International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.4 (2025) pp. 10198-10211

http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Optimization of Prochloraz Concentration and Hot-Water Treatment Time in the Mango Production Process Using Response Surface Methodology to Extend Postharvest Shelf-Life for Export

Nopparat Paivimut[1]*, Wichan Chuaiphan[2], Parinya Srisattayakul[3]

[1]Department of Engineering and Technology Management, Faculty of Engineering,Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand
* **Corresponding Author Email:** 649041810031@mail.rmutk.ac.th- **ORCID:** 0000-0002-8847-7050

[2]Department of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand
Email: wicha2n@gmail.com- **ORCID:** 0000-0002-5247-7750

[3]Department of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand
Email: pariny2a@gmail.com- **ORCID:** 0000-0002-5997-7850

Article Info:

DOI: 10.22399/ijcesen.4788
Received : 25 October 2025
Revised : 07 December 2025
Accepted : 10 December 2025

Keywords

Hot-water treatment;
response surface methodology;
mango production process;
postharvest shelf-life for export

Abstract:

This study aimed to optimize prochloraz concentration and hot-water immersion time within a commercial mango production process to extend the postharvest storage life of export mangoes. Mangoes were processed through a six-step production line. The experiment focused on the hot-water treatment stage and was designed using Response Surface Methodology. Mangoes were immersed in hot water at 54 °C containing prochloraz at concentrations of 5, 10, 15, 20, and 25 mL per 20 L of water for immersion times of 1, 8, and 15 min. Processed mangoes were stored under ambient conditions. Peel color changes, surface condition, and storage life were monitored daily, and the data were analyzed using standard statistical software. The results showed that mangoes treated with prochloraz at 20 mL per 20 L of hot- water for 15 min achieved the longest storage life, extending up to 15 days, with significant differences among treatments ($p < 0.05$). A lower concentration of 15 mL per 20 L resulted in a comparable storage life of 14 days. Considering export operations requiring transportation periods of up to 15 days, the 15 mL treatment was identified as a more suitable option due to its effectiveness with reduced chemical input. In Overall, the interaction between prochloraz concentration and hot-water immersion time plays a critical role in extending mango postharvest life within a commercial export-oriented production system. The findings support two practical treatment strategies: the use of lower chemical concentrations combined with longer immersion times, or shorter immersion times combined with moderately higher chemical concentrations.

1. Introduction

Mango (*Mangifera indica* L.) is one of the most economically important tropical fruits in Thailand and plays a significant role in both domestic consumption and international trade. Its popularity is attributed to its distinctive flavor, high nutritional value, and substantial contribution to national export revenue [1], [2]. However, mango is a highly perishable climacteric fruit with a limited postharvest life, generally not exceeding seven days under ambient conditions. Following harvest, rapid physiological changes associated with ripening accelerate fruit softening and senescence, thereby increasing susceptibility to postharvest diseases and quality deterioration [3]. Among the major postharvest challenges in mango handling are fungal diseases, particularly anthracnose caused by *Colletotrichum gloeosporioides* and stem-end rot caused by *Lasiodiplodia theobromae*. In addition, moisture loss during storage often leads to peel shriveling, further reducing visual quality and marketability. These factors substantially shorten the commercial life of mangoes and represent critical constraints in export supply chains that require extended transportation and distribution periods [4], [5].

Hot-Water treatment (HWT) has been widely adopted in mango export production systems as an effective postharvest intervention to suppress fungal decay, maintain fruit quality, and reduce dependence on intensive chemical applications. The technique is considered environmentally friendly and acceptable to consumers when properly applied [6]. In commercial practice, HWT is commonly integrated with fungicide dipping and hydrocooling operations to enhance disease control efficacy [7]. Among the fungicides used, prochloraz, an imidazole compound with broad-spectrum antifungal activity, has been extensively applied in mango postharvest management [8]. Numerous studies have demonstrated the effectiveness of prochloraz, either alone or in combination with Hot-Water treatment, in reducing postharvest decay and extending mango storage life. In Thailand, dipping mangoes in prochloraz at a concentration of 250 ppm for 30 s significantly reduced disease incidence, with combined Hot-Water treatment showing superior performance compared to single treatments [9], [10]. Similar results have been reported internationally. In the Philippines, Hot-Water treatment at 52–55 °C combined with prochloraz (550 μL L^{-1}) for 10 min extended the storage life of 'Carabao' mangoes from 7–10 days to approximately 20 days, while also reducing respiration rate and ethylene production [11]. Studies in Israel demonstrated that integrating prochloraz with Hot-Water treatment and biological control agents effectively suppressed *C. gloeosporioides* [12]. In South Africa, application of prochloraz at 40.5–81 g a.i./hl in combination with Hot-Water treatment at 55 °C for 2 min significantly reduced anthracnose and soft brown rot severity [13]. Likewise, in India, 'Kesar' mangoes treated with Hot-Water at 52 °C and prochloraz for 10 min achieved storage lives of up to 28 days, enabling successful export to Middle Eastern and European markets [14].

Despite its proven efficacy, the exclusive or excessive use of chemical fungicides such as prochloraz has raised concerns related to fungicide resistance development, chemical residues, and potential risks to consumer health [15]– [17]. As a result, contemporary postharvest management strategies increasingly emphasize Integrated Postharvest Management (IPM), which combines chemical, physical, and biological approaches to achieve effective disease control while enhancing sustainability and food safety [18], [19]. Although resistance to prochloraz has not yet been directly reported in *L. theobromae*, several studies have highlighted the strong adaptive capacity of this pathogen to develop resistance to other fungicides, indicating a potential risk associated with prolonged chemical reliance [20], [21]. In addition, concerns regarding fungicide residues and their possible health implications have been documented [22]. In contrast, integrating prochloraz with physical postharvest treatments such as Hot-Water washing and fruit coating has been shown to effectively suppress disease development and extend mango storage life [23]. In export-oriented, large-scale production systems, optimizing the concentration of prochloraz within the postharvest processing line is therefore essential to maintaining fruit quality and ensuring compliance with safety standards, while minimizing chemical input [24]. However, systematic investigations addressing this optimization under commercial processing conditions remain limited. In postharvest research, Response Surface Methodology (RSM) has been widely recognized as a powerful statistical tool for evaluating interactive effects among processing variables and identifying optimal operating conditions [25]– [27].

Therefore, the objective of this study was to evaluate the effects of prochloraz concentration and Hot-Water immersion time within a commercial production process on extending the postharvest storage life of '*Nam Dok Mai Si-Thong*' mangoes intended for export. The assessment focused on physical quality attributes and flesh firmness following postharvest processing. Response Surface Methodology (RSM) was employed to determine the optimal combination of treatment parameters that maximizes storage life while maintaining postharvest quality.

2. Materials and Methods

Materials

The raw materials and equipment used in this study were obtained from an export-standard fruit packing house operated by the Mango Community Enterprise Group, Ban Tha-Thong, Doem Bang Nang Buat District, Suphan Buri Province, Thailand. The materials are described as follows:

2.1.1 Mangoes

Nam Dok Mai Si-Thong mangoes were harvested from orchards certified under Good Agricultural Practices (GAP). Fruits weighing ≥ 400 g (Grade A) were selected. A total of 39 baskets were used, with 15 mangoes arranged in each basket.

2.1.2 Clean water

2.1.3 Prochloraz

Prochloraz (45% w/v EC) is a fungicide formulated as an emulsifiable concentrate (EC), containing 45 g of active ingredient per 100 mL of product (equivalent to 450 mg/mL). The fungicide must be diluted with water prior to application. The recommended standard application rate is 200 mL per 200 L of water. One cubic centimeter (cc) is equivalent to one milliliter (mL).

2.1.4 Mango Production Process for Expor

The Mango Production Process for Export consists of six continuously operated processing steps. This Production line was designed and developed by the researchers based on conventional farmer practices and upgraded to a semi-automated industrial Production Process. Optimal parameters for several processing steps had been previously investigated, including the optimal temperature and immersion time for hot-water treatment in Step 3 and the optimal temperature and immersion time for cold-water treatment in Step 4 [28]. However, the optimal concentration of prochloraz mixed in Hot-Water and the appropriate hot-water immersion time had not yet been studied. Therefore, the present study focused on investigating the optimal prochloraz concentration and immersion time within this Production Process. The six Production Process steps are as follows: 1) Size sorting and grading 2) Washing and inspection of fruit maturity 3) Hot-water immersion with prochloraz (water temperature fixed at 54 °C) 4) Cold-water immersion (temperature fixed at 25 °C) 5) Air blowing and water removal (conveyor belt speed fixed at level 2) and 6) Packaging

2.1.5 Data recording instruments

Data collection instruments included experimental record sheets, a digital camera, and a mango firmness tester (Texture Analyzer, model TA1, Lloyd Instruments).

3. Methods

Experimental design

The experiment was conducted using the complete six-step Production Process described above. Among these steps, hot-water immersion (Step 3) was selected as the primary experimental stage because prochloraz was applied during this process. According to the product label, the standard recommended dosage of prochloraz is 20 mL per 20 L of water. Response Surface Methodology (RSM) was employed to design the experiment to investigate two independent variables: prochloraz concentration and hot-water immersion time. Prochloraz concentration was evaluated at five levels based on dilution in 20 L of water: 5, 10, 15, 20, and 25 mL Hot-water immersion time was selected based on previous studies conducted by the researchers and evaluated at three levels: 1, 8, and 15 min. Each experimental treatment was performed in three independent replicates, resulting in a total of 39 experimental runs. Mangoes from each treatment group were processed sequentially through all six processing steps. After processing, mangoes from all experimental groups were stored at room temperature for observation. Changes during storage were recorded, including storage duration (days), peel color, and visible surface characteristics, until clear signs of deterioration appeared, while at least 80% of the mangoes remained free from decay. Subsequently, firmness of the remaining mangoes was measured to demonstrate their suitability for commercial application.

4. Experimental procedures

Nam Dok Mai Si-Thong mangoes harvested from GAP-certified orchards were transported to the processing facility within 24 h of harvest and introduced into the production line. Fruits were arranged in plastic baskets containing 15 mangoes per basket. A total of 39 baskets were used, corresponding to all treatment combinations with three replications per treatment. Prochloraz concentration and Hot-Water immersion time were assigned according to the experimental design at the third processing step. Experiments were conducted sequentially, with one treatment group processed per production run through all six steps of the production line. A schematic representation of the experimental production process is provided in Figure 1.Each experimental run corresponded to one complete production cycle and was conducted through six sequential processing steps, as described below.

Production line step 1: Fruit grading

Mangoes were graded according to fruit weight into Grades A, B, and C. Only Grade A mangoes, with a minimum weight exceeding 400 g, were selected for the experiment. Selected fruits were arranged in baskets containing 15 mangoes each, with three baskets assigned per treatment, and subsequently transferred to the second processing step.

Production line step 2: Washing and maturity assessment of fruit maturity

Mangoes were thoroughly washed to remove surface contaminants, and fruit stems were trimmed. Fruit maturity was assessed using a water flotation test. Mangoes that sank to the bottom of the tank were classified as over-mature, whereas fruits floating on the surface were considered under-mature; both categories were excluded from the experiment. Mangoes that remained suspended in the water were selected, returned to baskets, and transferred to the third processing step.

Production line step 3: Hot-Water immersion
Mangoes were immersed in Hot-Water maintained at 54 °C. Prochloraz concentration and immersion time were applied according to the experimental design. Upon completion of the designated immersion time, all three baskets were removed simultaneously and transferred to the fourth processing step.
Production line step 4: Cold-Water immersion
Mangoes were immersed in Cold-Water at 25 °C for 1 min to terminate heat exposure. After cooling, the baskets were transferred to the fifth processing step.
Production line step 5: Air blowing and water removal
Surface moisture was removed using forced air blowing. Airflow intensity and conveyor belt speed were fixed at level 2. After drying, the baskets were transferred to the final processing step.
Production line step 6: Packaging
Manual inspection was conducted to ensure uniform surface dryness, with no visible water droplets remaining on the fruit. Mangoes were then packaged and stored at ambient temperature for subsequent postharvest evaluation.

Recording of experimental observations

Postharvest changes in peel appearance and color were visually assessed and recorded daily for mangoes from all treatment groups. The number of days during which fruits remained fresh and free from anthracnose symptoms, decay, and shriveling was recorded. As the experiment was conducted under commercial-scale production conditions, complete product integrity was desired. However, to account for natural biological variability, a tolerance threshold of 20% deterioration was accepted. Storage life was defined as the number of days until more than 20% of the mangoes within a treatment group exhibited visible deterioration. Once this threshold was reached, storage duration recording was terminated. The remaining sound fruits (≥80%) were subsequently cut open and evaluated for flesh firmness to confirm their commercial acceptability.

Statistical analysis

Storage life data obtained from all treatment groups were analyzed using Minitab statistical software (version 19). Response Surface Methodology (RSM) was applied to develop a statistical model describing the relationship between the independent variables-prochloraz concentration and Hot-Water immersion time-and the response variable, storage life. Analysis of variance (ANOVA) was conducted to evaluate the significance of model terms, with statistical significance determined at $p < 0.05$. Optimal treatment conditions were identified by locating the maximum point on the response surface, corresponding to the combination of variables that resulted in the longest postharvest storage life of mangoes.

5. Results and Discussion

The results indicated that prolonged Hot-Water immersion time (15 min), in combination with appropriate prochloraz concentration, significantly influenced storage life, peel color development, surface appearance, and flesh firmness of mangoes processed through the export production line. Among the evaluated quality parameters, flesh firmness was considered a key indicator for assessing postharvest quality and market readiness of '*Nam Dok Mai Si-Thong*' mangoes during ripening. Flesh firmness decreased progressively as ripening advanced. When firmness values approached approximately 12 N or lower, mangoes entered an advanced ripening stage characterized by soft flesh, which limits suitability for long-distance transportation and extended storage [29[, [30[. Accordingly, firmness was regarded as a critical threshold parameter for determining commercial acceptability and effective shelf-life extension in the present study. Detailed observations of postharvest changes, including storage duration, peel color, surface condition, and flesh firmness, are summarized in Tables 1–5.Based on the data presented in Table 1, the application of prochloraz at 5 mL per 20 L of water combined with Hot-Water immersion for 15 min influenced both the physical quality attributes and postharvest storage life of mangoes processed through the production line. On the first day of storage, mangoes exhibited good overall quality, characterized by a smooth peel surface, bright yellow coloration, firm flesh, and the absence of visible decay or black spot symptoms. After five days of storage under ambient conditions, early signs of quality deterioration were observed in a proportion of the fruit. These symptoms included the appearance of brown to black spots on the peel, internal flesh discoloration, and progressive softening. Correspondingly, flesh firmness declined to 51.0 ± 2.9 N, reflecting a substantial reduction in tissue integrity associated with ripening and softening processes. With further extension of the storage period, the incidence and severity of decay increased markedly. Black lesions expanded across both peel and internal tissues, accompanied by a pronounced decrease in firmness to 9.81 ± 0.98 N. Such low firmness values indicate an advanced stage of ripening and tissue breakdown, rendering the fruit unsuitable for consumption and commercial distribution. Overall, these results indicate that although the application of prochloraz at 5 mL per 20 L combined with prolonged Hot-Water treatment delayed the initial onset of postharvest deterioration, this concentration was insufficient to effectively extend storage life over an extended period. The limited efficacy observed at this concentration suggests inadequate suppression of fungal development and insufficient maintenance of fruit structural integrity during prolonged storage.As shown in Table 2, the application of prochloraz at 10 mL per 20 L of water in combination with Hot-Water immersion for 15 min significantly influenced physical quality changes during storage of mangoes processed through the export production line. Observable quality deterioration became evident by day 7 of storage, when some fruits began to exhibit visible symptoms of decline, including the development of brown to black spots on the peel and a deeper yellow coloration of the flesh. In parallel with these visual changes, flesh firmness declined to 49.08 ± 3.92 N, indicating a marked reduction in tissue firmness associated with progressive ripening and senescence. With continued storage and the onset of decay, firmness decreased sharply to 11.77 ± 1.96 N, a level considered unsuitable for both consumption and commercial distribution. Overall, these results indicate that increasing the prochloraz concentration to 10 mL per 20 L improved the delay of quality deterioration and extended storage life compared with the lower concentration of 5 mL per 20 L. However, this concentration remained insufficient to fully suppress postharvest deterioration during prolonged storage beyond approximately 5–7 days. The findings suggest that although higher prochloraz concentrations enhance decay control and firmness retention, further optimization is required to achieve effective long-term storage stability.As presented in Table 3, the application of prochloraz at a concentration of 15 mL per 20 L of water combined with Hot-Water immersion for 15 min exerted a pronounced effect on maintaining mango quality during storage. Mangoes subjected to this treatment exhibited a clear delay in quality deterioration compared with those treated with lower prochloraz concentrations. By day 14 of ambient storage, distinct quality changes became evident. While some fruits remained in acceptable condition, retaining suitable peel color and internal flesh appearance, a substantial proportion began to exhibit visible deterioration. These symptoms included the development of brown to black lesions on the peel, which progressively expanded into larger necrotic areas. Concurrently, the internal flesh color intensified to a darker yellow, indicative of advanced ripening and tissue degradation. At this stage, flesh firmness declined to 47.07 ± 2.94 N, reflecting a marked reduction in tissue strength and progressive softening. Once fruits entered the deterioration or decay stage, flesh firmness decreased sharply to 9.81 ± 0.98 N, a level considered unsuitable for commercial distribution or consumption. Overall, these findings indicate that although prochloraz at 15 mL per 20 L substantially improved storage life relative to lower concentrations, it remained insufficient to effectively prevent postharvest deterioration beyond approximately 14 days under ambient storage conditions.As shown in Table 4, the application of prochloraz at a concentration of 20 mL per 20 L of water combined with Hot-Water immersion for 15 min markedly extended the postharvest storage life of mangoes processed through the production line. Clear differences in quality retention were observed throughout 15 days of storage. At day 15, a proportion of the mangoes maintained acceptable quality with respect to both peel appearance and internal flesh condition. These fruits exhibited a gradual reduction in flesh firmness to 46.11 ± 2.94 N, indicative of controlled softening associated with normal ripening rather than rapid tissue breakdown. In contrast, some fruits began to show evident symptoms of deterioration, including the development of brown to black lesions and fungal growth on the peel, as well as darker internal flesh coloration and mushy texture. These deteriorated fruits exhibited very low firmness values (9.81 ± 0.98 N), characteristic of advanced decay. Overall, these results demonstrate that a prochloraz concentration of 20 mL per 20 L effectively extended the storage life of mangoes to beyond two weeks under ambient conditions. Compared with lower concentrations, this treatment provided superior suppression of postharvest deterioration while maintaining commercially acceptable firmness for an extended period, highlighting its potential as an optimal treatment condition within the production process.As presented in Table 5, the application of prochloraz at a concentration of 25 mL per 20 L combined with 15-min Hot-Water immersion significantly influenced the postharvest quality of mangoes during storage. After 15 days, pronounced quality changes were observed. The mango peel exhibited noticeable discoloration, including the development of spots and blemishes, while the internal flesh color darkened to a deeper yellow. Concurrently, fruit firmness declined markedly to 36.28 ± 2.94 N, indicating substantial loss of tissue integrity and progressive softening. Although severe decay was less prevalent compared with lower prochloraz concentrations, the overall fruit quality deteriorated considerably in terms of peel appearance, firmness, and sensory attributes. These results indicate that, despite its capacity to delay deterioration, the use of prochloraz at 25 mL per 20 L may induce unfavorable physical characteristics, limiting its suitability for commercial marketing. Therefore, excessively high concentrations of prochloraz, while extending Shelf Life, can adversely affect marketable quality. A comparative evaluation of the effects of five prochloraz concentrations applied with a constant -min Hot-Water immersion on postharvest mango quality is summarized in Table 6.As summarized in Table 6, prochloraz concentrations of 15 and 20 mL per 20 L combined with 15-min Hot-Water immersion exhibited comparable effects on the postharvest Shelf Life of mangoes. Mangoes treated with 15 mL per 20 L maintained acceptable quality for approximately 14 days, whereas those treated with 20 mL per 20 L retained marketable quality for up to 15 days. Both treatments demonstrated similar peel color, surface appearance, and flesh firmness throughout the storage period. Physical observations indicated that excessively high prochloraz concentration (25 mL per 20 L) effectively suppressed decay; however, prolonged storage led to increased transpiration, resulting in peel shriveling and internal flesh dehydration. These quality deteriorations render the fruit unsuitable for commercial distribution. These findings are consistent with reports by ARC [31], which noted that while high prochloraz levels can control fungal pathogens effectively, excessive concentrations may negatively affect fruit physical quality. Conversely, low prochloraz concentration (5 mL per 20 L) was insufficient to inhibit fungal growth, leading to earlier onset of decay compared with other treatments. This observation aligns with the findings of Prusky [32], emphasizing that optimal fungicide concentrations must balance efficacy and safety to maintain postharvest quality. Overall, the results of this study indicate that 20 mL per 20 L prochloraz provides the most suitable balance between shelf-life extension and maintenance of physical quality, as illustrated in Figure 2 The collected physical data were subsequently analyzed using Response Surface Methodology (RSM) in Minitab software. The RSM results were consistent with the observed changes in fruit quality. Detailed outcomes of the RSM analysis are provided in Tables 7 and 8 and illustrated in Figures 3, 4, and 5.

Table 7 summarizes the two independent variables used in the RSM analysis. The first variable was Prochloraz concentration, tested at five levels: 5, 10, 15, 20, and 25 mL per 20 L of water. The second variable was the duration of Hot-Water treatment (HWT), evaluated at three levels: 1, 8, and 15 min.Table 8. Analysis of variance (ANOVA) for the Response Surface Methodology (RSM) model The ANOVA results summarized in Table 8 indicate that the RSM model was highly statistically significant ($F = 159.01$, $p < 0.001$). Both linear terms—Prochloraz concentration ($F = 206.30$, $p < 0.001$) and Hot-Water treatment duration ($F = 244.87$, $p < 0.001$)—had significant effects on the response variable, with Hot-Water treatment duration exerting the strongest influence on mango Shelf Life. The significant quadratic effect, particularly Prochloraz² ($F = 85.08$, $p < 0.001$), suggests a pronounced nonlinear relationship between Prochloraz concentration and Shelf Life. Additionally, the interaction between Prochloraz concentration and Hot-Water treatment duration was statistically significant ($F = 44.56$, $p < 0.001$), indicating that the effect of one factor depended on the level of the other. Although the lack-of-fit test was significant ($F = 10.16$, $p < 0.001$), the relatively low pure error (MS = 0.252) confirms that the model is adequate for prediction and optimization. The interaction effects of Prochloraz concentration and Hot-Water treatment duration on mango Shelf Life are illustrated in Figure 3.The interaction plot in Figure 3 illustrates that all response curves display a parabolic trend, indicating significant nonlinear quadratic effects on Shelf Life. Mango Shelf Life increased progressively as Prochloraz concentration was raised from 5 to 20 mL per 20 L of Hot-Water, reaching a peak before slightly decreasing at concentrations above 20 mL The dashed green line, corresponding to a Hot-Water treatment duration of 15 min, resulted in the longest average Shelf Life (~16 days), followed by 8 min (~11 days) and 1 min (~8 days). These findings indicate that Hot-Water treatment duration is the primary determinant of Shelf-Life extension and that it interacts strongly with Prochloraz concentration. To further explore the combined effects of Prochloraz concentration and Hot-Water treatment duration on the Shelf Life of *Nam Dok Mai Si-Thong* mangoes, a three-dimensional response surface plot was generated using the RSM model, as depicted in Figure 4.The three-dimensional response surface in Figure 4 demonstrates that both factors exert a significant combined effect on mango Shelf Life. Increasing Prochloraz concentration in conjunction with prolonged Hot-Water treatment duration resulted in a progressive increase in Shelf Life, reaching an optimal region beyond which the response plateaued or slightly declined. This response surface highlights the nonlinear relationship and strong interaction between the two factors. This study underscores the practical application of experimental optimization within a commercial-scale production process to achieve high-quality outcomes suitable for transportation and distribution. The primary objective is to minimize processing time and operational costs while maintaining fruit quality in accordance with market standards. For mango transportation scenarios requiring a Shelf-Life of 7–14 days, parameter settings in production line Step 3 (Hot-Water treatment combined with Prochloraz application) must be carefully optimized to balance chemical concentration, treatment duration, fruit quality, and production cost. The optimization outcomes derived from the RSM model are illustrated in Figure 5. Figure 5 presents the combinations of Prochloraz concentration (X-axis) and Hot-Water treatment duration (HWT-Time; Y-axis) that achieve mango Shelf Life within the target range of 7–14 days. The region enclosed by the contour lines corresponding to 7 and 15 days defines the acceptable operational range. For the lower target range (~7–8 days), representative parameter combinations included Prochloraz concentration of approximately 9.64 mL per 20 L with a treatment duration of 1.32 min (Shelf Life = 7.08 days) and 9.35 mL per 20 L with 4.56 min (7.72 days). Within the mid-range (~12–13 days), suitable combinations comprised 19.20 mL per 20 L with 4.01 min (12.77 days), 19.01 mL per 20 L with 6.71 min (13.17 days), and 21.88 mL per 20 L with 1.22 min (13.01 days). The upper target range (~14–15 days) was attained with Prochloraz concentrations of approximately 17.40–18.86 mL per 20 L in combination with treatment durations of 11.83–14.46 min, yielding Shelf-Life values of 14.46–14.87 days.These results clearly indicate a nonlinear interaction between the two factors. Specifically, longer Hot-Water treatment durations reduce the Prochloraz concentration required to achieve a given Shelf Life, whereas higher Prochloraz concentrations can compensate for shorter treatment durations.

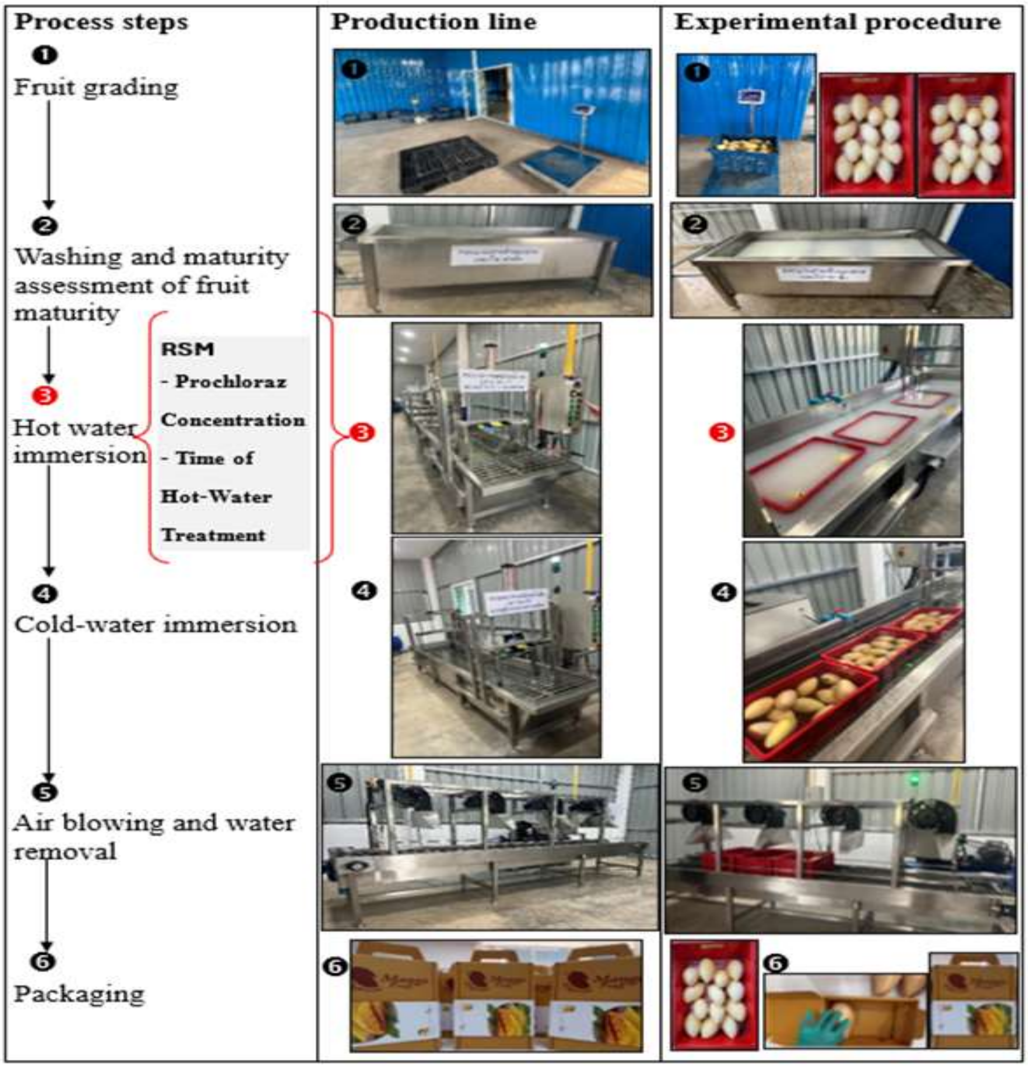

Figure. 1. Experimental procedures in the mango production process

Table 1. *Effect of Hot-Water immersion for* 15 *min combined with prochloraz at* 5 *mL per* 20 *L of water on postharvest changes of mangoes*

Day	Peel color of mango fruit	Surface characteristics of mango fruit	Internal quality of mango flesh	Fruit firmness (N)
1				
5				51.0 ± 2.9
				9.81 ± 0.98

Table 2.*. Effect of Hot-Water immersion for* 15 *min combined with prochloraz at* 10 *mL per* 20 *L of water on postharvest changes of mangoes*

Day	Peel color of mango fruit	Surface characteristics of mango fruit	Internal quality of mango flesh	Fruit firmness (N)
1				
7				49.08 ± 3.92
				11.77 ± 1.96

Table 3. *Effect of Hot-Water immersion for* 15 *min combined with prochloraz at* 15 *mL per* 20 *L of water on postharvest changes of mangoes*

Day	Peel color of mango fruit	Surface characteristics of mango fruit	Internal quality of mango flesh	Fruit firmness (N)
1				
14				47.07 ± 2.94
				9.81 ± 0.98

Table 4. *Impact of 15-min Hot-Water immersion combined with 20 mL per 20 L Prochloraz on postharvest quality of mangoes*

Day	Peel color of mango fruit	Surface characteristics of mango fruit	Internal quality of mango flesh	Fruit firmness (N)
1				
15				46.11± 2.94
				9.81± 0.98

Table 5. *Impact of 25 mL per 20 L Prochloraz combined with 15-min Hot-Water immersion on postharvest quality of mangoes*

Day	Peel color of mango fruit	Surface characteristics of mango fruit	Internal quality of mango flesh	Fruit firmness (N)
1				
>15				36.28± 2.94

Table 6. *Comparative impact of five Prochloraz concentrations combined with 15-min Hot-Water immersion on postharvest quality of mangoes*

Prochloraz concentration	Storage duration (days)	Fruit appearance (peel color)	Internal quality of mango flesh	Fruit firmness (N)
5 mL per 20 L of water	5			51.0 ± 2.9
10 mL per 20 L of water	7			49.08 ± 3.92
15 mL per 20 L of water	14			47.07 ± 2.94

Prochloraz concentration	Storage duration (days)	Fruit appearance (peel color)	Internal quality of mango flesh	Fruit firmness (N)
20 mL per 20 L of water	15			46.11 ± 2.94
25 mL per 20 L of water	>15			36.28± 2.94

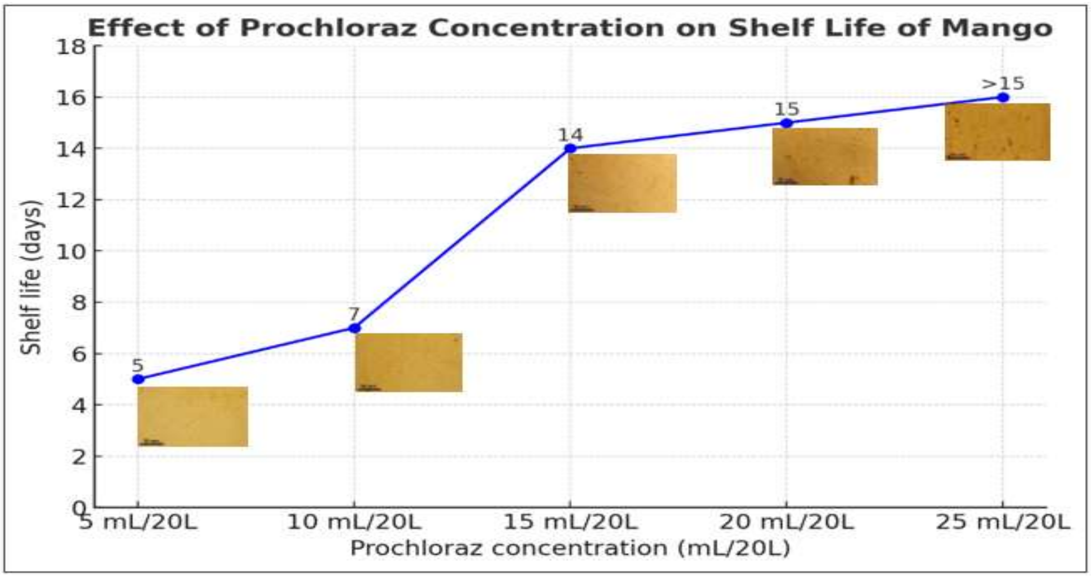

Figure 2. *Comparative assessment of shelf-life duration and peel quality of mangoes treated with five Prochloraz concentrations combined with 15-min Hot-Water immersion*

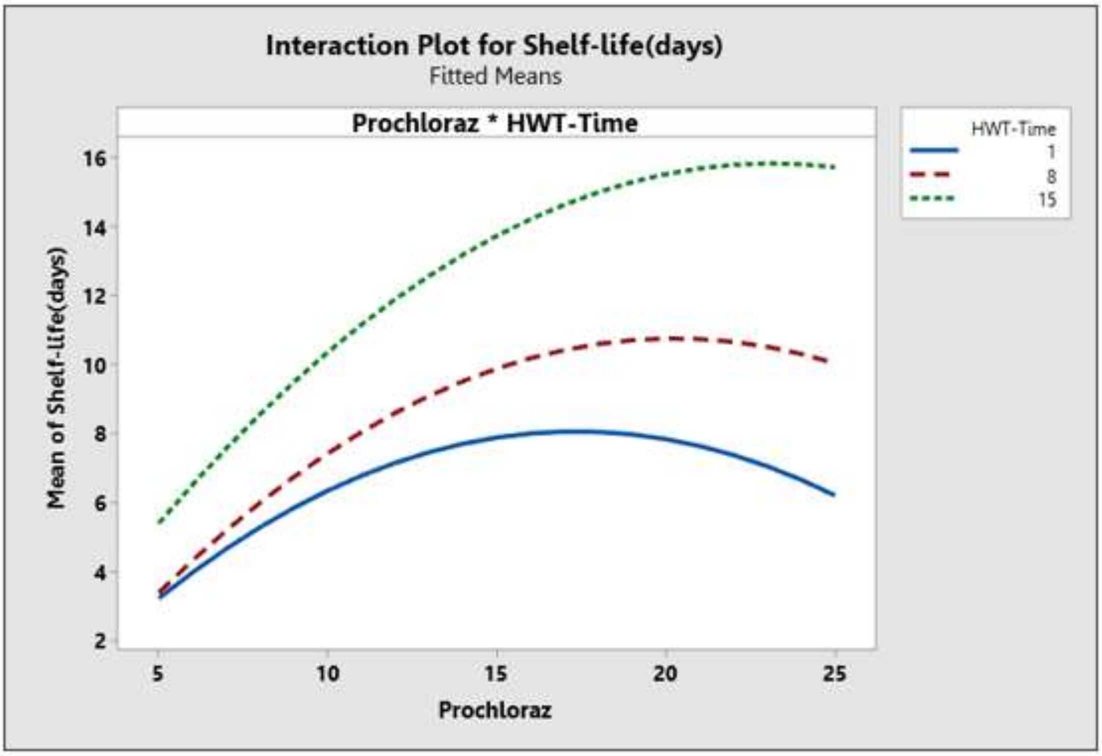

Figure 3. *Interaction effects of Prochloraz concentration and Hot-Water treatment duration on mango Shelf-Life*

***Table** 7. Factor Information*

Factor	Levels	Values
Prochloraz Concentration	5	5, 10, 15, 20, 25
Time of Hot-Water Treatment	3	1, 8, 15

Table 8. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	589.432	117.886	159.01	0.000
Linear	2	354.561	177.281	239.13	0.000
Prochloraz	1	152.941	152.941	206.30	0.000
HWT-Time	1	181.535	181.535	244.87	0.000
Square	2	64.608	32.304	43.57	0.000
Prochloraz*Prochloraz	1	63.072	63.072	85.08	0.000
HWT-Time*HWT-Time	1	7.811	7.811	10.54	0.003
2-Way Interaction	1	33.037	33.037	44.56	0.000
Prochloraz*HWT-Time	1	33.037	33.037	44.56	0.000
Error	33	24.465	0.741		
Lack-of-Fit	7	17.917	2.560	10.16	0.000
Pure Error	26	6.548	0.252		
Total	38	613.897			

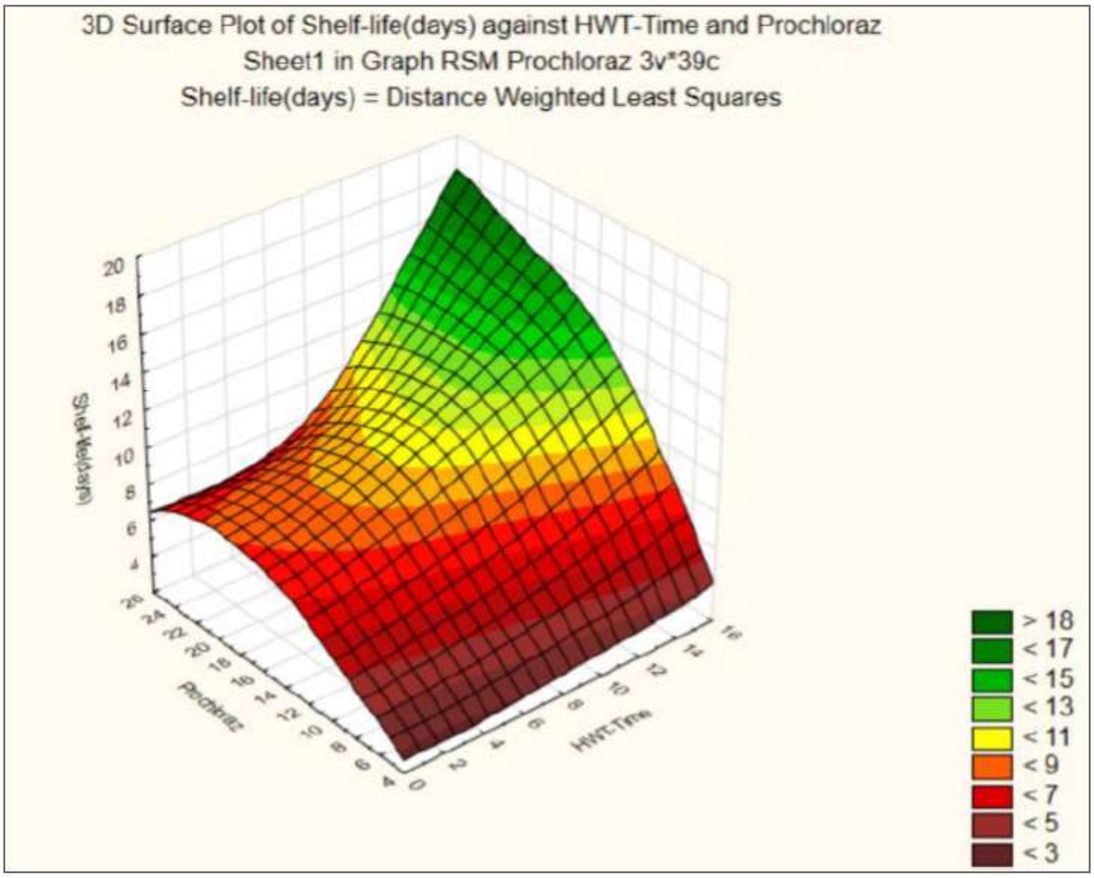

***Figure 4.** Three-dimensional response surface plot depicting the combined effects of Prochloraz concentration and Hot-Water treatment duration (HWT-Time) on the Shelf-Life of Nam Dok Mai Si-Thong mangoes*

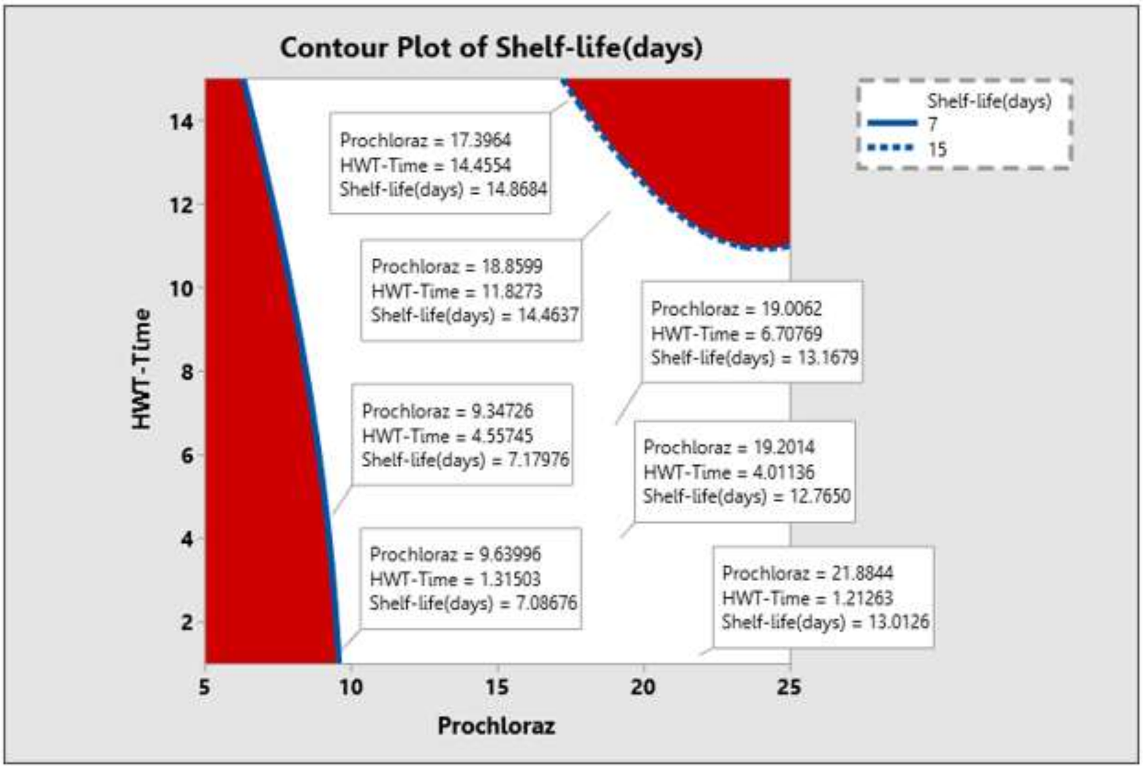

Figure 5. *RSM contour plot depicting the combined effects of Prochloraz concentration and Hot-Water treatment duration on mango Shelf-Life within the target range of 7–14 days*

6. Conclusions

The present study employed Response Surface Methodology (RSM) to optimize Prochloraz concentration and Hot-Water treatment (HWT) duration within a commercial mango production process, with the aim of extending the postharvest Shelf Life of *Nam Dok Mai Si-Thong* mangoes intended for export. The key conclusions are summarized as follows:

1. Effect of Prochloraz concentration and Hot-Water treatment duration Both Prochloraz concentration in Hot-Water and HWT duration significantly influenced the postharvest Shelf Life of *Nam Dok Mai Si-Thong* mangoes in an export-oriented production system. The combination of 20 mL Prochloraz per 20 L of water with Hot-Water immersion at 54 °C for 15 min was identified as the most effective condition, extending mango Shelf Life to 15 days. This treatment effectively maintained fruit quality, minimized postharvest losses, and enhanced consumer confidence in both domestic and international markets.

2. Limitations of insufficient or excessive Prochloraz application. Prochloraz concentrations below 10 mL per 20 L in combination with 15-min Hot-Water treatment were inadequate for decay control, resulting in rapid quality deterioration. Conversely, concentrations exceeding 20 mL per 20 L extended Shelf Life beyond 15 days without visible decay; however, excessive moisture loss led to fruit shriveling and dehydration, rendering the fruit unsuitable for commercial distribution. These findings underscore that unnecessarily high Prochloraz concentrations may compromise fruit quality and raise potential consumer safety concerns. The results are consistent with the principles of Integrated Postharvest Management (IPM), which emphasize the judicious use of chemical treatments to balance efficacy, safety, and sustainability [33–35].

3. Operational frameworks for industrial application. The study identifies two practical operational strategies for industrial implementation: (1) a "low-chemical–long-time" approach (e.g., Prochloraz ≈ 17–19 mL/20 L, HWT ≈ 12–14 min) achieving a Shelf Life of approximately 14–15 days; and (2) a "short-time–moderate-chemical" approach (e.g., Prochloraz ≈ 19–22 mL/20 L, HWT ≈ 1–7 min) achieving a Shelf Life of approximately 12–13 days. Selection of the appropriate strategy should consider production line constraints, including temperature and time control capabilities, as well as compliance with pesticide residue regulations, such as maximum residue limits (MRLs) established by international authorities and trade agreements [36, 37].

4. Economic considerations and cost optimization for export logistics. Large-scale export operations require stringent cost management. For export routes with transportation durations not exceeding 15 days, a Prochloraz concentration of 15 mL per

20 L can be selected instead of 20 mL per 20 L, extending Shelf Life to approximately 14 days while reducing chemical input costs. Optimized use of Prochloraz at appropriate concentrations thus contributes to both lower export costs and effective shelf-life extension. From economic and consumer safety perspectives, the concentration range of 15 mL per 20 L represents an optimal compromise between efficacy and cost-effectiveness.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

- **Acknowledgement:** We would like to thank Ban Tha-Thong Mango Community Enterprise in Doem Bang Nang Buat District, Suphan Buri Province, Thailand for supporting data, Nam Dok Mai Si-Tong mangoes, machine tools, Experimental area of this research.

- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1] N. Chomchalow, "The mango: king of fruits," *AU Journal of Technology*, vol. 12, no. 1, pp. 1–8, 2008.

[2] W. Spreer, "Mango and longan production in northern Thailand," in *Mango and Longan Production in Northern Thailand*. Springer, 2012, pp. 133–154.

[3] K. A. Kumar, M. Narayani, A. Subanthini, and M. Jayakumar, "Antimicrobial activity and phytochemical analysis of citrus fruit peels: utilization of fruit waste," *International Journal of Engineering Science and Technology*, vol. 3, pp. 5414–5421, 2011.

[4] R. E. Paull and N. J. Chen, "Heat treatment and fungicide application for postharvest control of mango diseases," *Hort Science*, vol. 35, no. 6, pp. 1074–1077, 2000.

[5] D. Prusky, I. Kobiler, and R. Ben-Arie, "Prochloraz treatment for controlling anthracnose in mangoes during storage," *Postharvest Biology and Technology*, vol. 10, no. 2, pp. 129–135, 1997.

[6] N. L. Bambalelea, A. Mditshwa, L. S. Magwaza, and S. Z. Tesfay, "Assessing gaseous ozone and edible coatings as postharvest treatments for mango (*Mangifera indica* L.) fruit," *2021*.

[7] M. P. Montecalvo, O. S. Opina, T. U. Dalisay, and E. B. Esguerra, "Efficacy of postharvest treatments in reducing stem end rot of 'Carabao' mango (Mangifera indica L.) fruit," *Philippine Journal of Crop Science*, vol. 44, no. 1, pp. 36–43, 2019.

[8] Kasetsart University, "Effects of Prochloraz, hot Prochloraz, Hot-Water, and cinnamon extract on fruit

[9] quality and anthracnose disease of 'Yuwen' mango," *Kasetsart Journal of Agricultural Science*, vol. 49, Suppl. 4, pp. 473–480, 2018

[10] U. Chinwang, et al., "Effects of postharvest Hot-Water treatment and storage temperatures on physicochemical qualities of 'Mahachanok' mangoes," *Agritech*, vol. 34, no. 3, pp. 291–300, 2015.

[11] Department of Agriculture, "Postharvest disease control in mango using fungicides and Hot-Water treatment," *Technical Report*, Bangkok, Thailand, 2014.

[12] J. Arevalo, E. B. Esguerra, and F. S. Dela Cruz, "Integrated postharvest treatments for extending Shelf Life and maintaining quality of 'Carabao' mango," *Philippine Agricultural Scientist*, vol. 95, no. 3, pp. 231–240, 2012.

[13] Kobiler, D. Prusky, S. Droby, N. O. Akerman, and R. Ben-Arie, "Integration of preharvest application of yeast antagonist and postharvest Hot-Water and prochloraz treatments for controlling anthracnose in mango," *Plant Disease*, vol. 85, no. 11, pp. 1240–1246, 2001.

[14] South African Mango Growers' Association (SAMGA), *Technical Yearbook: Postharvest Disease Management in Mangoes*, Nelspruit, South Africa, 2018.

[15] K. Shinde, B. B. Desai, and A. N. Wagh, "Hot-Water and fungicide treatment for extending storage life of 'Kesar' mango," *Indian Journal of Horticulture*, vol. 68, no. 3, pp. 332–337, 2011.

[16] D. Prusky and S. Droby, "Postharvest disease control: new approaches for reducing chemical fungicide dependence," *Current Opinion in Biotechnology*, vol. 21, no. 2, pp. 147–152, 2010.

[17] S. Bautista-Baños, M. Hernández-López, E. Barrera-Necha, and E. Bosquez-Molina, "Antifungal activity of plant extracts on postharvest pathogens of mango fruit," *Postharvest Biology and Technology*, vol. 29, no. 1, pp. 99–107, 2003.

[18] M. Wisniewski and S. Droby, "The use of biocontrol agents to reduce postharvest fungicide dependence," *Annual Review of Phytopathology*, vol. 48, pp. 243–268, 2010.

[19] D. Spadaro and S. Droby, "Developing alternative strategies to synthetic fungicides for the control of postharvest diseases," *Trends in Plant Science*, vol. 21, no. 4, pp. 303–315, 2016.

[20] S. Droby and M. Wisniewski, "Biological control of postharvest diseases of fruits and vegetables: Alternatives to synthetic fungicides," *Postharvest Biology and Technology*, vol. 13, no. 3, pp. 171–177, 1998.

[21] J. Yan, N. Wu, and L. Zhang, "Molecular analysis of fungicide sensitivity in *Lasiodiplodia theobromae*," *Journal of Applied Microbiology*, vol. 131, no. 5, pp. 2108–2118, 2021.

[22] J. Marques, D. Lima, and A. Phillips, "Fungicide sensitivity of Botryosphaeriaceae species including *Lasiodiplodia theobromae*," *European Journal of Plant Pathology*, vol. 135, no. 4, pp. 655–666, 2013.

[23] B. Singh, S. R. Sharma, and R. K. Gupta, "Pesticide residue analysis and risk assessment in mangoes collected from agricultural markets," *Environmental Monitoring and Assessment*, vol. 189, no. 9, pp. 1–12, 2017.

[24] Kobiler, D. Prusky, S. Droby, N. O. Akerman, and R. Ben-Arie,"Integration of preharvest application of yeast antagonist and postharvest Hot-Water and prochloraz treatments for controlling anthracnose in mango," *Plant Disease*, vol. 85, no. 11, pp. 1240–1246, 2001.

[25] M. P. Montecalvo, O. S. Opina, T. U. Dalisay, and E. B. Esguerra, "Efficacy of postharvest treatments in reducing stem end rot of 'Carabao' mango (*Mangifera indica L.*) fruit," *Philippine Journal of Crop Science*, vol. 44, no. 1, pp. 36–43, 2019.

[26] D. C. Montgomery, *Design and Analysis of Experiments*, 7th ed., Wiley, 2008.

[27] M. A. Hossain and S. Rahman, "Optimization of postharvest treatment of fruits using response surface methodology," *Postharvest Biology and Technology*, vol. 110, pp. 140–150, 2016.

[28] H. Bas and P. Boyaci, "Modeling and optimization of process parameters for enzyme inactivation using response surface methodology," *Journal of Food Engineering*, vol. 78, no. 3, pp. 846–854, 2007.

[29] N. Paivimut, W. Chuaiphan, and P. Srisattayakul, "Development of a semi-automatic post-harvest production system for quality control and value addition to mangoes of community enterprises," *Journal of Physics: Conference Series*, vol. 3160, no. 1, p. 012011, Dec. 2025, doi: 10.1088/1742-6596/3160/1/012011.

[30] "Preparation of Methylcellulose Film-Based CO_2 Indicator for Monitoring the Ripeness Quality of Mango Fruit cv. Nam Dok Mai Si-Thong," *Polymers*, vol. 14, no. 17, art. 3616, 2022.

[31] P. Penchaiya *et al.*, "Dynamics of firmness and colour of Thai mango cultivar 'Nam Dok Mai Si-Thong'," *Acta Horticulturae*, no. 1091, pp. (conference paper), 2015, doi: 10.17660/ActaHortic.2015.1091.32.

[32] Agricultural Research Council (ARC), "Prochloraz in mango pack houses," ARC Institute for Tropical and Subtropical Crops, South Africa, Tech. Rep., 2018. [Online]. Available:https://www.arc.agric.za/arcitsc/News%20Articles%20Library/Prochloraz%20in%20mango%20 pack%20houses.pdf

[33] European Commission, "EU Pesticides Database: Maximum Residue Levels (MRLs)," European Union, 2023. [Online]. Available:https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database

[34] W. Ledger, "Post-harvest storage management of mango fruit," *Acta Horticulturae*, vol. 645, pp. 551–556, 2004.

[35] G. Ciofini, "Sustainable approaches in postharvest disease management of tropical fruits: A review," *Frontiers in Plant Science*, vol. 13, p. 956872, 2022.

[36] D. Prusky, "Reduction of the incidence of *Alternaria* rot in mangoes treated with prochloraz in a modified wax coating," *Postharvest Biology and Technology*, vol. 42, no. 2, pp. 134–140, 2006. doi:10.1016/j.postharvbio.2006.05.007

[37] Z. Li, Y. Zhang, and L. Wang, "Food safety and maximum residue limits of pesticides: a framework for evaluation," Regulatory Toxicology and Pharmacology, vol. 106, pp. 294–302, 2019, doi:10.1016/j.yrtph.2019.05.019.

[38] APEC, "Import MRL Guideline for Pesticides," Asia-Pacific Economic Cooperation, 2016. [Online]. Available: https://www.apec.org/docs/default-source/Publications/2016/12/Import-MRL-Guideline-for-Pesticides.pdf