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Optimization of Hot- and Cold-Water Treatment Parameters in a Postharvest Production Line for Shelf-Life Extension of Nam Dok Mai Si-Tong Mangoes for Export Using Response Surface Methodology (RSM)

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

[1]Department of Engineering and Technology Management, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand,

Corresponding author's email: 649041810031@mail.rmutk.ac.th

[2]Department of Industrial Engineering,

Faculty of Engineering, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand, Email: Wichan.c@mail.rmutk.ac.th

[3]Department of Industrial Engineering,

Faculty of Engineering, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand, Email: Parinya.sr@mail.rmutk.ac.th

Abstract

This study aimed to identify the optimal production line conditions for extending the shelf life of *Nam Dok Mai Si-Tong* mangoes intended for export markets that do not require steam treatment. The research uniquely integrates Design of Engineering Experiments (DOE) and Response Surface Methodology (RSM) within a semi-automatic, continuous postharvest production system, reflecting real-world industrial constraints. Mangoes harvested within 24 hours from GAP-certified orchards and at a maturity level of 80–85% were subjected to controlled hot-water and cold-water dipping treatments. The experimental factors consisted of hot water dipping at 54 °C and cold-water dipping at 25 °C, each varied for 1, 4, 8, 12 and 15 minutes. Statistical analysis revealed that both dipping durations significantly affected mango shelf life at a 0.05 significance level. Longer hot water dipping times combined with shorter cold-water dipping times were found to be most effective in extending storage life. The optimal conditions identified were hot-water dipping at 54 °C for 15 minutes followed by cold-water dipping at 25 °C for 1 minute, enabling processed mangoes to be stored at ambient temperature for 14–20 days without spoilage. This research demonstrates a practical, time-efficient optimization strategy suitable for mass production lines, balancing quality preservation with operational efficiency. The findings offer direct applicability to the mango export industry, allowing process adjustments based on transportation distance, thereby reducing postharvest losses, lowering production costs, and enhancing product value.

Key words: Optimization of Hot- and Cold-Water Treatment; Postharvest Production Line Nam Dok Mai Si –Tong mangoes; Shelf-Life Extension; Exports; RSM

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1. Introduction

Fruit and vegetable production is a business that grows alongside technological advances, continually evolving in response to consumer demand [1,2]. The industry's ability to sell produce globally generates substantial income for many countries [3]. Thailand, the world's third-largest mango producer after India and China [4], is renowned for its Nam Dok Mai Si- Tong mangoes, a highly popular variety in both domestic and foreign markets due to its unique taste [5].

However, mango exports face challenges, including substandard raw material quality, short shelf life, and high air freight costs [6]. Damage occurs at various stages: harvest (23.75%), transportation (31.05%), and post-harvest (20.0%), with anthracnose disease being the primary cause due to its impact on preservation [7]. This disease significantly threatens mangoes, which typically have a pre-spoilage age of only seven days [8]. In addition to physical damage, strict fruit sanitation regulations in foreign markets hinder exports [9].

To address these issues, extending shelf life through optimal production conditions is crucial for reducing transportation costs, increasing competitiveness, and boosting export revenue [10]. This study employs engineering experimental design (DOE) and Response Surface Methodology (RSM) to determine optimal conditions for maximizing mango shelf life and market share [11].

2. Materials and Methods

2.1 Materials

The machinery used in the production line for processing mangoes to meet export standards for countries that do not require steam treatment was studied, developed, and improved by the researchers from the conventional farmer-based processing method into a semi-automatic production system [12]. This production process is located at the Ban Tha-Thong Mango Community Enterprise, Doem Bang Nang Buat District, Suphan Buri Province, Thailand. The facility is a large-scale industrial mango processing enterprise that focuses on the production of fresh mangoes for export markets. The production line operates continuously through 7 sequential processing stages, consisting of: 1) mango size sorting, 2) cleaning, 3) hot-water dipping, 4) cold-water dipping, 5) air blowing and water drainage, 6) packaging, and 7) storage of the processed mangoes in temperature-controlled rooms. The detailed configuration of the production process is illustrated in Figure 1.

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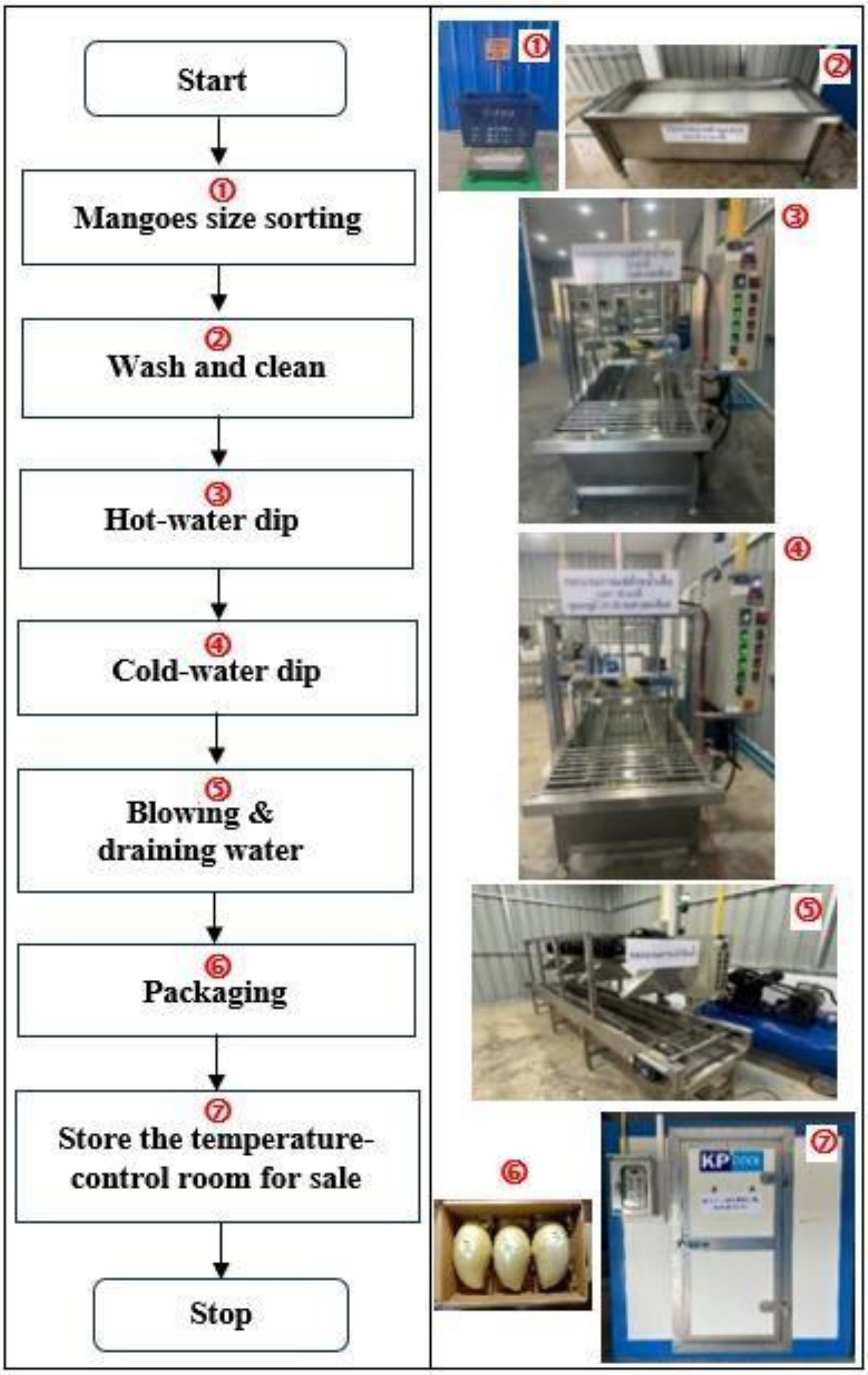

Figure 1. Mango production process for export.

2.2 Method

To identify the key factors in the production line that influence the delay of mango spoilage during processing, a fishbone diagram was used to analyze the causes of the problem as shown in Figure 2.

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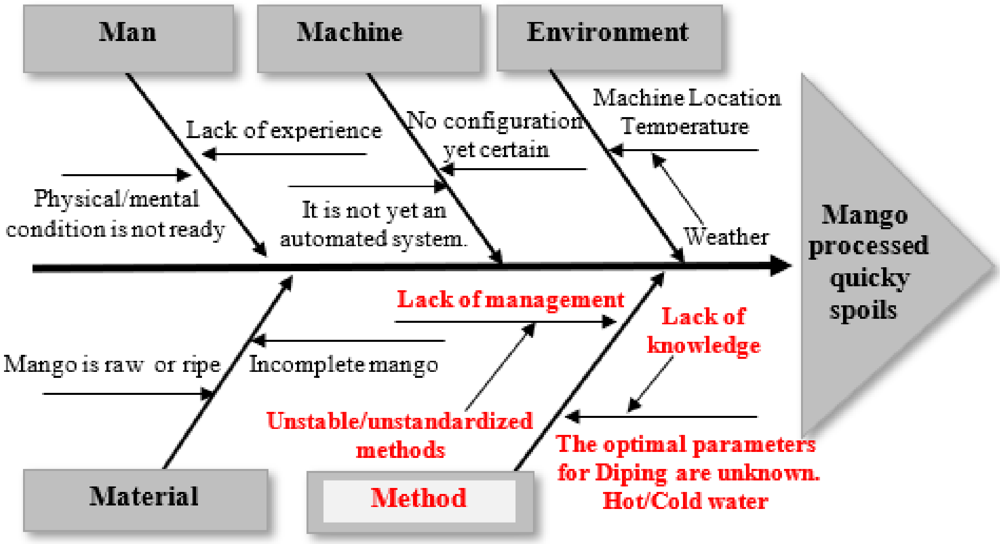

Figure 2. Cause and effect diagram of the cause and effect of the problem in the line Production work that affects the spoilage of mangoes.

From Figure 2. Based on the analysis of the problem's causes, it was determined that numerous factors can contribute to mango spoilage during processing. However, the majority of these issues are related to the production process itself as it is a continuous operation.

Especially the outstanding hot-water and cold-water production line. Numerous studies have demonstrated that hot-water treatment is a globally recognized and highly effective method as it poses no harm to consumer health. Consequently, research has been conducted to optimize the factors involved in treating mangoes with hot water at varying temperatures and durations for different mango species, as investigated by Ndlela S. et al. [13].

In this research, the researcher focused on studying the water temperature and dipping time in the production line. Given that previous research in tropical and cold Regions has explored hot-water temperatures similar to 54 °C, including 46.1,47, 50, 51, 53 and 55 °C, depending on the mango species [14 - 24], the researchers selected 54 °C for this study. This choice was influenced by the results of prior research, suggesting an inverse relationship between water temperature and dipping time. Higher temperatures require shorter dipping times, while lower temperatures necessitate longer durations. Given the large-scale mango production in this research and the aim of reducing production time while achieving optimal results, 54 °C was deemed the ideal temperature within the studied range.

Regarding the cold-water dipping stage, the water temperature must be sufficient to cool all mangoes to a uniform level. Previous research by Apiradee Muangdet [14] indicated that the cooling process can impact the skin and texture of Nom Dok Mai Si-thong mangoes, potentially leading to chilling injury and a decrease in fruit quality compared to mangoes cooled at 25 °C. Therefore, the researchers maintained the cold-water dip temperature at 25 °C. For the time variables in the production line's hot-water and cold-water dipping, related research studies [15 - 26] established a range of 1 to 15 minutes.

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The researchers conducted their study at 1, 3, 5, 10, 12 and 14 minutes, with additional undocumented time intervals of 2, 4, 6, 7, 8, 9, 11, 13 and 15 minutes. To determine the optimal time factors, a pre-test was conducted at 1, 8, and 15 minutes. Based on these results, the researchers selected 1, 4, 8, 12, and 15 minutes as the time factors for the experiment, as shown in Table 1.

Table 1. Factors and levels of factors used to design the experiment.

Factor	Levels of factors (time : minute)				
Hot-water dip time (temperature of 54 °C)	1	4	8	12	15
Cold-water dip time (temperature of 25 °C)	1	4	8	12	15

Conducting experiments with design techniques and Response Surface Methodology (RSM) to identify the optimal conditions in the production line for extending mango shelf life. Using Minitab V.19 for experimental design, we controlled replication schedule with three replication and control the experiment by blocking, for other factors that might have influenced the study's response by implementing a totaling 39 trials. that shows the sequence of the production line as follows:

Production Stage 1: Mangoes were sorted by weight into grades A, B, and C. Only grade A mangoes were selected for further processing.

Production Stage 2: Mangoes were washed, cleaned, and sorted based on their softness and maturity. Only mangoes with 80-85% maturity were chosen for the experiment.

Production Stage 3: A solution containing prochloraz (10 CC per 20 liters of water) was prepared to eliminate fungal diseases. The water temperature was set to 54 °C and mangoes were dipped in the hot-water solution for the specified experimental duration.

Production Stage 4: The water temperature was set to 25 °C for cold-water dipping. This step was crucial for controlling the mango skin's condition after hot-water dipping and ensuring its integrity.

Production Stage 5: Mangoes were inflated and drained to remove excess moisture from the skin. This process was essential for ensuring even drying of all mangoes.

Production Stage 6: Mangoes were divided into two groups: B1 and B2. Group B1 mangoes were packaged and stored at room temperature for observation, while group B2 mangoes were packaged and prepared for distribution.

Production Stage 7: For mangoes in group B2, which were intended for distribution or export, they were stored in a temperature-controlled room. The shelf-life extension and preservation of mangoes were evaluated through sensory and physical properties. Daily observations were recorded to monitor changes in skin appearance, black spots, anthracnose, and overall fruit quality. The experiment concluded when all mangoes in a group had deteriorated. The recorded data was then analyzed using statistical methods. This experimental plan was carried out within a single production cycle as illustrated in Figure 3.

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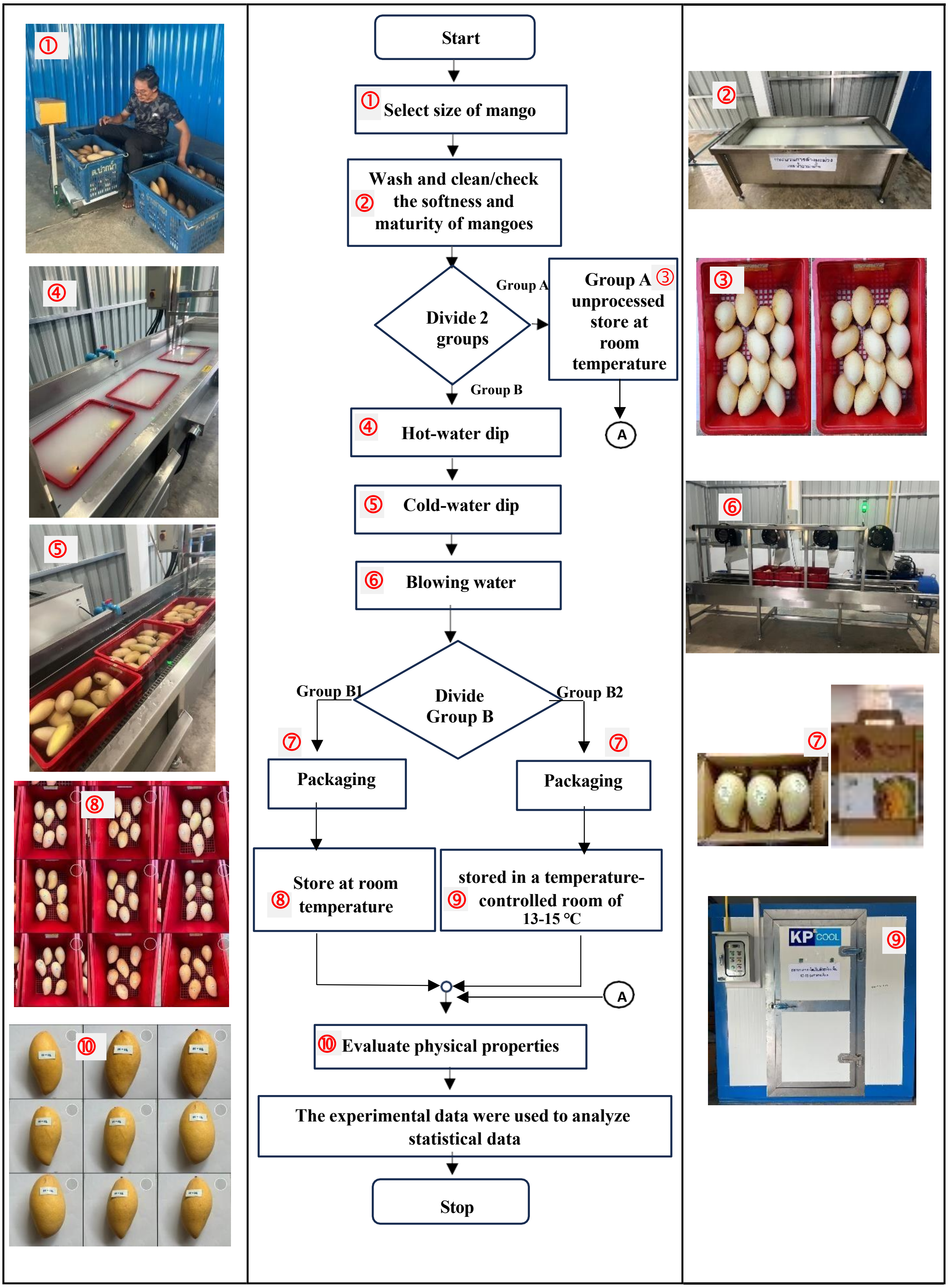

Figure 3. Experimental plan per 1 production of cycle.

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3. Results and Discussion

3.1 Data Collection

Data was collected by observing changes in the physical characteristics of each batch of mangoes according to the experimental plan. Group A mangoes, which were not processed and stored at room temperature, exhibited skin colour changes and hyperpigmentation from anthracnose within four days. In contrast, group B1 mangoes, which were processed and stored at room temperature, maintained their condition for 14 days, with consistent skin colour and texture, as depicted in Figure 4 and Table 2 summarizes the recorded data. However, Group B2 mangoes, stored in a temperature-controlled room, could last for more than 30 days.

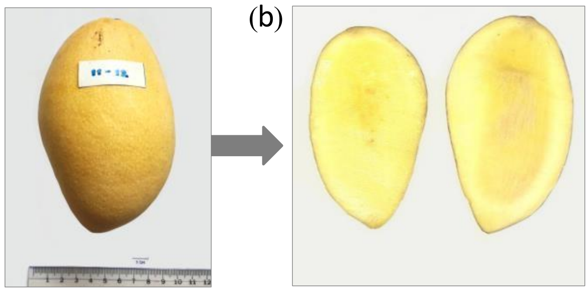

Figure 4. External appearance and internal quality of processed mangoes after 14 days of storage at room temperature: (a) intact peel and uniform shape; (b) longitudinal sections showing normal flesh colour without internal defects (≥80% quality retention).

Table 2. Record of mangoes retention data from the production line (Group B1)

Set	HWT	CWT	Day																					Expired
	(min)	(min)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Date
1	4	4	100	100	100	100	100	80	60	60	60	20	20	0										6
2	12	4	100	100	100	100	100	100	100	100	100	80	60	20	0									10
3	4	12	100	100	100	80	60	40	40	0														4
4	12	12	100	100	100	100	100	80	40	20	0													6
5	8	8	100	100	100	100	100	80	60	60	0													6
6	8	8	100	100	100	80	80	60	60	60	60	0												5
7	8	8	100	100	100	100	80	60	60	60	40	40	20	20	20	0								5
8	1	8	100	100	100	100	80	40	20	20	0													5
9	15	1	100	100	100	100	100	100	100	100	100	100	100	100	100	80	40	40	40	40	20	20	0	14
10	8	1	100	100	100	100	100	100	100	100	80	80	80	80	60	40	0							12
11	8	15	100	100	100	80	40	40	20	20	0													4
12	8	8	100	100	100	100	80	60	60	60	40	40	0											5
13	8	8	100	100	100	80	60	40	20	0														4
14	8	8	100	100	100	100	80	40	40	40	0													5
15	4	4	100	100	100	100	80	60	40	20	0													5
16	12	4	100	100	100	100	100	100	100	80	80	60	40	20	20	0								9
17	4	12	100	100	100	80	40	20	20	0														4
18	12	12	100	100	100	100	80	60	60	40	20	0												5
19	8	8	100	100	100	100	80	60	20	20	0													5
20	8	8	100	100	100	100	100	80	20	20	0													6
21	8	8	100	100	100	100	80	60	40	0														5
22	1	8	100	100	100	80	60	0																4
23	15	1	100	100	100	100	100	100	100	100	100	100	100	80	60	60	40	20	20	20	0			12
24	8	1	100	100	100	100	100	100	100	100	100	100	80	60	60	40	20	0						11
25	8	15	100	100	100	100	80	40	0															5
26	8	8	100	100	100	100	80	60	20	0														5
27	8	8	100	100	100	100	80	40	20	0														5
28	8	8	100	100	100	80	40	20	20	0														4
29	4	4	100	100	100	100	80	20	0															5
30	12	4	100	100	100	100	100	100	100	100	100	100	80	60	60	40	0							11
31	4	12	100	100	100	80	40	0																4
32	12	12	100	100	100	100	100	80	60	40	40	20	0											6
33	8	8	100	100	100	80	40	40	40	0														4
34	8	8	100	100	80	60	60	40	20	20	20	0												3
35	8	8	100	100	100	100	80	40	20	20	0													5
36	1	8	100	100	100	100	80	40	0															5
37	15	1	100	100	100	100	100	100	100	100	100	100	100	100	100	80	60	60	40	40	20	0	0	14
38	8	1	100	100	100	100	100	100	100	100	80	60	60	40	40	20	20	20	0					9
39	8	15	100	100	100	80																		4

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3.2 Data Analysis

The experimental data was analyzed using Minitab V.19 to assess the accuracy of the experimental model as shown in Figure 5.

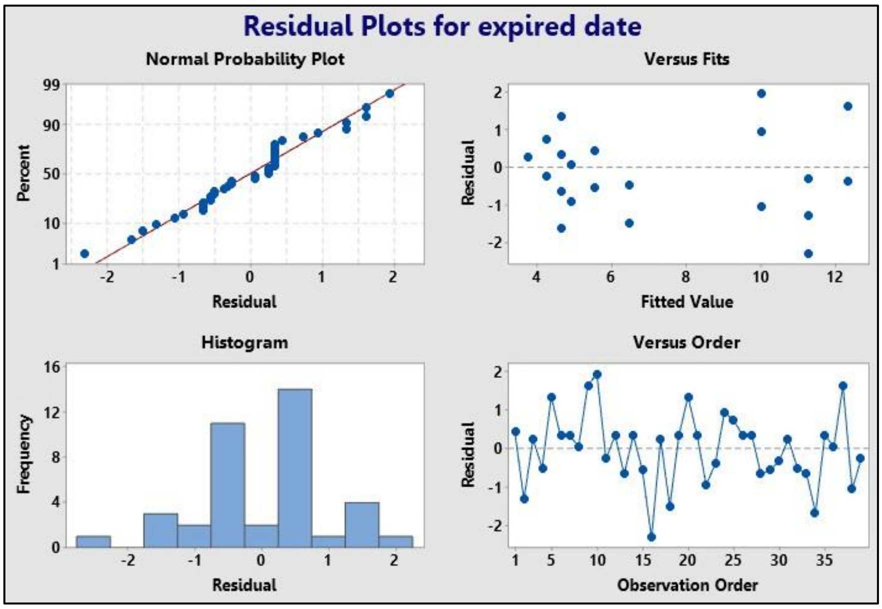

Figure 5. Show the analysis of the data.

From Figure 5, the residual values exhibited a normal distribution pattern, and the points on the residual plot demonstrated a linear and independent relationship, indicating that the distribution was independent and not dependent on the end of the experiment. Therefore, it can be concluded that the experiment was accurate and reliable, aligning with the data analysis results. Both factors, hot-water dipping time and cold-water dipping time, were found to significantly influence the response variable at a significance level of 0.05 when considered in combination. Furthermore, these factors were also shown to have significance impact on the response variable individually as presented in Table 3.

Table 3 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	307.918	61.584	62.74	< 0.001*
Linear	2	220.093	110.046	112.12	< 0.001*
HWT	1	136.963	136.963	139.54	< 0.001*
CWT	1	83.130	83.130	84.70	< 0.001*
Square	2	81.076	40.538	41.30	< 0.001*
HWT*HWT	1	70.987	70.987	72.32	< 0.001*
CWT*CWT	1	27.746	27.746	28.27	< 0.001*
2-Way Interaction	1	6.750	6.750	6.88	0.013
HWT*CWT	1	6.750	6.750	6.88	0.013
Error	33	32.389	0.981		
Lack-of-Fit	3	11.989	3.996	5.88	0.003
Pure Error	30	20.400	0.680		
Total	38	340.308			

Based on the analysis of factors influencing the delay of mango spoilage after processing, the optimal combination of hot water dipping time (15 minutes) and cold-water dipping time (1 minute) was identified. The comparative graph is illustrated in Figure 6.

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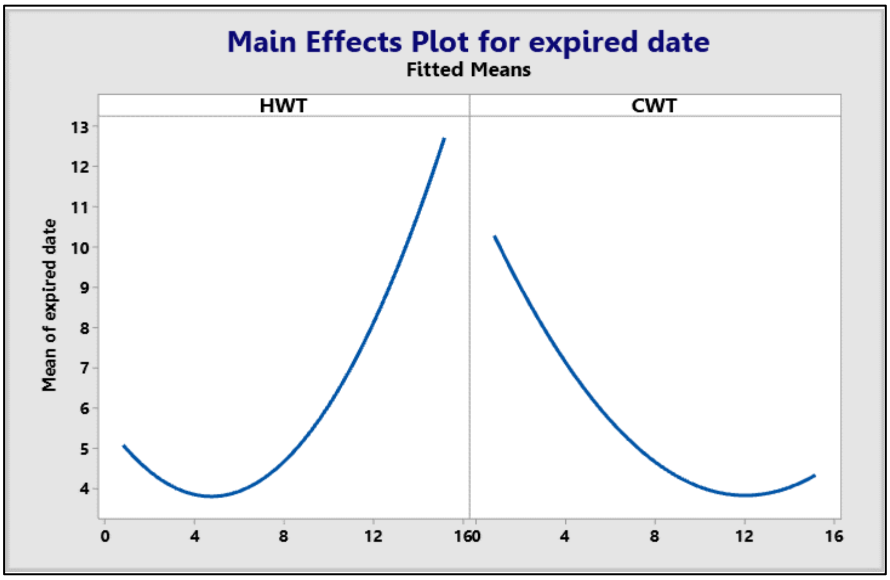

Figure 6. Show the analysis of the optimal.

When considering the mutual influence of these two factors on the production line, it was found that both hot water dipping time and cold-water dipping time significantly impact the long-term storage of mangoes as evidenced by the intersection of the graph lines in Figure 7.

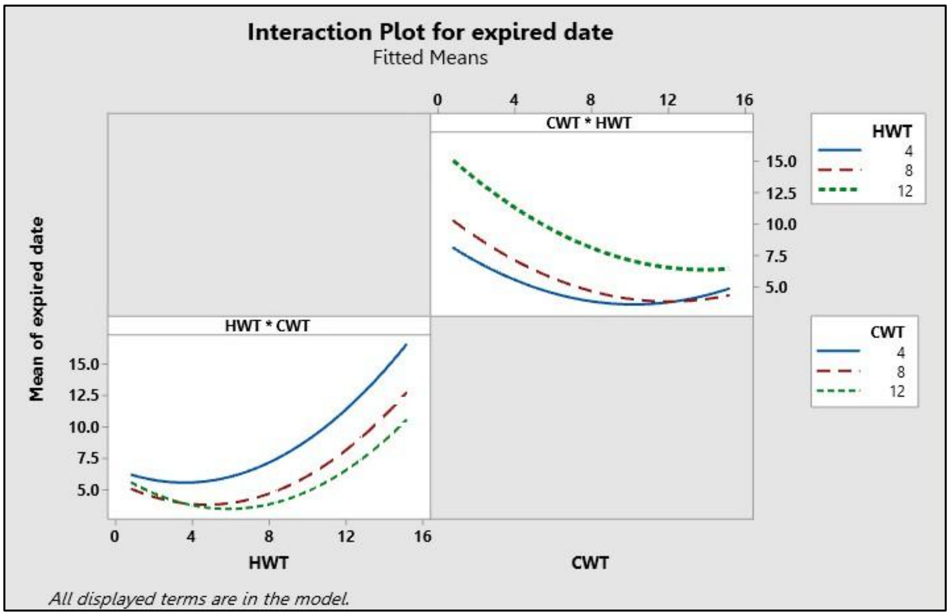

Figure 7. Show the co-influence between factors.

To determine the optimal factor settings for maximizing mango shelf life while maintaining acceptable physical characteristics, the researcher focused on ensuring that the mangoes did not exhibit withering, skin discoloration, or black spots caused by anthracnose, as reported by Barman, K., and R. Asrey [27]. The experimental results and subsequent data analysis confirmed the effectiveness of the identified factors in preserving mango quality and extending shelf life. Through response optimization, it was determined that the physical characteristics of mangoes could be maintained with a confidence level and probability of 95% for a shelf life of 14-20 days at a significance level of 0.05. The optimal factor values for the production line were found to be hot water dipping at 54 °C for 15 minutes and cold-water dipping at 25 °C for 1 minute. The comparative trend of these values was shown in Figure 8.

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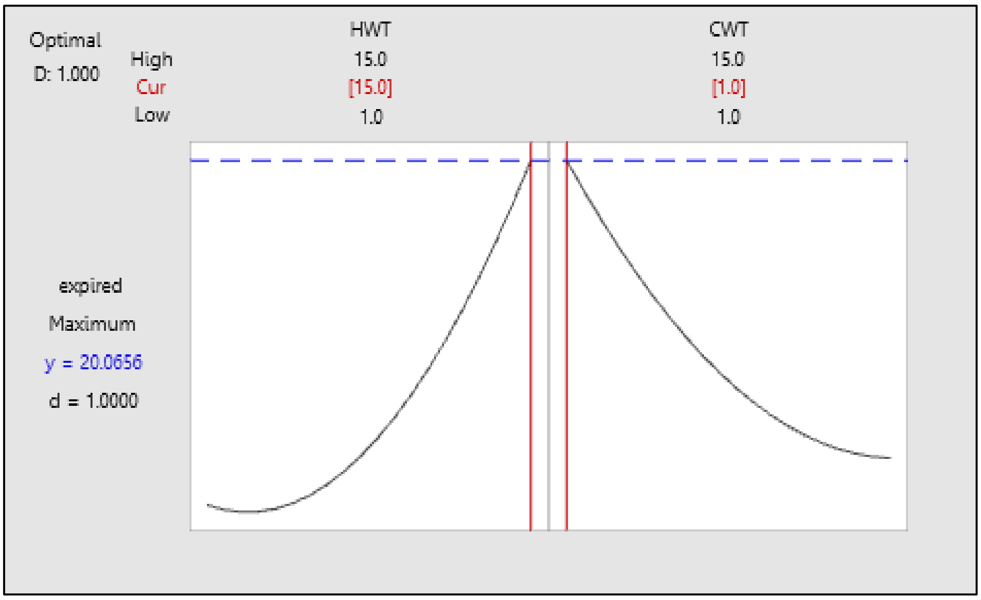

Figure 8. Shows the level of the best factor.

When analyzing the data using Response Surface Methodology (RSM), it became evident that the shelf life of processed mangoes is inversely related to the time spent in the Figure 9. Surfaces the relationship between each pair of factors of conditions suitable for the expiration date of mangoes. production line for both hot water dipping and cold-water dipping. Figure 9 illustrates this relationship, with the green area representing the optimal combination of dipping times for achieving maximum shelf life from 14 to 20 days.

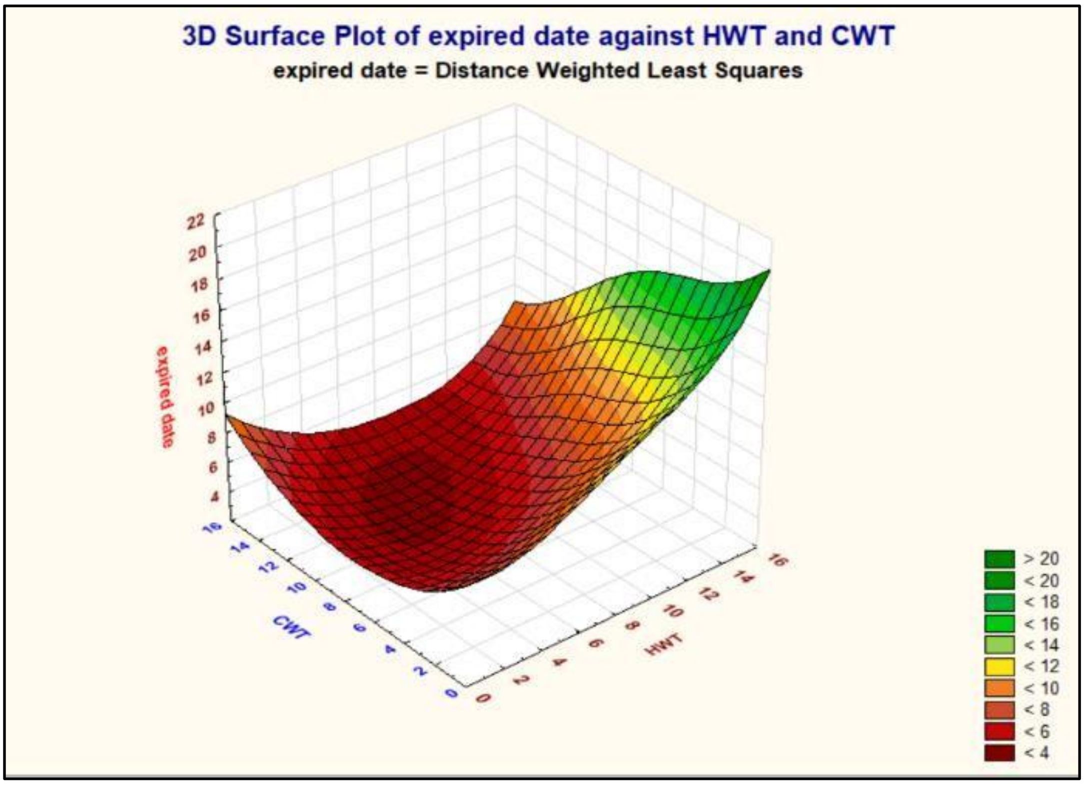

Figure 9. Surfaces the relationship between each pair of factors of conditions suitable for the expiration date of mangoes.

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When analyzing and predicting the factors of each pair, it is evident that the relationship between these factors can be used to determine the optimal time settings in the production line to control mango storage quality and select the most suitable transportation method for cost- effective production. Illustrated in Figure 10, based on the data in Table 4.

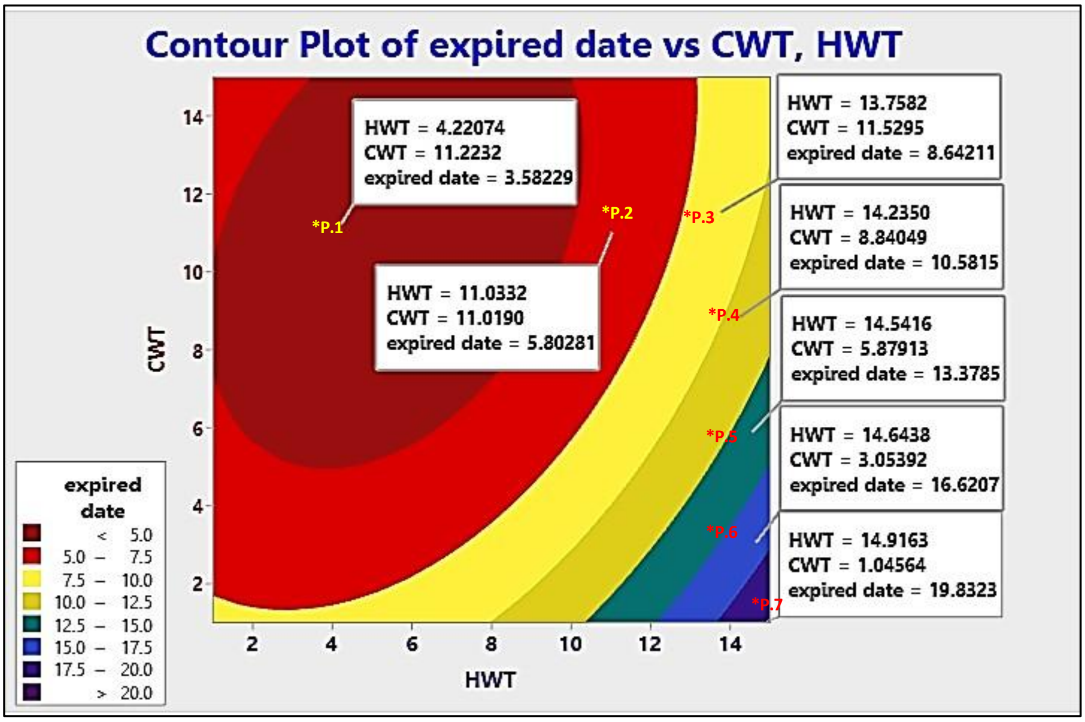

Figure 10. Graph predicts the relationship between the pairs of factors that affect the expiration date of mango storage.

Table 4. Example of predicting double factors affecting the expiration date of processed Mangoes

Point	Time HWT	Time CWT	Expire date
*P.1	4.22074	11.2232	3.58229
*P.2	11.0332	11.0190	5.80281
*P.3	13.7582	11.5295	8.64221
*P.4	14.2350	8.84049	10.5815
*P.5	14.5416	5.87913	13.3785
*P.6	14.6838	3.05392	16.6207
*P.7	14.9163	1.04564	19.8323

For short-distance transportation and storage requirements of 1-2 weeks, predicting the optimal factor pair can help minimize production costs. The inverse relationship between time of hot- water dipping and cold-water dipping is evident as show in the graph's predictions Figure 11, it shows the various zones representing different pairs of variables that influence mango storage duration for target expiration dates of 7-14 days, as exemplified by the data in Table 5.

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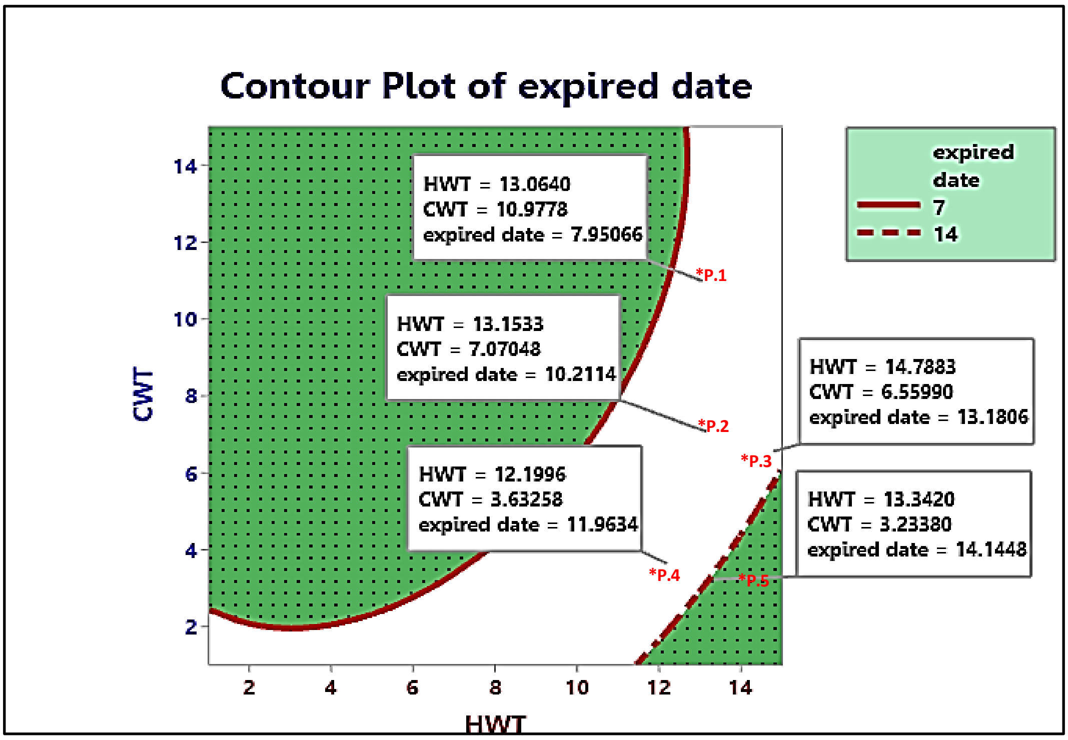

Figure 11. Graph predicts the relationship between factors of each pair has a target expiration date of 7-14 days.

Table 5. Example of data from predicting the double factors that affect the expiration date of mangoes by setting a target of 7-14 days.

Point	Time HWT	Time CWT	Expire date
*P.1	13.0640	10.9778	7.95066
*P.2	13.1533	7.07048	10.2114
*P.3	12.1996	3.63258	11.9334
*P.4	14.7884	6.55990	13.1806
*P.5	13.3420	3.23380	14.1448

4. Conclusions

Research on the optimal conditions of Hot- and Cold-Water Treatment Parameters in a Postharvest Production Line by the Design of Engineering Experiment (DOE) and Response Surface Methodology (RSM). The following conclusions can be drawn.

1. Both hot water dipping time and cold-water dipping time significantly impact the shelf life of mangoes that have undergone the production line at a significance level of 0.05.

2. Adjusting the hot-water and cold-water dipping times within the range of 1-15 minutes can influence the shelf life of processed mangoes. The results indicate that longer hot water dipping times and shorter cold-water dipping times are beneficial for maximizing shelf life.

3. Given the mass production and continuous nature of the production line, optimizing the process for minimal time while maintaining high quality is crucial. The identified optimal conditions are hot water dipping at 54 °C for 15 minutes and cold-water dipping at 25 °C for 1 minute, which enable processed mangoes to be stored at room temperature for an extended period without spoilage.

4. The findings of this research can be applied to the mango export industry to adjust production line factors based on transportation distance, thereby reducing losses, production costs, and increasing the value of mangoes effectively.

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