^*) value among all herbal-MS samples: Nutmeg-MS (10.72), Ginger-MS (10.57), and Nutmeg/Ginger-MS (10.36). This implies that adding herbs to MS helps reduce the formation of browning compounds. The positive b^* value referred to the yellowness color. The yellowness (b^*) value of MS showed a change in the same direction as the redness (a^*) value. All herbal-MS samples decreased the yellowness (b^*) value significantly compared to the Control-MS (17.23). There was no significant difference in yellowness (b^*) value among all herb-treated samples: Nutmeg-MS (14.04), Ginger-MS (14.07), and Nutmeg/Ginger-MS (14.14).

The sensory evaluation results in a mean of liking scores of samples for all characteristics (color, aroma, taste, texture, and overall acceptability) presented in Table 5. Color is a crucial indicator of food and is an essential quality parameter influencing the purchase decision of consumers. The results of color evaluation showed that the Control-MS, Nutmeg-MS, Ginger-MS, and Nutmeg/Ginger-MS mean scores were 7.83, 8.02, 8.00, and 8.07, respectively, described as "like very much". This implies that the application of herbs in MS did not affect the sensory evaluation of the product's color, even though the color value (brightness (L^*), redness (a^*), and yellowness (b^*)) obtained from instrumental measurements showed significantly different results. "Aroma" refers to the distinctive smell or fragrance of a substance, often associated with food. It is largely determined by volatile compounds released during cooking, ripening, or fermentation processes. Aroma is one of the most important factors in evaluating the physical and chemical quality attributes of food and is directly associated with product

acceptance by the consumers. The aroma evaluation presented that the liking of the aroma attribute received "like extremely" in Ginger-MS (8.23), "like very much" in both Control-MS (8.00) and Nutmeg-MS (7.27), and "like slightly" in Nutmeg/Ginger-MS (6.17). Ginger has aroma substances, which yield phenylpropanoids, monoterpenes, and other phenolic chemicals. Its volatile oils zingiber, zingiberene, phellandrene, and linalool, produce improved new food products (Rakhi *et al.*, 2018). Limpaphayom *et al.* (2014) reported the analysis of fresh ginger in both young and mature stages, grown in Nakhon Si Thammarat province, Thailand, found the highest content of zingiberene. The amount of ginger commonly used to enhance the flavor of food was 1.0-1.25% (El-Sayed and Youssef, 2019). Konsue and Chuemchaitrakul (2004) used 2.70% dry ginger in the development of a ready-to-drink ginger jelly formula. In this experiment, MS was added with 4% fresh ginger. Sipahelut *et al.* (2020) reported that nutmeg pulp oil contains 32 components, with major constituents including α -pinene (18.0%), myristicin (14.1%), α -terpineol (9.4%), β -pinene (8.9%), limonene (8.5%), and terpinene-4-ol (8.4%). Although nutmeg contains essential oils, it was found that Nutmeg-MS received lower mean scores for the aroma attribute than the Control-MS. Taste, or gustation, refers to the sensation that occurs when chemicals stimulate taste receptors. Food taste is the overall sensory experience (sweet, sour, salty, bitter, and umami combined experience of taste, smell (aroma), texture, and temperature, known as flavor) that is interpreted by the brain, which is consumers' willingness to buy/eat a product. Any small amount can be eaten or consumed to assess the influence on sensory receptors. In this research, after conducting the taste test, the panelists were instructed to rinse their mouths with water following the evaluation of each sample treatment. In this experiment, the results of the taste attribute showed that Ginger-MS had the highest mean score of 8.73, described as "like extremely". The use of nutmeg had a significant ($p < 0.05$) impact on taste perception. Nutmeg-MS, with the mean score of 7.27, described as "like very much," while Control-MS, with the mean score of 8.17 described as "like extremely". This implies that ginger addition did not affect to the taste characteristic because Ginger-MS and Control-MS had in close proximity result. The use of nutmeg and ginger got the Nutmeg/Ginger-MS with the lowest mean score of 5.23, described as "neither like nor dislike". Texture is the physical characteristic of food that is generally perceived by the sense of touch. Food texture plays an important role in whether the consumers like or dislike the food product. In addition to the direct contribution to consumer acceptance, texture also has a vital secondary role in modulating flavor release and perception. The results of texture evaluation showed that the liking of the texture attribute was "like extremely" in both Control-MS (8.43) and Ginger-MS (8.63). In Nutmeg-MS and Nutmeg/Ginger-MS the mean score was the same, at 7.76, described as "like very much". Overall

acceptability is a sensory evaluation measure that encapsulates the general preference and satisfaction of consumers for a product based on sensory attributes. It evaluates how well products are received by assessors, focus to the importance of sensory characteristics in determining consumer approval. In this research, the mean score of Control-MS was 8.05, described as "like very much", Nutmeg-MS was 7.13, described as "like moderately", and Nutmeg/Ginger-MS was 5.87, described as "like slightly". The highest mean score was Ginger-MS, which has a mean of 8.70, described as "like extremely".

Therefore, in this experimental step, Ginger-MS was selected for further study in the appropriate concentration of MS on dried BS quality in the drying process.

Nutritional value was expressed in terms of proximate composition. The mean value result of proximate composition of Ginger-MS showed that it contained 26.79% moisture content, 0.36% crude fat, 4.81% crude protein, 6.00% ash content, and 1.14% crude fiber. Its water activity was 0.66, which did not exceed 0.85, the standard limit specified in Thai Community Product Standard "Miang-kham Sauce" 671/2004.

Table 4 Effect of herbal ingredients on color value (brightness (L^*), redness (a^*), and yellowness (b^*)) of MS.

Treatment	Brightness (L^*) value	Redness (a^*) value	Yellowness (b^*) value
1. Control-MS	16.99±0.62 ^a	12.42±0.35 ^a	17.23±0.25 ^a
2. Nutmeg-MS	14.17±0.67 ^c	10.72±0.49 ^b	14.05±0.25 ^b
3. Ginger-MS	15.28±0.25 ^b	10.57±0.78 ^b	14.07±0.38 ^b
4. Nutmeg/Ginger-MS	14.54±0.36 ^c	10.39±0.15 ^b	14.14±0.52 ^b

Mean value of 3 replicate measurements ± standard deviation.

^{abc} Different letters in a column are significantly different level ($p < 0.05$) according to Duncan's multiple range test.

Table 5 Effect of herbal ingredients on liking score of sensory evaluation of MS.

Treatment	Color	Aroma	Taste	Texture	Overall acceptability
1. Control-MS	7.83±0.65 Like very much	8.00±0.46 Like very much	8.17±0.80 Like extremely	8.43±0.50 Like extremely	8.05±0.51 Like very much
2. Nutmeg-MS	8.02±0.89 Like very much	7.27±0.91 Like very much	7.27±0.74 Like very much	7.67±0.89 Like very much	7.13±0.78 Like moderately
3. Ginger-MS	8.00±0.46 Like very much	8.23±0.44 Like extremely	8.73±0.52 Like extremely	8.63±0.50 Like extremely	8.70±0.47 Like extremely
4. Nutmeg/Ginger-MS	8.07±0.91 Like very much	6.17±0.80 Like slightly	5.23±1.55 Neither like nor dislike	7.67±1.27 Like very much	5.87±1.22 Like slightly

Mean value of 30 replicate measurements ± standard deviation.

3.2 Effect of the preparation methods on the BS quality

In drying agricultural materials, substance preparation is crucial since enzymes cause browning. Phenolic oxidation first produces unstable quinones, which then react with other compounds to form browning pigment (Robards *et al.*, 1999). Anusuya *et al.* (2013) reported the total phenolic and total flavonoids in various solvent extracts of pseudo-stem of different banana cultivars vary from 7.58 to 291 mg gallic acid equivalent and from 4 to 80 mg catechin equivalent, respectively. Ramirez-

Bolanos *et al.* (2021) reported phenolic compounds in dried banana pseudo-stem (% dw): 49.02 mg protocatechuic acid, 1.26 mg ferulic acid, 0.48 mg *p*-coumaric acid, and 0.05 mg *p*-coumaric acid ethyl ester. The browning reaction could be prevented by inactivating the enzyme with different methods such as heat, reducing the pH on the material surface (e.g., adding citric acid or another acids), reducing the amount of available oxygen (e.g., vacuum or modified atmosphere packaging), or by adding certain preservative chemicals (such

as sulfur dioxide). Since the browning from the enzymatic browning reaction will affect the product's color in the step of the study of the appropriate concentration of MS in the BS drying process, an optimal method of BS preparation had to be researched to reduce the error problem from the above causes. Supapvanich *et al.* (2015) found that 1% ascorbic acid with blanching at 80°C for 8 min effectively inhibited browning in banana syrup. Constant *et al.* (2021) reported reduced browning in fresh eggplant by heat treatment at 65°C for 30 min, while Paengkanya *et al.* (2021) showed that thermal preparation lowered enzyme activity and browning in fresh banana. Blanching banana slices with heat and steaming can reduce PPO activity by 91.2% and 92%, respectively, when compared to untreated bananas. As for peroxidase activity (POD), it was found that both sample preparation methods reduced POD activity by 100%. According to the previous research data, the combined methods were chosen to study in this experiment, including acid solution (two level of acetic acid, 0.5% and 1.0% w/w) and heat (steaming and boiling). The results showed that preparation methods significantly ($p < 0.05$) affected on the BS quality. The initial brightness (L^*) value was 70.78 in F-BS. The brightness (L^*) value of S-BS (66.36) was significantly higher than B-BS (47.56) (Table 6). Both S-BS and B-BS had the brightness (L^*) value significantly lower than F-BS. This difference is because heating by boiling causes the plant cell tissue to break down, while steaming, on the other hand, does not cause the breakdown of plant cell tissue. The breakdown of tissue layers eliminates gaps between layers, leading to increased tissue overlap and a decrease in brightness (L^*) value. In the case of steaming, although there is no rupture of the cell structure, the heat applied softens the tissue structure, resulting in a denser structure than plant tissue in its natural state. Immersion of BS in an acidic solution lowers its pH, inhibiting browning caused by enzyme reactions. The results presented that higher acid concentration was significantly higher brightness (L^*) value of BS in both boiling and steaming. The brightness (L^*) values of S-BS < 0.5AIS-BS < 1.0AIS-BS were 66.36 < 69.02 < 72.95, respectively, and B-BS < 0.5AIB-BS < 1.0AIB-BS were 47.56 < 59.33 < 63.97, respectively. The changes in brightness (L^*) value of BS of this experimental method were in the same direction as the report by Kaweewong and Sombatma (2020), who soaked banana blossoms in citric acid solutions at concentrations of 0.0, 1.0, and 3.0% for 5 min, with brightness (L^*) values 46.32, 56.18, and 65.19, respectively. The redness (a^*) value of BS in this experiment was found to be changing in the same direction as the brightness (L^*) value. A boiling state made the plant cells rupture, and in a neutral solution, the enzyme that causes browning can leak from the cell wall into boiling water and then contact oxygen, causing a reaction that produces brown matter. Therefore, B-BS had the highest redness (a^*) value. Various research used acidic solvents to lower the pH of substances to

inhibit enzymatic reactions that cause browning. Chansri and Kongkum (2022) reported that the increased positive a^* value in fresh eggplant fruit indicated more browning. Supapvanich *et al.* (2015) reported that blanching with ascorbic acid significantly inhibited browning. Pizzocaro *et al.* (1993) reported that a citric acid concentration of 0.2–1.0% could inhibit browning in fresh-cut apple. In steaming, the BS immersed in a higher concentration acid solution exhibited the lowest redness (a^*) value. Boiling treated BS presented the redness (a^*) value in the same direction as the steaming method. The redness (a^*) values of S-BS, 0.5AIS-BS, and 1.0AIS-BS were 0.28, 0.16, and -0.30, respectively, whereas those of B-BS, 0.5AIB-BS, and 1.0AIB-BS were 11.09, 0.73, and -0.68, respectively. The effect of preparation methods on the yellowness (b^*) value of BS was as follows: all methods significantly decreased the yellowness (b^*) values compared to F-BS. However, differences in heating methods did not result in a significant difference in the yellowness (b^*) values between BS samples S-BS (15.41) and B-BS (15.98), nor did the combined method: 0.5AIS-BS (12.50), 1.0AIS-BS (11.10), 0.5AIB-BS (11.88), and 1.0AIB-BS (9.02). The changing of the whiteness index was in the same direction as the same changing in the brightness (L^*) value and the redness (a^*) value. It presented that the acid and heat treated to BS affected the whiteness index. The whiteness index of S-BS < 0.5AIS-BS < 1.0AIS-BS was 62.99 < 66.59 < 70.75, respectively, and B-BS < 0.5AIB-BS < 1.0AIB-BS was 44.07 < 57.61 < 62.85, respectively. Therefore, an appropriate preparation method of BS was 1.0AIS-BS.

3.3 Effect of the difference concentration of MS on dried BS quality in drying process

The highest sensory evaluation score sample, Ginger-MS, was selected to study the effect of the different concentrations of MS on the BS quality in the drying process. In this step, the BS from the appropriate preparation method, 1.0% AIS-BS, were boiled in different concentrations of Ginger-MS. Then, the surface of the boiled BS was washed with water before drying. The washing step was necessary to remove any adhering substances such as sugar and others to prevent the error effect from creating a blocking condition on the surface (Thammaratwasik, 1989 and Atiwirakul, 1984). This study found that MS concentration significantly affected the color value (brightness (L^*), redness (a^*), and yellowness (b^*)) (Table 7). In NGinger-MS-BS, the brightness (L^*) value was 70.21. Increasing the concentration of MS resulted in a decrease in brightness (L^*) value as follows: 20Ginger-MS-BS (47.32), 25Ginger-MS-BS (44.80), and 33Ginger-MS-BS (42.74). This indicates that the solid compounds in the Ginger-MS had adhered to the dried BS. Sinchaiphani *et al.* (2000) reported on the drying of morning glory. They found that the characteristics of the drying process could be divided into 3 stages. The first stage was called setting down, which created an equilibrium between the surface of the solid and the drying environment.

The second stage, the constant rate period of drying, occurred from the saturation of the liquid or water at the surface of the food from the movement of water in the food to the surface at a rate higher than the rate of evaporation from the surface of the food. The third stage, the drying process, had a reduced rate of movement of water within the food to the surface, and the surface of the food was dry, making drying more difficult. In this study, drying at 65°C was adapted from Thianchai and Soponronnarit (1991), who reported the optimum temperature for drying preserved pineapple at 55–65°C. Conversely, increasing the concentration of the Ginger-MS resulted in a significantly higher redness (a^*) value as follows: NGinger-MS-BS (2.59), 20Ginger-MS-BS (7.77), 25Ginger-MS-BS (8.52), and 33Ginger-MS-BS (8.67). The redness (a^*) value indicated the formation of a browning reaction commonly found in heat-

dried products. The yellowness (b^*) values in dried Ginger-MS-BS showed a slight increase in the yellowness (b^*) values, but the difference was statistically significant. However, the change in the yellowness (b^*) values was not related to the increasing concentration of the Ginger-MS. The yellowness (b^*) values of NGinger-MS-BS, 20Ginger-MS-BS, 25Ginger-MS-BS, and 33Ginger-MS-BS were 21.01, 22.75, 23.73, and 22.05, respectively. The delta E value is based on the delta L^* , delta a^* , and delta b^* color value. It is a standard measurement that indicates the color difference between the sample and the control that appear on a screen. The results showed that the dried Ginger-MS-BS presented in a similar color between the Ginger-MS-treated samples and the control (NGinger-MS-BS). The delta E values of 20Ginger-MS-BS, 25Ginger-MS-BS, and 33Ginger-MS-BS were 23.54, 26.23, and 28.16, respectively.

Table 6 Color value (brightness (L^*), redness (a^*), yellowness (b^*)) and whiteness index of BS prepared with different methods.

Treatment	Brightness (L^*) value	Redness (a^*) value	Yellowness (b^*) value	Whiteness index
1. F-BS	70.78±3.44 ^{ab}	0.37±0.61 ^{bc}	19.09±4.88 ^a	65.03±5.50 ^b
2. S-BS	66.36±0.35 ^c	0.28±0.13 ^{bc}	15.41±0.53 ^{bc}	62.99±0.10 ^b
3. B-BS	47.56±0.05 ^e	11.09±0.78 ^a	15.98±0.25 ^{ab}	44.07±0.07 ^d
4. 0.5AIS-BS	69.02±0.41 ^b	0.16±0.11 ^{bc}	12.50±0.85 ^{bcd}	66.59±0.69 ^b
5. 1.0AIS-BS	72.95±0.52 ^a	-0.30±0.14 ^{cd}	11.10±0.44 ^d	70.75±0.56 ^a
6. 0.5AIB-BS	59.33±0.96 ^d	0.73±0.24 ^b	11.88±1.24 ^{cd}	57.61±0.62 ^c
7. 1.0AIB-BS	63.97±0.52 ^c	-0.68±0.08 ^d	9.02±0.28 ^d	62.85±0.56 ^b

Mean value of 3 replicate measurements ± standard deviation.

^{abcd} Different letters in a column are significantly different level ($p < 0.05$) according to Duncan's multiple range test.

Table 7 Effect of the concentration of MS on color value (brightness (L^*), redness (a^*), and yellowness (b^*)) and delta E of dried BS.

Treatment	Brightness (L^*) value	Redness (a^*) value	Yellowness (b^*) value	Delta E
1. NGinger-MS-BS	70.21±0.48 ^a	2.59±0.17 ^c	21.01±0.45 ^c	-
2. 20Ginger-MS-BS	47.32±2.13 ^b	7.77±0.27 ^b	22.75±0.74 ^{ab}	23.54±2.10
3. 25Ginger-MS-BS	44.80±1.86 ^{bc}	8.52±0.51 ^a	23.73±0.49 ^a	26.23±2.08
4. 33Ginger-MS-BS	42.74±1.42 ^c	8.67±0.08 ^a	22.05±0.13 ^{bc}	28.16±1.65

Mean value of 3 replicate measurements ± standard deviation.

^{abc} Different letters in a column are significantly different level ($p < 0.05$) according to Duncan's multiple range test.

Delta E = 11-49 (Color are more similar than opposite).

The concentration of Ginger-MS significantly affected the yield of dried BS. In this experiment, it was found that the of dried 33Ginger-MS-BS > 25Ginger-MS-BS > 20Ginger-MS-BS; however, there was no statistically significant difference in the yield between 20Ginger-MS-BS and 25Ginger-MS-BS. The yield of dried BS obtained from using different concentrations of Ginger-MS was as follows: NGinger-MS-BS (13.58%), 20Ginger-MS-BS (17.82%), 25Ginger-MS-BS (19.18%), and 33Ginger-MS-BS (23.60%). This was consistent with Kabuo *et*

al. (2014), who reported the yield of dried pineapple and banana as follows: pineapple and bananas that were not soaked in a sugar solution before drying had yields of 13.78% and 20.76%, respectively, which were lower than pineapple and bananas that were soaked in sugar solution of 50% concentration at 40°C for 8 hr, which had yields of 21.42% and 23.88%, respectively. The concentration of Ginger-MS did not significantly affect the water activity of dried BS. The water activity of dried BS ranges from 0.24–0.27, which did not exceed the specified recommendation

of 0.6 according to the Thai community product standards for dried fruits and vegetables 136/2015. The moisture content of dried Ginger-MS-BS was significantly higher than dried NGinger-MS-BS (5.43%); however, there was no significant difference in moisture content among all Ginger-MS-BS: 20Ginger-MS-BS (7.33%), 25Ginger-MS-BS (7.37%), and 33Ginger-MS-BS (7.73%). Their moisture content did not exceed the specified recommendation of 12.0, according to the Thai Community Product Standards for dried fruits and vegetables 136/2015 (Table 8).

Dried Ginger-MS-BS was evaluated for sensory acceptability by using it as a filling for fried wonton sheets. The mean liking scores were described as “like extremely” in all characteristics: color (8.47), aroma (8.27), taste (8.13), texture (8.13), and overall acceptability (8.30) (Table 9). Proximate composition (%) of dried Ginger-MS BS was moisture content 7.73, crude protein 2.39, crude fat 0.26, ash content 6.71, and crude fiber 16.39 (Table 10). Its water activity was 0.24.

Table 8 Effect of the concentration of MS on yield, water activity and moisture content of dried BS.

Treatment	Yield (%)	Water activity ^{ns}	Moisture content (%)
1. NGinger-MS-BS	13.58 ± 1.20 ^c	0.26 ± 0.02	5.43 ± 0.35 ^b
2. 20Ginger-MS-BS	17.82 ± 1.26 ^b	0.27 ± 0.02	7.33 ± 0.25 ^a
3. 25Ginger-MS-BS	19.18 ± 2.00 ^b	0.25 ± 0.02	7.37 ± 0.67 ^a
4. 33Ginger-MS-BS	23.60 ± 1.51 ^a	0.24 ± 0.02	7.73 ± 1.07 ^a

Mean value of 3 replicate measurements ± standard deviation.

^{abc} Different letters in a column are significantly different level ($p < 0.05$) according to Duncan's multiple range test.

Table 9 Liking score of sensory evaluation of dried Ginger-MS-BS.

Sensory evaluation	Liking score	Description
Color	8.47 ± 0.51	Like extremely
Aroma	8.27 ± 0.58	Like extremely
Taste	8.13 ± 0.57	Like extremely
Texture	8.13 ± 0.57	Like extremely
Overall acceptability	8.30 ± 0.65	Like extremely

Mean value of 30 replicate measurements ± standard deviation.

Table 10 Proximate composition of dried Ginger-MS-BS.

Proximate composition		Thai community product standards 136/2015 “Dried fruit and vegetable”
Water activity	0.24 ± 0.02	0.6
Moisture content (%)	7.73 ± 1.07	≤ 12
Crude protein (%)	2.39 ± 0.08	Not specified
Crude fat (%)	0.26 ± 2.16	Not specified
Ash content (%)	6.71 ± 0.12	Not specified
Crude fiber (%)	16.39 ± 2.04	Not specified

Mean value of 3 replicate measurements ± standard deviation.

4. Conclusion

This research found that the herbs used as ingredients in the MS formula, the BS raw material preparation method, and the concentration of the MS applied to BS in the drying process significantly affected in the color value (brightness (L^*), redness (a^*), and yellowness (b^*)) and sensory acceptability. The best

choice for the herbal MS formula was Ginger-MS, adding 4.0% ginger into the Control-MS formula. The optimal conditions for the preparation method of the BS raw materials were using the 1.0% acetic acid solution combined with steaming (1.0AIS-BS). The appropriate concentration of Ginger-MS was 33.33%. The resulting dried Ginger-MS-BS received the highest mean liking score, described as “like extremely”, in all evaluation attributes:

color (8.47), aroma (8.27), taste (8.13), texture (8.13), and overall acceptability (8.30). It had water activity, and moisture content did not exceed the standard values in Thai Community Product Standard “dried fruit and vegetable” 136/2015. This study presented the information for the basic knowledge in the production of dried BS flavored with Ginger-MS, which is a healthy food product. Further, research should be developed to market this product placement by focusing on the appropriate packaging method and product shelf life.

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