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Optimization of Hot Water Treatment Temperature and Duration in a Semi-Industrial Postharvest Process for Enhancing Shelf Life and Quality of Mango (*Mangifera indica* L.) Using Response Surface Methodology

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Abstract

This study aimed to determine the optimal conditions of hot water treatment temperature and immersion time in the postharvest production process using Response Surface Methodology (RSM) to evaluate the interactive effects of processing variables and predict optimal conditions for shelf-life extension. The experiment was designed using a Central Composite Design (CCD), with hot water temperature (48–56°C) and immersion time (1–15 min) as independent variables. The response variables included shelf life, physical quality attributes, and fruit sweetness. The results demonstrated that hot water temperature and immersion time significantly affected the shelf life and quality of mango fruit ($p < 0.05$). The developed quadratic model showed good predictive capability with an R^2 value of 92.71%. The optimal processing condition was identified at 54.02°C for 12.13 min, which extended mango shelf life to 12.66 days while maintaining acceptable physical quality and sweetness levels according to export standards. The distinctive contribution of this study lies in the application of RSM under an actual semi-industrial postharvest production system to optimize processing conditions in relation to transportation duration and destination market requirements. The proposed approach has strong potential to reduce postharvest losses, improve supply chain efficiency, and enhance the export value of mango fruit.

Keywords:
Mango (Mangifera indica L.), Hot water treatment, Temperature and duration, Semi-Industrial Postharvest processing, Shelf life, Response Surface Methodology

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1. Introduction

Mango (*Mangifera indica* L.) is one of the most economically important tropical fruits in the global market, particularly in tropical countries where production and export activities continue to expand. The economic value of mango fruit largely depends on postharvest quality attributes, including external appearance, peel color, texture, nutritional value, and storage performance, all of which are critical factors influencing long-distance transportation and consumer acceptance in destination markets (Pawde et al., 2025; Taiti et al., 2025). However, fresh fruits remain highly susceptible to postharvest losses caused by physiological deterioration, microbial decay, and mechanical damage during handling, transportation, and storage, which directly affect market value and export competitiveness (Food and Agriculture Organization of the United Nations [FAO], 2019; Taiti et al., 2025).

Postharvest management plays a crucial role in extending shelf life and maintaining mango quality. Among available techniques, Hot Water Treatment (HWT) has been widely recognized as an effective method for reducing microbial contamination and controlling postharvest diseases, particularly anthracnose caused by *Colletotrichum gloeosporioides* (Abdel-Sattar et al., 2024; Yahaya et al., 2024). In addition, HWT can delay fruit deterioration through several physiological mechanisms, including inhibition of ripening-related enzymes, suppression of cell wall degradation, and reduction of microbial activity on the fruit surface (Wang et al., 2024; Yahaya et al., 2024). Nevertheless, the effectiveness of HWT strongly depends on appropriate control of treatment temperature and immersion time. Excessive temperature or prolonged exposure may induce tissue damage, such as heat injury and loss of firmness, whereas insufficient treatment conditions may fail to effectively suppress microbial growth and postharvest decay (Islam et al., 2024; Wang et al., 2024).

Although numerous studies have investigated the effects of HWT on mango quality and shelf-life extension, most previous studies focused primarily on single-factor experiments conducted under laboratory-controlled conditions (Inyang et al., 2023; Islam et al., 2024). Such approaches are insufficient to comprehensively explain the interaction effects between temperature and immersion time, thereby limiting the practical application of the findings in semi-industrial or commercial postharvest systems. Furthermore, studies on process optimization have indicated that neglecting interactions among critical factors may result in inaccurate determination of optimal processing conditions and reduced reliability in real industrial applications.

Response Surface Methodology (RSM) is a powerful statistical approach for experimental design, modeling, and optimization of complex processes involving multiple variables. The technique enables systematic evaluation of both main effects and interaction effects among process parameters (Madamba, 2002; Montgomery, 2020). Compared with conventional single-factor experimentation, RSM reduces the number of experimental runs, minimizes operational costs, and improves prediction accuracy under complex processing conditions (Bezerra et al., 2008). Consequently, RSM has been extensively applied in food engineering and postharvest technology studies to optimize processing conditions and enhance the shelf life and quality of horticultural products (Bas & Boyacı, 2007; Jani et al., 2022).

Therefore, the present study applied RSM to investigate the interactive effects of hot water temperature and immersion time under an actual semi-industrial postharvest production system. The objective was to determine the optimal processing conditions for extending mango shelf life while maintaining acceptable fruit quality and improving export logistics performance.

This study specifically aimed to optimize hot water treatment conditions in the postharvest production process in order to extend shelf life and improve mango quality using Response Surface Methodology for experimental design and response analysis.

The distinctive contribution of this research lies in the integration of statistical optimization with a real semi-industrial postharvest production process, providing practical outcomes that can be directly implemented in commercial mango export operations.

2. Materials and Methods

2.1 Materials

Nam Dok Mai Si Thong mangoes (*Mangifera indica* L.) were obtained from a Good Agricultural Practices (GAP)-certified orchard operated by the Ban Tha Thong Mango Community Enterprise, Doem Bang Nang

Buat District, Suphan Buri Province, Thailand. Fruits were selected based on uniformity in size and weight (300–450 g) and physiological maturity at 95–110 days after fruit set to ensure sample consistency throughout the experiment, as shown in Figure 1.

Figure 1. Representative mango fruits selected for experimental use in the postharvest production process

The hot water treatment unit used in this study was integrated into a semi-automatic postharvest production system previously developed by the researchers (Paivimut et al., 2025). The production system consisted of seven sequential processing stages operating under a continuous production flow for postharvest mango handling and quality management. The hot water treatment process represented the third stage of the production line, receiving mango fruits from the second stage, which involved fruit washing and maturity inspection. The fruits were subsequently subjected to hot water treatment before being transferred to the next stage for cold water treatment, followed by the remaining postharvest processing stages until completion of all seven processes. The hot water treatment machinery integrated within the production line is illustrated in Figure 2(a) and (b).

(a) (b)

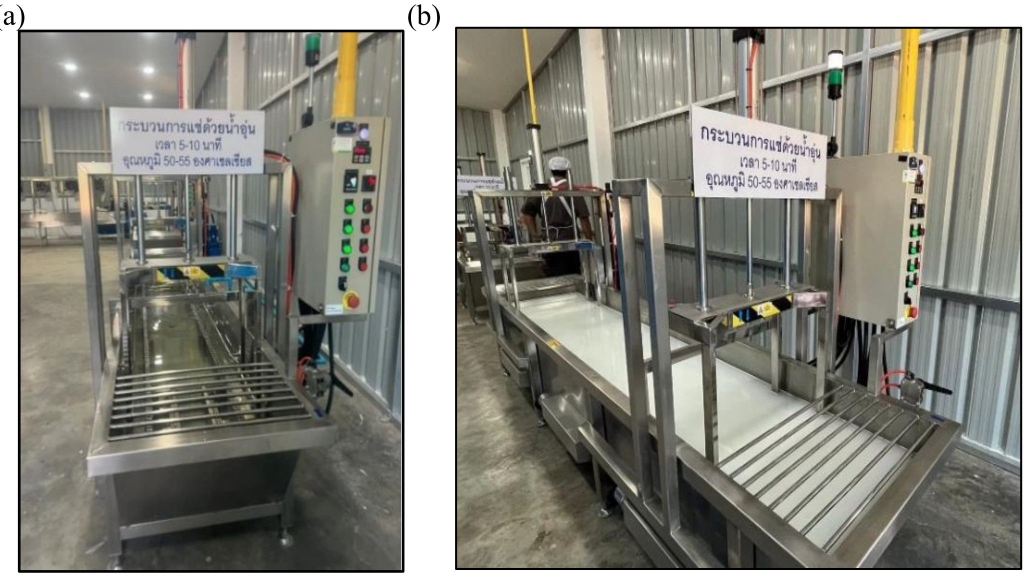


Figure 2. (a) Front view and (b) side view of the hot water treatment machinery integrated into the postharvest production line.

2.2 Methods

2.2.1 Experimental design

The experiment was designed using Response Surface Methodology (RSM) based on a Central Composite Design (CCD) and analyzed using Minitab Version 19 software to evaluate the effects of two independent variables: hot water treatment temperature (48–56°C) and immersion time (1–15 min). The CCD structure consisted of four factorial points, four axial points, and five center points, resulting in a total of 13 experimental conditions. Each condition was performed in triplicate, giving a total of 39 experimental units. The response variables included shelf life, defined as the number of days that mango fruits remained acceptable without exceeding the predetermined decay threshold, and fruit sweetness, which was measured using a Master Refractometer (ATAGO, Japan) and expressed as total soluble solids (°Brix). The fruits were stored under ambient conditions at 25 ± 2 °C and 70–80% relative humidity until the mangoes no longer met the predetermined quality criteria.

The experimental data were analyzed using analysis of variance (ANOVA) and multiple regression modeling to evaluate the effects of independent variables and their interaction on the response variables. Model adequacy was assessed based on the coefficients of determination (R^2, adjusted R^2, and predicted R^2) together with lack-of-fit analysis. Statistical significance was determined at $p < 0.05$. Subsequently, the desirability function approach was employed to determine the optimal processing conditions for the hot water treatment process.

2.2.2 Experimental procedures

The experiment was conducted under a continuous production-line operation. In this study, the researchers focused specifically on the third stage of the production line, namely the hot water treatment process. Experimental trials and data analysis were performed to determine the optimal temperature and immersion time conditions for this processing stage. The overall experimental procedure is illustrated in Figure 3.

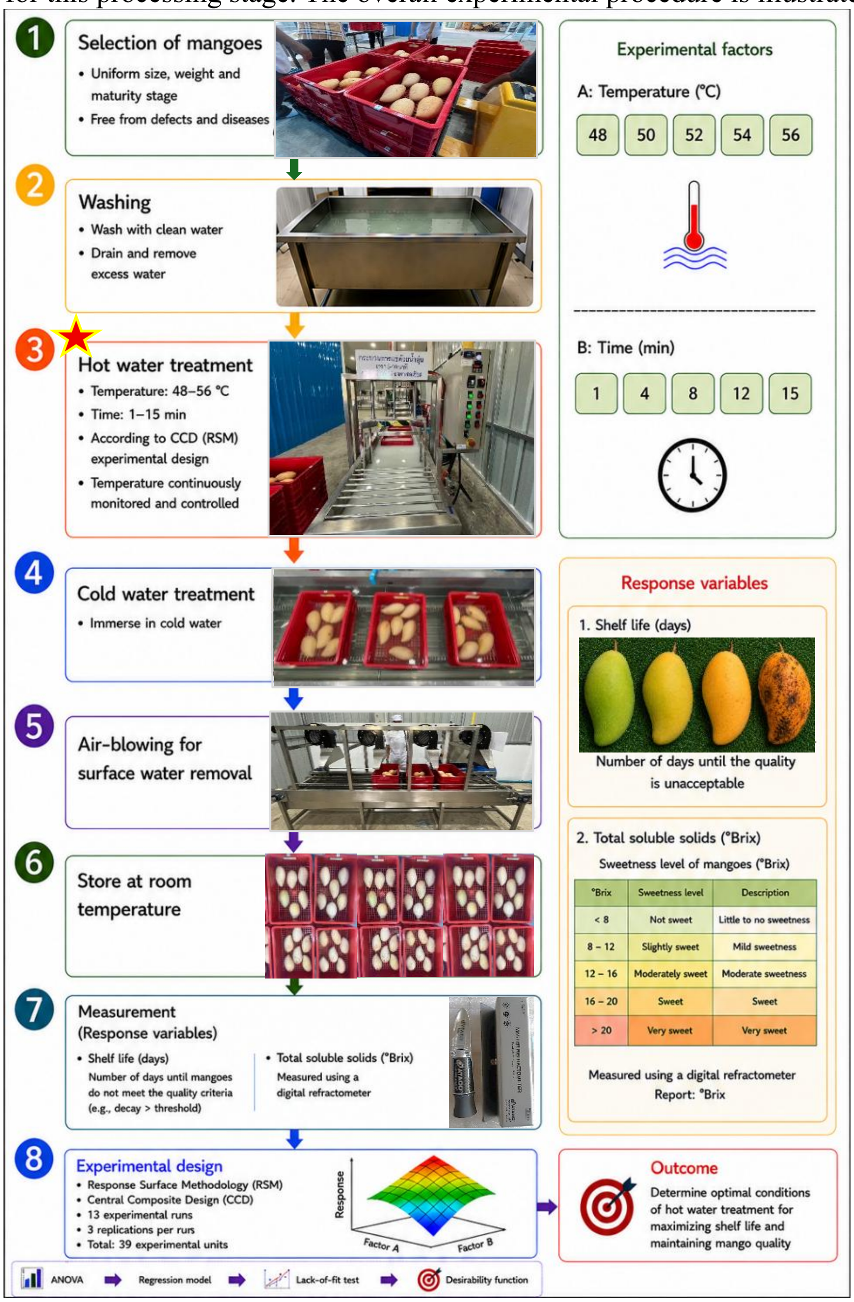


Figure 3. Experimental flow diagram of hot water treatment and response surface methodology for optimizing postharvest quality and shelf life of mango

The experimental procedure illustrated in Figure 3 was conducted as follows:

1. Mango fruits (*Mangifera indica* L.) with uniform size, weight, and maturity level were selected. Fruits showing visible defects, physical damage, or disease symptoms on the peel surface were excluded from the experiment.
2. The selected mangoes were washed with clean water to remove dirt and contaminants from the fruit surface and subsequently drained under ambient conditions.
3. The mangoes were introduced into the production line and subjected to hot water treatment according to the Central Composite Design (CCD) under Response Surface Methodology (RSM), using treatment temperatures ranging from 48 to 56 °C and immersion times ranging from 1 to 15 min.
4. After hot water treatment, the mangoes were transferred to the subsequent production-line stage for cold water treatment under predetermined conditions, followed by air drying at room temperature.
5. The treated mangoes were stored at 25 ± 2 °C and 70–80% relative humidity until the physical appearance of the fruits no longer met the predefined quality criteria.
6. The response variables evaluated included shelf life, expressed as the number of storage days before unacceptable deterioration occurred, and fruit sweetness, reported as Total Soluble Solids (°Brix).
7. The experimental data were analyzed using analysis of variance (ANOVA), regression modeling, and the desirability function approach to determine the optimal hot water treatment temperature and immersion time for extending shelf life and maintaining export-quality mango fruit.

2.2.3 Recording of experimental observations

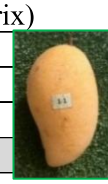
The criteria for shelf-life termination were defined prior to data collection. Mango fruits were considered to have reached the end of their shelf life when visible decay symptoms appeared on the fruit surface or when unacceptable physical characteristics were observed, including peel discoloration, shriveling, abnormal softening of the flesh, or fungal growth on the fruit surface.

The experimental observations obtained from the Central Composite Design (CCD) under Response Surface Methodology (RSM) are presented in Table 1. to evaluate the effects of hot water treatment temperature and immersion time on mango shelf life and fruit quality. The independent variables consisted of hot water treatment temperatures ranging from 48 to 56 °C and immersion time ranging from 1 to 15 min.

The experimental design included a total of 13 treatment conditions with three replications per condition, resulting in 39 experimental units.

The response variables included shelf life (days), fruit sweetness, and physical quality attributes of mango fruits after storage.

Table 1. Experimental observations recorded according to the experimental design.

Run Replicate 3	Hot water temperature (°C)	Immersion time (min)	Shelf life (days)	Physical appearance after storage Passed quality Total Soluble criteria Solids (°Brix)		Failed to meet quality criteria
1	50	4	4			
2	54	4	7			
3	50	12	7			
4	**54**	**12**	**12**	✓ 	**23** °Brix	
5	48	8	4			
6	**56**	**8**	**10**			✓ 
7	52	1	3			
8	52	15	11			
9	52	8	6			
10	52	8	6			
11	52	8	6			
12	52	8	6			
13	50	4	4			

Run Replicate 3	Hot water temperature (°C)	Immersion time (min)	Shelf life (days)	Physical appearance after storage Passed quality criteria	Total Soluble Solids (°Brix)	Failed to meet quality criteria
14	50	4	4			
15	54	4	7			
16	50	12	7			
17	**54**	**12**	**12**	✓ 	**20** °Brix	
18	48	8	4			
19	**56**	**8**	**9**			✓ 
20	52	1	3			
21	52	15	11			
22	52	8	6			
23	52	8	6			
24	52	8	6			
25	52	8	6			
26	50	4	4			
27	50	4	4			
28	54	4	7			
29	50	12	7			
30	**54**	**12**	**12**	✓ 	**24** °Brix	
31	48	8	4	✓		
32	**56**	**8**	**10**			✓ 
33	52	1	3			
34	52	15	11			
35	52	8	6			
36	52	8	6			
37	52	8	6			
38	52	8	6			
39	50	4	4			

2.2.4 Statistical analysis

The experimental data were statistically analyzed using Minitab version 19 to evaluate the effects of hot water treatment temperature, immersion time, and their interaction on mango shelf life and quality. Analysis of variance (ANOVA) was performed to determine the significance of the model terms at $p < 0.05$. A second-order polynomial regression model was developed within the framework of Response Surface Methodology (RSM) to describe the relationship between the independent variables and response variables, including linear, quadratic, and interaction effects. Model adequacy was evaluated using R^2, adjusted R^2, predicted R^2, lack-of-fit test, and residual analysis. The desirability function was subsequently applied to determine the optimal hot water treatment conditions, with the objective of maximizing shelf life while maintaining acceptable mango quality.

3. Results and Discussion

3.1. Descriptive Results

The experimental results demonstrated that hot water treatment temperature and immersion time had significant effects on mango shelf life. The average shelf life ranged from approximately 7.52 to 16.80 days under different experimental conditions. An increasing trend in shelf life was observed when appropriate temperature and immersion time conditions were applied. However, excessive temperature or prolonged immersion time resulted in a decline in physical quality and the appearance of heat-related damage symptoms. Regarding fruit sweetness, the total soluble solids (TSS) values measured at the maximum acceptable storage period varied depending on the hot water treatment conditions, ranging from approximately 20 to 24°Brix. The results indicated that hot water treatment did not adversely affect mango sweetness, as the treated fruits-maintained sweetness levels within the acceptable export standard (>16°Brix). These findings suggest that properly controlled hot water treatment can effectively extend mango shelf life without negatively affecting the sensory quality and sweetness of the fruit. The present findings are consistent with the study of Darshan et al. (2024), who reported that hot water treatment had no significant effect on total soluble solids (TSS) or fruit sweetness, despite its effectiveness in reducing microbial contamination and extending self-life. Similarly, Azzam et al. (De La Cruz Padilla et al., 2025). demonstrated that hot water treatment under optimal temperature conditions could maintain acceptable sweetness levels throughout storage without causing deterioration in sensory quality.

3.2. ANOVA and Model Significance

The results obtained from Response Surface Methodology (RSM) analysis revealed that the second-order polynomial regression model was statistically significant ($p < 0.001$), with an F-value of 83.95, indicating that the model effectively described the relationship between hot water treatment temperature, immersion time, and mango shelf life (Table 1). The ANOVA results demonstrated that both linear factors, temperature ($p = 0.000$) and immersion time ($p = 0.000$), significantly affected mango shelf life. In addition, the interaction effect between temperature and immersion time (Temperature × Time) was also statistically significant ($p = 0.000$), indicating that the influence of temperature on shelf life depended on the immersion duration applied during the hot water treatment process. Regarding the quadratic effects, Time² showed a statistically significant effect ($p = 0.004$), whereas Temperature² exhibited a marginal significance level ($p = 0.052$), suggesting a potential curvature effect of temperature within the experimental region. Model adequacy evaluation showed a coefficient of determination (R^2) of 92.71%, an adjusted R^2 of 91.61%, and a predicted R^2 of 88.87%, indicating strong explanatory and predictive capability of the developed model. Furthermore, all Variance Inflation Factor (VIF) values were below 5, confirming the absence of multicollinearity among the independent variables.

Although the lack-of-fit test was statistically significant ($p = 0.000$), which may indicate that certain variability in the system was not fully captured by the model, the high R^2 and predicted R^2 values suggest that the model remained sufficiently reliable for process analysis and optimization. The statistical analysis results are illustrated in Figure 4.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.897773	92.71%	91.61%	88.87%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	338.325	67.665	83.95	0.000
Linear	2	312.351	156.175	193.77	0.000
Temperature	1	117.434	117.434	145.70	0.000
Time	1	189.060	189.060	234.57	0.000
Square	2	8.644	4.322	5.36	0.010
Temperature*Temperature	1	3.285	3.285	4.08	0.052
Time*Time	1	7.755	7.755	9.62	0.004
2-Way Interaction	1	15.015	15.015	18.63	0.000
Temperature*Time	1	15.015	15.015	18.63	0.000
Error	33	26.598	0.806		
Lack-of-Fit	3	25.265	8.422	189.48	0.000
Pure Error	30	1.333	0.044		
Total	38	364.923			

Figure 4. Model Summary and Analysis of Variance

3.3. Model Adequacy

The developed model exhibited an R^2 value of 92.71%, an adjusted R^2 of 91.61%, and a predicted R^2 of 88.87%, indicating a high capability of the model to explain and predict the experimental data. In addition, the difference between adjusted R^2 and predicted R^2 was less than 0.2, suggesting good agreement and stability of the model for response prediction. Although the lack-of-fit test was statistically significant ($p = 0.000 < 0.05$), indicating that certain variability within the experimental data was not completely explained by the model, the high R^2 and predicted R^2 values demonstrated that the model remained sufficiently reliable for process analysis and optimization purposes. Furthermore, residual analysis showed that the residuals were randomly distributed without any obvious pattern, confirming the validity of the statistical assumptions and supporting the reliability and adequacy of the developed model for this study.

3.4. Regression Model

The relationship between hot water treatment temperature, immersion time, and mango shelf life was described using a second-order polynomial regression model in uncoded units, as presented in the following equation:

$$\text{Shelf life (days)} = 163.5 - 6.02T - 6.49t + 0.0566T^2 + 0.02823t^2 + 0.1278Tt$$

where:

T = hot water treatment temperature (°C)

t = hot water immersion time (min)

The regression equation indicated that the linear terms of temperature and immersion time had negative coefficients, suggesting that excessive increases in these variables could adversely affect mango quality and shelf life. However, the quadratic and interaction terms showed positive coefficients, reflecting the existence of an optimum region within the experimental range where the hot water treatment conditions provided the most favorable response.

3.5. Effect of Variables

The analysis results demonstrated that hot water treatment temperature and immersion time significantly influenced mango shelf life. The average shelf life showed a continuous increasing trend with increasing temperature and immersion duration, as illustrated in Figure 5. The main effects plot revealed that increasing the treatment temperature from 48°C to approximately 54–56°C markedly enhanced mango shelf life. Similarly, increasing the immersion time from 1 min to approximately 12–15 min also contributed positively to shelf-life extension.

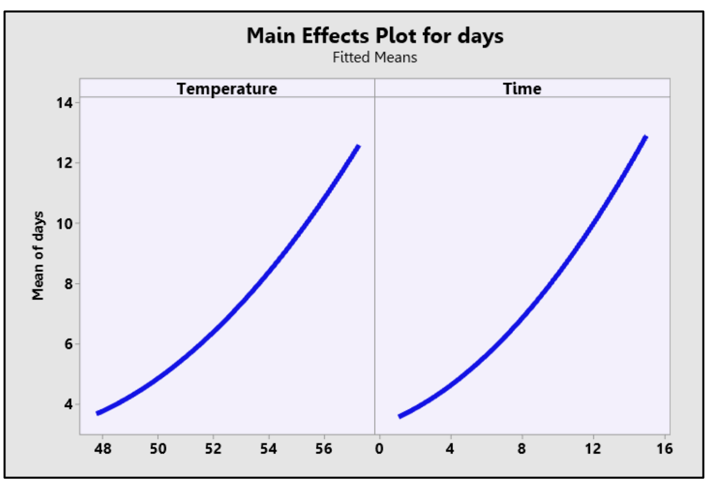


Figure 5. Main effects plots showing the influence of hot water treatment, temperature and immersion time on mango shelf life.

The interaction effect between hot water treatment temperature and immersion time was clearly illustrated by the interaction plot shown in Figure 6. The non-parallel pattern of the plotted lines indicated the presence of a significant interaction effect between temperature and immersion time. This observation was consistent with the ANOVA results, which demonstrated that the Temperature × Time interaction term was statistically significant (p < 0.001). These findings suggest that the effect of temperature on mango shelf life was strongly dependent on the immersion duration applied during the hot water treatment process.

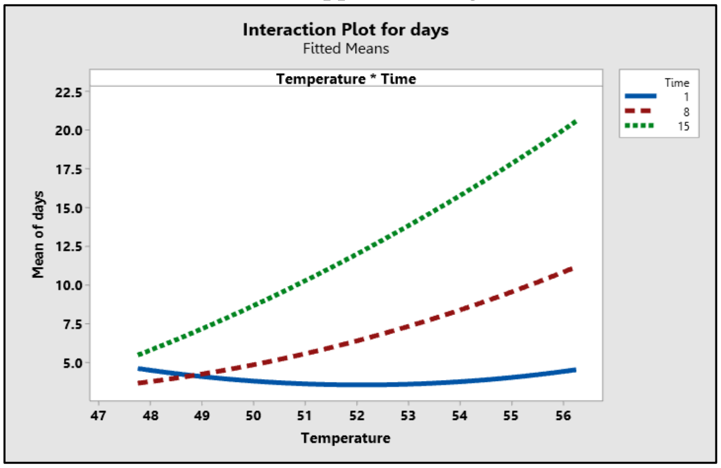


Figure 6. Interaction plot showing the combined effects of hot water treatment temperature and immersion time on mango shelf life.

3.6. Contour Plot and Surface Plot

The contour plot presented in Figure 7 illustrates the combined effects of hot water treatment temperature and immersion time on mango shelf life. The gradual change in color regions within the contour plot indicated an increasing trend in shelf life as both temperature and immersion time increased simultaneously. In addition, the curved contour lines reflected the presence of an interaction effect between the two variables, which was consistent with the ANOVA results showing that the Temperature × Time interaction term was statistically significant (p < 0.001).

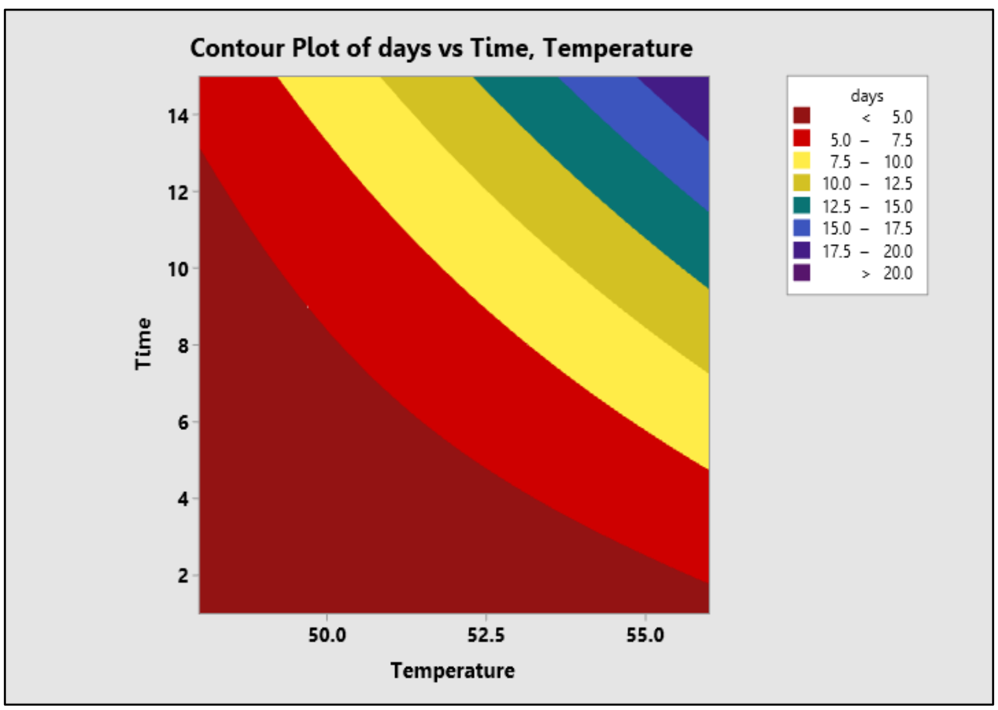


Figure 7. Contour plot of the effects of temperature and immersion time on mango shelf life.

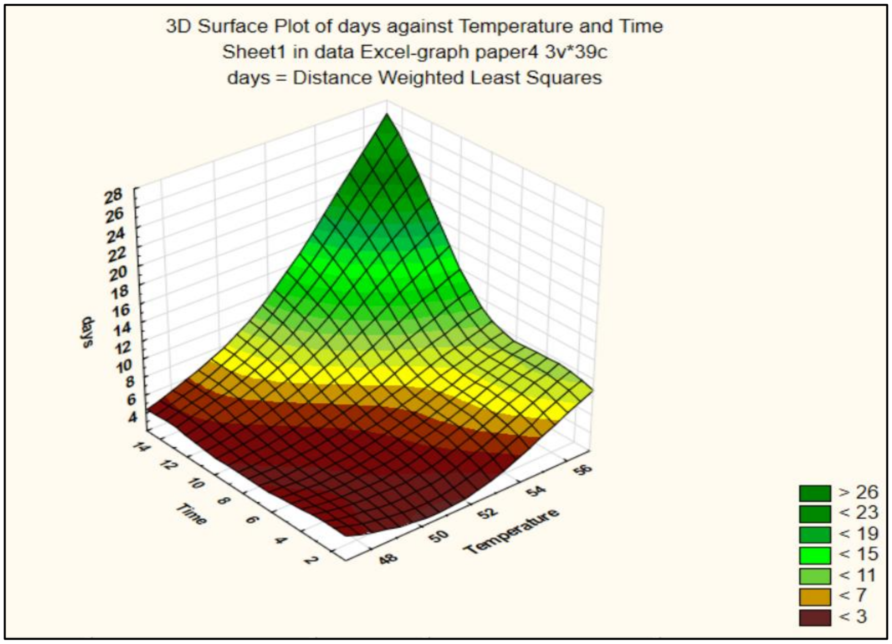


Figure 8. Response surface plot of temperature and immersion time effects on mango shelf life**.**

Figure 8 illustrates the response surface plot, demonstrating that the region associated with the maximum mango shelf life was observed at hot water treatment temperatures of approximately 54–56°C combined with immersion times of approximately 12–15 min. This region can therefore be considered the optimum region for the hot water treatment process. However, when physical quality attributes of the mango fruits were simultaneously considered, excessively high temperatures combined with prolonged immersion durations were found to potentially induce tissue damage and heat-related injury. Therefore, the selection of optimal processing conditions should balance both shelf-life extension and the maintenance of acceptable fruit quality. These findings are consistent with the study of Inyang et al., (2023)., who reported that hot water treatment effectively reduced postharvest deterioration and extended mango shelf life, provided that treatment temperature and immersion duration were carefully controlled to avoid heat-induced damage to fruit tissues.

3.7. Optimal Condition

The optimization analysis revealed that the optimal processing conditions were within a hot water treatment temperature range of approximately 54.09–56.00 °C and an immersion time range of approximately 12.04–15.00 min, resulting in a predicted mango shelf life of approximately 12.92–20.04 days, as illustrated in Figure 9.

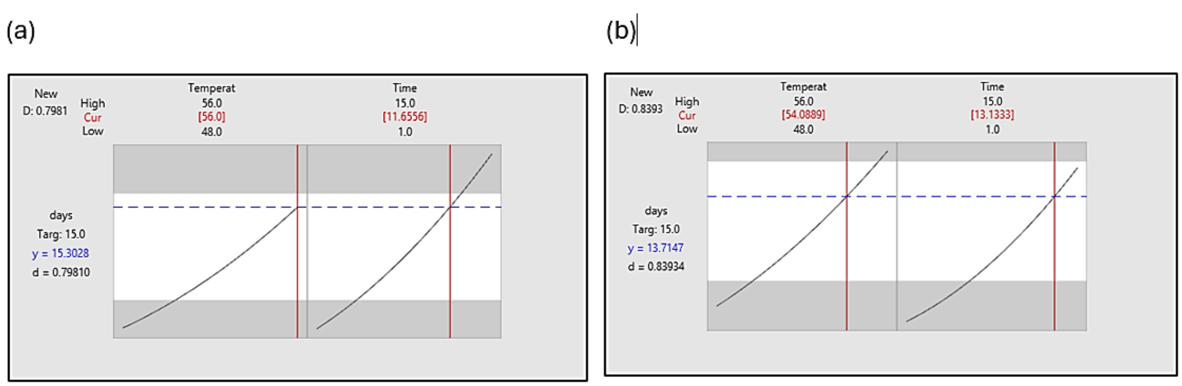


Figure 9. Response optimizer plots based on desirability function analysis showing (a) the maximum predicted shelf-life condition and (b) the optimal practical condition for hot water treatment of mangoes

The optimization result shown in Figure 9(a) provided the maximum predicted shelf life of approximately 20.04 days under treatment conditions of 56°C for 15.00 min, with a desirability value of 0.000. However, when the physical quality of mango fruits was simultaneously considered, these conditions tended to increase the risk of heat-induced tissue damage. In contrast, Figure 9(b) demonstrated a more balanced optimal condition at approximately 54.36°C for 12.04 min, yielding a predicted shelf life of approximately 12.92 days with a higher desirability value of 0.741. This result indicates greater practical suitability for the process by providing a better balance between shelf-life extension and maintenance of acceptable mango fruit quality.

Therefore, the treatment condition of approximately 54 °C with an immersion time of 12 min was selected as the most appropriate condition for the hot water treatment process in this study.

3.8. Comparison with Previous Studies

The findings of this study are consistent with previous reports indicating that hot water treatment can effectively reduce postharvest decay, delay ripening processes, and extend mango shelf life (Inyang et al., 2023; Islam et al., 2024). Heat treatment plays an important role in suppressing postharvest microbial growth and slowing biochemical activities associated with fruit deterioration. The present results also agree with recent studies reporting that thermal treatment can activate defense mechanisms in mango fruit, enhance antioxidant enzyme activities, and reduce the severity of postharvest diseases (Abdel-Sattar et al., 2024). Similarly, Yahaya et al. (2024). reported that heat application during postharvest handling reduced physiological disorders and helped maintain mango quality during storage.

However, most previous studies primarily focused on evaluating the effects of temperature or immersion time independently or were conducted under laboratory-scale conditions. In contrast, the present study applied Response Surface Methodology (RSM) to investigate the interaction effects between temperature and immersion time under an actual semi-industrial postharvest production system, allowing more precise determination of optimal processing conditions. The interaction plot, contour plot, and response surface plot clearly demonstrated that increasing treatment temperature must be accompanied by appropriate control of immersion duration. Although higher temperatures improved shelf-life extension, excessive exposure time increased the risk of heat injury and deterioration of physical fruit quality, an aspect that has been only limitedly addressed in previous studies. Therefore, the present study not only confirms the effectiveness of hot water treatment in extending mango shelf life, but also highlights the importance of multivariable analysis for determining optimal processing conditions applicable to real postharvest production systems and commercial export operations.

3.9. Mechanism Explanation

The experimental results may be explained by the effect of heat treatment in suppressing physiological processes associated with fruit ripening and deterioration, as well as reducing the growth of postharvest microorganisms. Heat treatment can also stimulate the natural defense mechanisms of fruit tissues and enhance the activity of antioxidant-related enzymes, including peroxidase (POD), polyphenol oxidase (PPO), and phenylalanine ammonia lyase (PAL), which play important roles in reducing oxidative damage and delaying postharvest disease development (Ampa et al., 2025; Aghdam et al., 2023). In addition, hot water treatment contributes to maintaining cell membrane integrity, reducing lipid peroxidation, and alleviating chilling injury and other physiological disorders associated with postharvest storage (Aghdam et al., 2023; Yahaya et al., 2024). However, excessive temperature or prolonged immersion duration may induce heat injury, resulting in tissue damage, internal disorders, and deterioration of fruit quality (Khanal et al., 2024).

The observed effects may also be associated with structural and physiological changes occurring on the mango peel surface during hot water treatment. Exposure to appropriate temperature and immersion conditions may cause expansion of the fruit surface tissues, thereby improving the removal efficiency of microorganisms and pathogens attached to the peel surface and effectively reducing postharvest fungal contamination (Islam et al., 2024; Schirra et al., 2000). Furthermore, heat treatment can inhibit the activity of fungal pathogens responsible for major postharvest diseases in mangoes, including anthracnose and stem-end rot, which are among the most critical problems affecting export-quality mangoes (Abdel-Sattar et al., 2024). Moreover, hot water treatment is considered a consumer-safe postharvest technology because it is a physical treatment method that does not leave chemical residues on fruit surfaces and has been widely accepted in the export fruit industry (Usall et al., 2016). Several studies have reported that properly controlled heat treatment does not adversely affect food safety or the nutritional quality of fruit, while also serving as an effective alternative for reducing dependence on chemical fungicides in postharvest management systems (Wang et al., 2024).

3.10. Research Contribution

This study contributes both academically and practically to postharvest mango technology by demonstrating the potential application of Response Surface Methodology (RSM) for analyzing and optimizing hot water treatment temperature and immersion time under an actual semi-industrial production system. A key strength of this research lies in the investigation of the interaction effect between temperature and immersion time, enabling more accurate determination of optimal processing conditions for extending shelf life while maintaining mango quality. This approach differs from most previous studies, which primarily focused on evaluating individual factors under laboratory-scale conditions. In addition, the study demonstrates that hot water treatment can serve as a consumer-safe and environmentally friendly postharvest technology. The proposed treatment conditions can be effectively applied in commercial mango export operations to reduce postharvest losses and improve product quality. In industrial production systems, accurate prediction of mango shelf life according to transportation duration is critically important for export logistics management. Based on the contour plot and response prediction analysis presented in Figure 10, hot water treatment temperature and immersion time were found to strongly influence storage performance and production efficiency. The results demonstrated that adjusting temperature and immersion time within the optimal range could regulate mango shelf life from approximately 7 to 15 days, corresponding to the requirements of destination markets with different transportation durations.

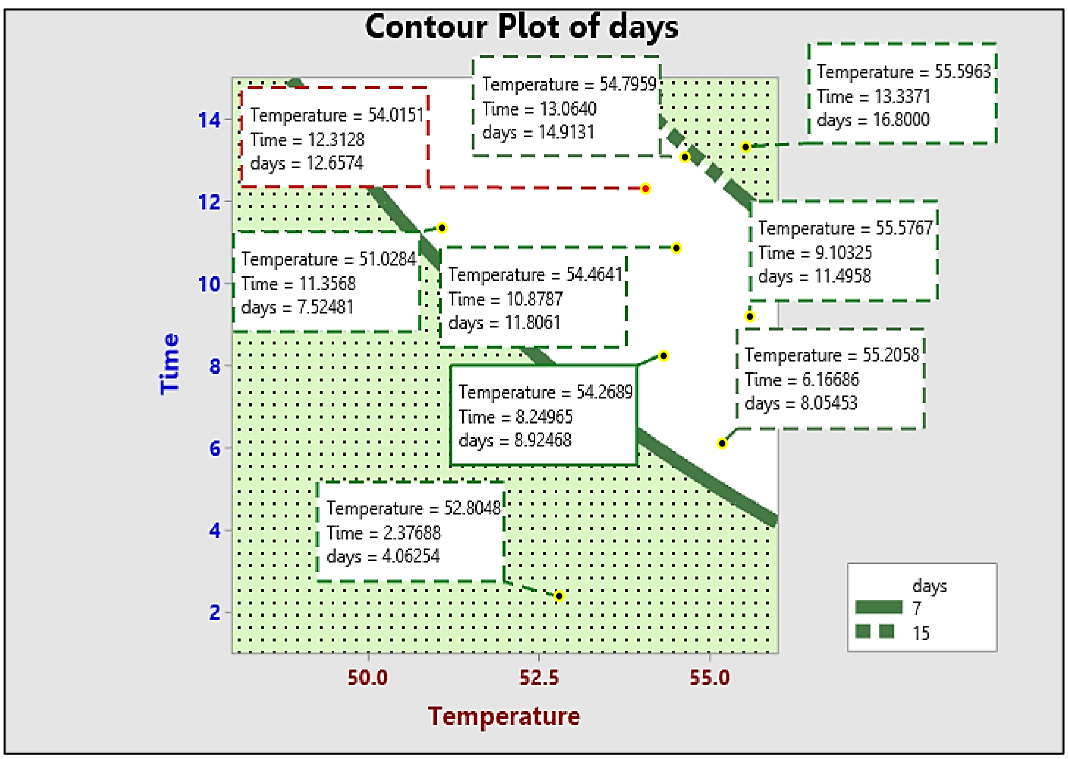


Figure 10. Prediction plot of mango shelf life in relation to transportation duration for export logistics management.

Based on the results presented in Figure 10, the application of a hot water treatment temperature of approximately 51.03°C with an immersion time of 11.36 min resulted in a predicted shelf life of approximately 7.52 days, which may be suitable for short-distance transportation or domestic distribution systems. Increasing the treatment conditions to approximately 54.80°C and 13.06 min extended the predicted shelf life to approximately 14.91 days, while further increasing the conditions to approximately 55.60°C and 13.34 min provided a maximum predicted shelf life of approximately 16.80 days. Such conditions may therefore be more appropriate for long-distance transportation and export markets requiring extended shipping durations.

The region highlighted by the red dashed line indicated that treatment conditions of approximately 54.02°C with an immersion time of 12.31 min resulted in a predicted mango shelf life of approximately 12.66 days. This prediction showed good agreement with the experimental observations recorded in Table 1, demonstrating the strong predictive capability and reliability of the developed model in accurately estimating the response behavior of the postharvest treatment process.

These findings indicate that hot water treatment conditions in postharvest production systems do not necessarily need to be standardized for all destination markets. Instead, processing conditions can be strategically designed according to transportation duration and supply chain requirements, which represents an important concept in modern industrial postharvest quality management (Abdel-Sattar et al., 2024; Pawde et al., 2025).

Recent studies have further reported that the integration of predictive techniques and optimized postharvest process design tailored to logistics routes can significantly reduce transportation losses, improve supply chain efficiency, and enhance the economic value of exported fruit products. (Usall et al., 2016; Taiti et al., 2025). Therefore, this study demonstrates strong potential for practical application in designing postharvest mango production processes that can be tailored to actual transportation conditions for both domestic distribution and commercial export operations.

4. Conclusions

This study successfully determined the optimal hot water treatment conditions for postharvest mango (*Mangifera indica* L.) production by applying Response Surface Methodology (RSM) under an actual semi-industrial production system. The developed second-order polynomial model effectively described and predicted the effects of treatment temperature and immersion time on mango shelf life and quality. The model exhibited high predictive capability, with R^2, adjusted R^2, and predicted R^2 values of 92.71%, 91.61%, and 88.87%, respectively, indicating strong reliability and accuracy of the developed model.

The major findings of this study can be summarized as follows:

1. Hot water treatment temperature and immersion time significantly affected mango shelf life and fruit quality ($p < 0.05$). The optimal treatment condition was identified at approximately 54.02°C for 12.31 min, which extended mango shelf life to approximately 12.66 days while maintaining acceptable physical fruit quality.
2. Increasing treatment temperature and immersion duration contributed to reducing fruit deterioration and delaying postharvest decay. However, excessive temperature or prolonged immersion time increased the risk of heat injury and adversely affected the physical quality of mango fruits.
3. Appropriate control of hot water treatment conditions successfully extended shelf life without adversely affecting fruit sweetness, while maintaining total soluble solids (TSS) within the acceptable export-quality standard.
4. A key contribution of this research lies in the application of RSM to evaluate the interaction effects between treatment temperature and immersion time under a semi-industrial postharvest production system. This approach enabled more accurate determination of optimal processing conditions with direct applicability to industrial-scale operations.
5. The contour plot and response prediction analyses demonstrated that hot water treatment conditions could be used not only for process optimization but also for predicting and designing shelf-life conditions according to transportation duration and destination market requirements. The developed model showed the potential to regulate mango shelf life in accordance with logistics systems and transportation distances for both domestic distribution and long-distance export markets, thereby reducing postharvest losses, improving supply chain efficiency, and increasing the economic value of export mangoes (Pawde et al., 2025; Taiti et al., 2025).
6. Furthermore, hot water treatment represents a consumer-safe and environmentally friendly postharvest technology that can reduce dependence on chemical fungicides and support sustainable mango export production systems in the future (Abdel-Sattar et al., 2024; Taiti et al., 2025).

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