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Design and Performance Optimization of a Lab-Scale Pouch Pasteurization System for Crab Meat Using Retort Pouches: A Predictive Modelling Study

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Abstract

Retort pouches, known for their eco-friendly design, reduced material usage, and energy efficiency, present a sustainable solution for seafood including packaging of seafood like crab meat. This study developed and evaluated a lab-scale crab meat pasteurization system using retort pouches, incorporating a pouch-holding basket, immersion water heater, and temperature control with a PID controller. Heating efficiency and heat loss were assessed using preheated hot water (87°C) and cold water (33°C) at full, half, and quarter basket loadings. Maximum heating efficiency (91%) occurred with hot water (half- and quarter-loaded), while cold water (half-loaded) showed the lowest (61%). Heat loss was lowest (0.098 kW/h) with hot water (quarter-loaded) and highest (0.145 kW/h) with cold water (full-loaded). Box-Behnken Design results showed high predictive accuracy (R^2 adjusted: 0.9973 for preheated, 0.87 for non-preheated). Product quantity and water volume significantly affected heating time in cold water ($P<0.0001$) but were insignificant in hot water. Model validation showed F-values of 60.14 (hot water) and 974.52 (cold water) with reliable predictions. Crab meat temperature, product quantity, and water volume influenced heating time. Predicted values closely matched experimental results, offering critical insights for optimizing retort pouch pasteurization, ensuring food safety and quality.

Introduction

Decapod crustaceans, including shrimps and crabs, hold significant economic value in the global seafood trade (Boenish et al., 2022). Among these, crabs have gained remarkable prominence in the global market due to their higher value than finfish (Venugopal & Gopakumar, 2017). In addition to their economic importance, crab meat is highly nutritious, serving as an excellent source of protein (Narayanasamy et al., 2020; Küçükgülmez et al., 2006). However, crab meat's seasonal nature and perishability pose challenges for its long-term preservation. The economic significance of crabs is further highlighted by the increasing prominence of blue swimmer crabs in Asia (Romano & Zeng, 2008). Crab exports are crucial in strengthening national economies, ranking second only to shrimp in value. The growing demand for convenient and nutritious foods, such as crabs requiring minimal preparation time, is driven by changing lifestyles and an expanding working population (Das et al., 2019). These factors collectively contribute to the rising global crab demand (MPEDA, 2021). To meet consumer expectations for safe and high-quality crab products, manufacturers actively explore cost-effective and innovative technologies that ensure product safety and durability during processing (Olatunde & Benjakul, 2018).

The global crab market was valued at USD 10.74 billion in 2023 and is projected to reach USD 17.96 billion by 2032, growing at a CAGR of 5.88% (2024–2032). In 2022, global crab production exceeded 2.8 million tons, with 56.3% sourced from capture fisheries and 43.7% from aquaculture. China led production, contributing 62.7% of the global total. In 2023, global crab imports reached 443.4 thousand tons worth USD 5.5 billion, with the U.S. (25.3%), China (24.8%), and South Korea (16.7%) being the largest importers. Frozen crabs dominated imports (47.8% by volume), followed by live or fresh crabs (37.1%). Exports totalled 424 thousand tons in 2023, led by Canada (20.4%) and Russia (19.2%). Frozen crabs accounted for 51.7% of exports by volume, while live or fresh crabs comprised 35.2% (Dahl, 2025). These trends highlight the strong demand for crab products, especially in the U.S. and Asian markets, where crab remains a dietary staple. India is one of the growing key players in crab export, with a 120% increase with 6938 metric tonnes valued at 119.53 USD million in 2021 (MPEDA,2021). Blue swimming crabs (*Portunus pelagicus*) are predominantly found in tropical areas, particularly in Southeast and East Asia, as well as the eastern Indian Ocean and western Pacific Ocean (FAO, 2022). While wild harvests currently dominate the production of crabs, with 38760 tonnes in 2021 (CMFRI, 2021), and ongoing research explores the aquaculture potential of these crabs in India (Jitendra et al., 2014; Yusuf & Trondsen, 2014). To enhance seafood product diversity and promote exports, the Indian government has prioritized mud crab cultivation by advancing hatchery technology through the Rajiv Gandhi Centre for Aquaculture (RGCA) and expanding cultivation efforts across multiple states.

Crab meat exports encompass various forms, including chilled crab, frozen crab, and live crabs. Pasteurized crab meat, particularly from the blue crab (*Portunus pelagicus*), constitutes a significant portion, accounting for 70% to 80% of total crab exports from India (MPEDA, 2021). Pasteurization is a vital process for extending the shelf life of crab meat, achieved by subjecting it to mild heat treatment below 100°C, effectively reducing pathogenic microbial activity (Peng et al., 2017). The effectiveness of pasteurization is significantly influenced by factors such as product temperature, capacity, and water usage (Ranieri et al., 2009; Rasmussen et al., 2020). Traditionally, crab meat has been pre-processed and packaged in cylindrical tin cans, with notable limitations, including high environmental impact, energy-intensive production, and recycling challenges (Dickerson Jr & Berry Jr, 1974). In response to these concerns, alternative packaging materials such as plastic cups and pouches have been proposed for their lower environmental footprint (Almeida et al., 2021; Wiloso et al., 2022). Among these alternatives, retort pouches, made of laminated plastic films or foil, have gained widespread acceptance for processing and preserving Ready-to-Eat (RTE) foods from 90's to present times (Shukla et al., 2024; Bindu et al., 2004). These pouches offer several advantages, including longer storage life, shorter processing times, and better retention of nutrients, making them an attractive choice for the food industry (Kontominas et al., 2021).

This study addresses the critical gap in sustainable pasteurization technologies for crab meat by developing and optimizing a laboratory-scale Pouch Pasteurizer system specifically designed for retort pouches. Existing research has focused mainly on traditional packaging methods, such as cylindrical tin cans & other PE pouches, which present environmental and operational challenges (Dima et al., 2016). Although retort pouches have emerged as a sustainable alternative, no studies have investigated their application in the pasteurization of crab meat or explored optimising process parameters specific to their use. The novelty of this work lies in its focus on optimizing critical parameters—such as product temperature, capacity, and water usage—to maximize efficiency while minimizing environmental impact. By designing a tailored pasteurization system, this research provides an innovative and sustainable solution to meet the growing demand for eco-friendly packaging in the seafood industry.

The primary objective of this study is to design, develop, and evaluate a laboratory-scale pasteurization system called the Pouch Pasteurizer. The study evaluates the effectiveness of processing and preserving crab meat in retort pouches, identifies key parameters influencing the pasteurization process, and determines the appropriate heating time required for effective processing. This research aligns with the seafood industry's goals of sustainability, reduced environmental impact, and the adoption of innovative packaging solutions. With increasing consumer demand for sustainable packaging, the use of retort pouches in the seafood industry is expected to grow significantly.

Materials and Methods

The details of design, development, experimental setup and performance evaluation procedures are presented in this section. The materials used for fabricating the lab-scale pasteurization system include a pasteurization tank with a hinged lid, a product holding tank with a lid, a stand, and grit, all constructed from mild steel. Temperature measurements are managed using a PID controller (TC 303 Selec) with J- and RTD-type thermocouples. Heating is provided by a 6 kW electrical immersion heater, operating in batch mode with a capacity of 15 kg. Crab meat, specifically from the blue crab (*Portunus pelagicus*), is processed in retort pouches. The additional detailed specifications and process parameters are explained in the following section and Table 1.

Theoretical Considerations

The pasteurization tank serves as the heating medium, where water is heated in the inner section of the tank. Simultaneously, the product in contact with the heated water undergoes pasteurization. Mild steel was used as the material for constructing the pouch pasteurizer. Initially, the pasteurization tank and holding basket dimensions were determined based on a preliminary analysis, considering factors such as pouch dimensions, loading capacity, and freeboard.

The thickness of the mild steel sheet metal used for fabricating the pasteurization tank can be calculated using the following equation;

$$TPT = \frac{P}{\tau} \quad (1)$$

Where, TPT=Thickness of the pasteurization tank, P=Expected pressure inside the tank, τ=Shear stress of the mild steel

The specific heat capacity of water is the amount of heat (in joules) required to increase one kilogram of water to one degree Celsius. Accordingly, the amount of energy required to heat the water can be calculated using the following expression;

$$Q = \frac{MWxCpWxTD}{3600} \quad (2)$$

Where, Q=Energy requirement, MW= Mass of water, CpW=Cp of water, TD=Temperature difference

Development of Pouch Pasteurizer

In the present study, a lab-scale pouch pasteurizer was developed specifically for the pasteurization of crab meat in retort pouches. The system consists of a rectangular pasteurization tank made of mild steel, designed to hold water as the heating medium to transfer heat to the product (crab meat). The tank was constructed by bending and forming sheet metal to prevent leaks. The dimensions of the pasteurization tank were fixed at 0.6×0.3×0.32 m, with a sheet metal thickness of 3 mm selected to withstand the processing conditions (Table 1). A lid was provided at the top of the tank to maintain and sustain the temperature for extended periods (Figure 1A). The lid included perforations with a diameter of 1 cm to allow excess steam generated during pasteurization to escape, thus keeping the pressure inside the tank under control. A heating zone, separated by a grid, was incorporated into the tank. This zone houses the heater and an outlet valve (Figure 1A). The grid separates the heating and processing zones to prevent bubble formation.

An immersion heater with a capacity of 6 kW (Single/3 Phase) was used to heat the water. Preliminary studies revealed that heating one liter of water to its boiling point takes approximately 56 seconds while heating 100 liters requires about 93 minutes. The heater is connected to a PID controller to monitor and regulate the temperature. During the heat processing, the product temperature was continuously recorded using two types of thermocouples: J-type and RTD-type, both made of Copper-Nickel Constantan. The J-type thermocouple was fixed at the geometric center of the pouch, while the RTD-type thermocouple monitored the water temperature. A pouch holder was placed horizontally inside the pasteurization tank to securely hold the pouches during processing, as water turbulence could cause instability. The horizontal orientation of the product ensured effective heat transfer (Rippen et al., 1949; Jaczynski & Park, 2004). The pouch holder's dimensions were determined based on the dimensions of the pouches (Table 1). A lid was used to enclose the product and maintain the setup

Table 1. Standard consideration for designing the pasteurization system

Description	Material Used	Specification
Material for fabrication (Pasteurization tank with hinged lid, Product Holding tank with lid, stand & grit)	Mild Steel	Pouch holding tank = 0.6mx0.3m x 0.32 m
The shape of the tank – Pasteurization tank	Rectangle	0.6*0.38*0.56m.
Temperature Measurement	PID controller with J&RTD thermocouples	TC 303 selec controller
Medium for heating	Water	
Required water temperature	23-130°C	Product temperature – 87°C
Source of heat	Electrical immersion heater	6 Kw
Operation	Batch type	15 kgs
Product	Crab meat	Blue crab
Packaging material	Retort pouch	1. 4 layers (Sealant layer - Polyethylene (PE) or Polypropylene (PP) 2. Barrier layer - Aluminum Foil or Ethylene Vinyl Alcohol (EVOH) 3. Structural layer - Nylon or Polyester 4. Exterior layer - Polyester, Nylon or Polyethylene (PE)
Design software	Solid Work (2014)	Design expert 13.0.5.0

Selection of Controllers for Pouch Pasteurizer

Controllers and thermocouples were selected and interfaced with the pasteurization tank using single-phase electrical wiring. The system includes two PID controllers (TC303 SELEC controllers), one with an on/off system and the other without, to maintain and display processing and product temperatures. Additionally, a two-pole 32-amp MCB was installed to ensure the safe operation of the system (Supplementary Figure 1). Two thermocouples were integrated into the pouch pasteurizer for temperature measurement. The first is a J-type thermocouple, capable of measuring temperatures ranging from 0°C to 750°C (32°F to 1382°F), and is used to monitor the water temperature. The second is an RTD-type thermocouple, with a capacity to measure temperatures between -200°C and 850°C (-328°F to 1562°F). It measures the temperature of the crab meat packed in retort pouches.

Mechanism of Temperature Controlling System

The pouch pasteurizer system is equipped with two PID controllers: one to monitor the water temperature and the other to monitor the product temperature. The main power supply is connected to PID controller-1, which, in turn, supplies power to PID controller-2. PID controller-1 must be manually activated using a switch located in the controller box to enable the temperature monitoring mechanism. To initiate the system, the desired temperature is set in PID controller-1, activating the immersion heater at the bottom of the pasteurization tank. Once the water in the tank reaches the preset temperature, the thermocouple connected to the heater senses the temperature via a sensor and sends a signal to PID controller-1, automatically turning off the heater. If the water temperature fluctuates, PID controller-1 adjusts the heater accordingly by turning it on or off.

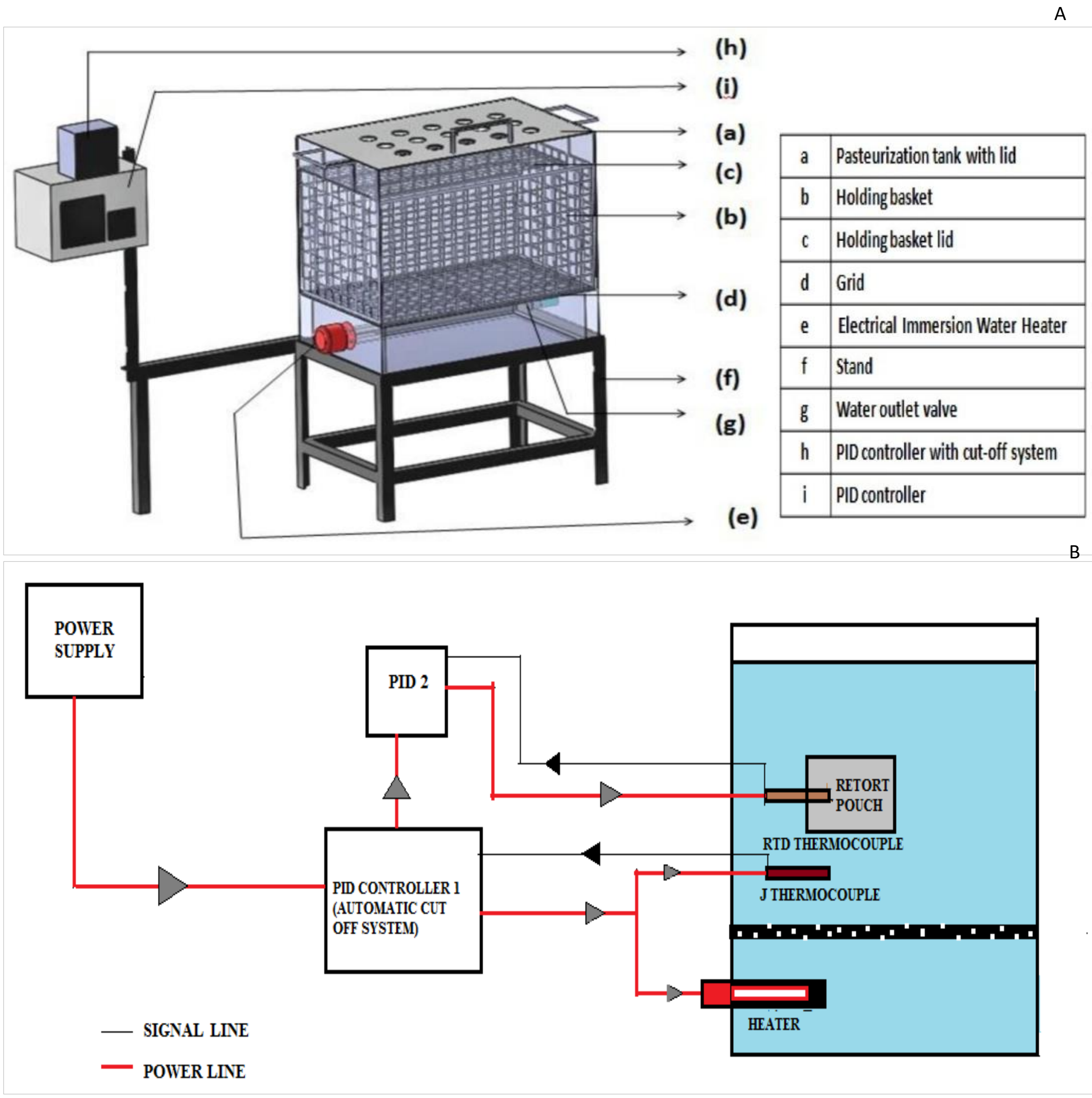


Figure 1. Schematic diagram of temperature measuring mechanism (A) and setup of Pouch Pasteurizer (B).

Simultaneously, PID controller-2 monitors the product temperature inside the retort pouch through a thermocouple connected to it and displays the temperature on the monitor for reference (Figure 1B).

Performance Evaluation of Pouch Pasteurizer

The performance evaluation of the pasteurization system on different combinations of input variables was conducted. The pasteurization system for crab meat in a retort pouch was optimized through a series of experimental trials designed using the Box-Behnken method with the assistance of Design of Experiments (DOE) software (Wu et al., 2012).

Process parameters such as product quantity, temperature, water volume, and heater capacity were identified as dominant factors influencing the processing time (Dixon et al., 2006) and considered input variables. In the study, the experimental trials were conducted using two different processing methods, the non-preheated method (cold water method) and the preheated method (hot water method), to optimize the equipment. This section discusses the effects of variations in the mentioned process parameters and their impact on the process time.

Experimental Setup and Design to Predict the Heating Time of Crab Pasteurization

The input parameters used to evaluate the heating time of crab pasteurization include crab meat temperature (CMT, °C), product quantity (PQ, kg), and the amount of water used in the pasteurization tank (WPT, litres). These parameters range from CMT=4°C to 87°C, PQ=0 to 15 kg, and WPT=65 to 100 litres. The ranges of these input parameters were determined based on a preliminary analysis of the threshold limits of the developed Pouch Pasteurizer (PP). The evaluation was conducted using the above input parameters under two different water conditions: hot water (87°C) and cold water (33°C). The Design of Experiments (DOE) software (Version 10.0.6) was employed to generate the schedule of experiments, resulting in a total of 25 trials for each hot-water and cold-water condition with varying combinations of input parameters. The experimental setup and step-by-step process flow for crab pasteurization in the pouch pasteurizer are presented in Figure 2.

Effect of Load Capacity of PPS on Heating Efficiency and Heat Loss

Experimental trials were conducted with hot water (87°C) and cold water (33°C) under three loading capacities of the pouch holding basket, viz., full load (60 pouches), half load (30 pouches) and quarter load (15 pouches) to find out the heating efficiency and heat loss of the developed Pouch Pasteurizer. The effect of load on the pasteurization tank's heating efficiency and heat loss was studied from the experimental data using sensitivity analysis (Table 2).

Heating Efficiency

The heating efficiency of the developed Pouch Pasteurizer System (PPS) was estimated using the below equation;

$$\text{Heating efficiency} = \eta = \frac{\text{Heatout}}{\text{Heatin}} = \frac{\text{Qout}}{\text{Qin}} \quad (3)$$

Where, $Q_{out}=mxC_p\Delta tT$ (m=total mass of the water (kg); Cp=specific heat of water (kJ/kg K) and ΔT=temperature change during the test period (^{0}C). $Q_{in}=Px\Delta t$ (P=Heater capacity (kW) and Δt=time (hr) to achieve the set temperature)

Heat Loss

The heat loss from the pasteurization tank during the heating process was calculated using equation (4).

$$q=UxAx\Delta t \quad (4)$$

Where q=total heat loss through the tank in kW/hr; U=Overall coefficient of heat transmission through the tank walls; A=area of the pasteurization tank assembly with the coefficient of heat transmission U in m^2 and Δt=temperature difference between inside and outside temperature in ^{o}C.

Result and Discussion

Performance Evaluation of Pouch Pasteurizer

Pasteurization is a more feasible method for retaining the quality and quantity of crab meat compared to other processing methods such as microwave sterilization, ultrasonic sterilization, and high-temperature sterilization (Zhu et al., 2021). The performance of the developed pouch pasteurization system was evaluated, and the results are presented in the following sections.

Determination of Heating Time for Crab Pasteurization

Experimental trials were conducted according to the schedule, and the responses are presented in Tables 3 and 4. The experiment was conducted using hot water (87°C) and cold water (33°C) to achieve the desired 'F' value, ensuring proper preservation of crab meat in retort pouches. Previous studies have reported that the thermal inactivation parameters of pathogenic bacteria during crab meat pasteurization range from 80°C to 86°C (Gates and Parker, 1992; Gate et al., 1993; Edwards and Early, 1981).

Analysis of Experimental Data and Model Fitting

The experimental results (Actual Time) were analytically examined using Response Surface Methodology (RSM) in the Design of Experiments software. The data were subjected to the Analysis of Variance (ANOVA) test, which serves as a proficient statistical decision-making tool used to assess the adequacy of a model for the response in experiments (Ghafari et al., 2009). The outcome of the ANOVA test (Supplementary Table 1) shows that the output variations (Actual Time) were well-fitted by the second-order/quadratic polynomial for all the experimental trials.

The ANOVA analysis presents results from two separate experiments: one conducted with cold water and the other with hot water. In both experiments, the response variable is not explicitly mentioned but is likely related to the product quality under different experimental conditions. The independent variables, or factors, in both experiments are product temperature (A), product quantity (B), and water volume (C). In both experiments, the ANOVA table indicates that the model is highly significant (P<0.0001), suggesting that at least one independent variable significantly affects the response variable. The F-value, which measures the ratio of variation between groups to variation within groups, is also large, indicating a strong effect size. The

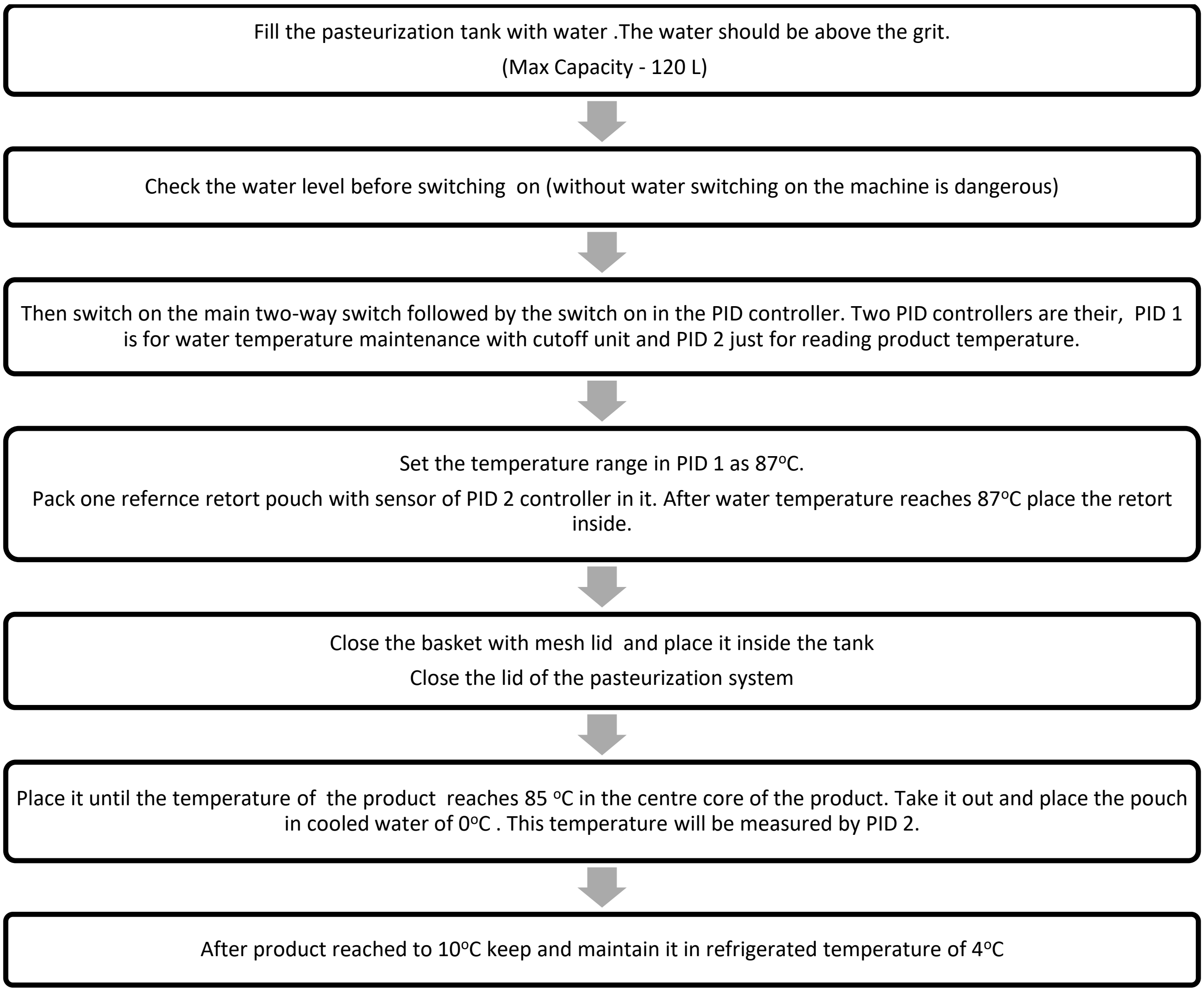


Figure 2. Process flow of crab pasteurization. (NOTE: similarly, for the cold-water method, the retort pouch was placed inside initially at room temperature, and the pouch and water were heated simultaneously from 30°C to 87°C).

Table 2. Effect of Load Capacity of PPS on Heating Efficiency and Heat Loss

Number of pouches	
Hot water (87°C)	Cold water (33°C)
60	60
30	30
15	15

F-value is a critical parameter used to quantify the effectiveness of heat treatment in crab meat pasteurization. The use of automated or mobile app-based F-value calculators can significantly reduce processing time while ensuring accuracy in achieving optimal pasteurization conditions (Harini et al., 2024). The significant inferences from the ANOVA are as follows:

Product Temperature (A)

In both experiments, product temperature (A) has a highly significant effect on the response variable (P<0.0001). This indicates that increasing or decreasing the product temperature significantly impacts its quality.

Cold Water Experiment

In the cold-water experiment, both product quantity (B) and water volume (C) have highly significant effects on the response variable (P<0.0001 for both variables). This result suggests that product quantity or water volume changes significantly affect product quality.

Hot Water Experiment

In the hot water experiment, the effects of product quantity (B) and water volume (C) are not significant (P>0.05). These variables do not significantly impact product quality when the water temperature is high (Montgomery et al., 2012).

Interaction Effects

The ANOVA analysis also reveals the interaction terms between independent variables. The AB interaction term is highly significant in both experiments (P<0.0001), indicating that the combination of product temperature and quantity significantly impacts the response variable.

Lack of Fit Test

The ANOVA includes a lack of fit test to determine whether the model fits the data well. The lack of fit tests in both experiments is insignificant (P>0.05), indicating that the model fits the data well.

In summary, as inferred from the above analysis, the model is highly significant in both experiments, with product temperature significantly affecting the response variable in both cases. The effects of the other independent variables and their interactions vary between the cold-water and hot-water experiments. The lack of fit tests shows that the model fits the data well in both experiments (Myers et al., 2016).

Model Equation for Hot Water Experiments

From Table 3, the F-value and P-value for the hot water experiments were 60.14 and 0.0500, respectively, indicating that the model terms are statistically significant. The total process time (F-value) determined in the present study was 60.14 minutes, which is slightly higher but closely aligns with the 58.25 minutes reported in the heat penetration study by Pathak et al.

Table 3. Experimental Schedule and the Response Obtained for performance evaluation of pasteurization tank with hot water (87°C)

Hot Water (87°C)						
Trails	Input Parameters			Results		
	Crab meat temperature(°C)	Product quantity(Kg)	Amount of water (L)	Actual Time	Predicted Time	Difference
1	45.5	7.5	65	22	22.85	0.85
2	45.5	7.5	100	18	18.89	0.89
3	4	7.5	100	0.2	-0.3252	-0.5252
4	45.5	15	82.5	24	24.86	0.86
5	45.5	1	82.5	16	16.45	0.45
6	45.5	15	100	24	22.70	-1.3
7	45.5	7.5	82.5	20	20.74	0.74
8	4	7.5	82.5	0.8	0.7170	-0.083
9	45.5	1	100	13	14.89	1.89
10	87	7.5	82.5	30	28.80	-1.2
11	45.5	1	82.5	16	16.45	0.45
12	87	7.5	100	28	26.15	-1.85
13	4	1	82.5	0	-2.84	-2.84
14	4	7.5	65	1	2.03	1.03
15	87	7.5	82.5	30	28.80	-1.2
16	4	7.5	82.5	0.8	0.7170	-0.083
17	4	15	82.5	1.5	4.00	2.5
18	45.5	1	65	18	18.28	0.28
19	45.5	7.5	65	22	22.85	0.85
20	87	1	82.5	24	23.78	-0.22
21	87	7.5	65	32	31.71	-0.29
22	45.5	15	82.5	29	24.86	-4.14
23	45.5	7.5	100	18	18.89	0.89
24	87	15	82.5	29	33.77	4.77
25	45.5	15	65	30	27.30	-2.7
					Mean	0.000752

(2023). Other significant model terms include A, B, C, and A^2. Additionally, the Lack of Fit F-value is 3.56, which is insignificant, suggesting that the model equation is well-suited for prediction.

$$\text{Heating Time (min)}=0.69+0.72A+0.81B-0.12C+0.003AB-0.001AC-0.002BC-0.003A^2-0.01B^2+0.0004C^2 \quad (5)$$

Where A=crab meat temperature, CMT (°C); B=product quantity, PQ (kg) and C=amount of water used in the pasteurization tank, WPT (litres).

Model Equations for Cold Water Experiments

From Table 4, the F-value and P-value for the cold-water experiments are 974.52 and 0.0500, respectively, implying that the model terms are significant. Also, other significant model terms include A, B, C, and A^2. Additionally, the Lack of Fit F-value is 3.61, which is insignificant and shows that the model equation best fits prediction.

$$\text{Heating Time (min)}=-36.17+0.031A+1.61B+0.63C+0.03AB+0.002AC-0.004BC+0.01A^2-0.03B^2-0.0031C^2 \quad (6)$$

Where A=crab meat temperature, CMT (°C); B=product quantity, PQ (kg) and C=amount of water used in the pasteurization tank, WPT (litre).

Correlative Effects of the Input Parameters

From this equation, it is inferred that the crab meat temperature, product quantity, amount of water used in the pasteurization tank, the quadratic effect of crab meat temperature, the interaction between crab meat temperature and product quantity, and, finally, the interaction between crab meat temperature and the amount of water used in the pasteurization tank all have a positive effect on the heating time. All the parameters mentioned above are proportional to the heating time and increase simultaneously. At the same time, the interaction between product quantity and the amount of water used in the pasteurization tank, the quadratic effect of product quantity, and the quadratic effect of the amount of water used in the pasteurization tank have a negative effect on the heating time and are inversely proportional. If the heating time increases, all these parameters decrease.

From the equation, it can be inferred that the crab meat temperature, product quantity, the quadratic effect of the amount of water used in the pasteurization tank, and the interaction between crab meat temperature and product quantity positively affect the heating time. All the parameters mentioned above are proportional to the heating time and increase simultaneously. At the same time, the linear effect of the amount of water used in the pasteurization tank, the interaction between product quantity and crab meat temperature, the interaction between crab meat

Table 4. Experimental Schedule and the Response Obtained for Performance Evaluation of Pasteurization Tank with Cold Water (33°C)

Cold Water (33°C)						
Trails	Input Parameters			Results		
	Crab meat temperature(°C)	Product quantity(Kg)	Amount of water(L)	Actual Time	Predicted Time	Difference
1	45.5	15	82.5	55	54.31	-0.69
2	45.5	7.5	65	35	34.36	-0.64
3	45.5	7.5	100	42	42.19	0.19
4	87	7.5	82.5	98	98.11	0.11
5	87	7.5	100	102	102.43	0.43
6	45.5	15	82.5	55	54.31	-0.69
7	45.5	0	65	14	15.72	1.72
8	45.5	0	100	25	24.55	-0.45
9	45.5	0	82.5	19	20.98	1.98
10	4	7.5	82.5	5	6.94	1.94
11	45.5	7.5	100	42	42.19	0.19
12	45.5	15	65	50	50.05	0.05
13	4	7.5	82.5	9	6.94	-2.06
14	4	15	82.5	12	13.13	1.13
15	45.5	7.5	65	35	34.36	-0.64
16	4	7.5	65	3	3.43	0.43
17	87	7.5	65	93	92.09	-0.91
18	45.5	7.5	82.5	40	39.12	-0.88
19	45.5	0	82.5	19	20.98	1.98
20	87	15	82.5	120	122.30	2.3
21	4	0	82.5	1	-2.20	-3.2
22	87	0	82.5	73	70.97	-2.03
23	87	7.5	82.5	98	98.11	0.11
24	4	7.5	100	7	8.76	1.76
25	45.5	15	100	59	56.88	-2.12
					Mean	0.0004

temperature and the amount of water used in the pasteurization tank, the interaction between product quantity and the amount of water used in the pasteurization tank, the quadratic effect of product quantity, and the quadratic effect of crab meat temperature have a negative effect on the heating time, making them inversely proportional. If the heating time increases, all these three parameters decrease.

Model Validation

In addition to the verification through ANOVA, the Models were validated by conducting experiments with a new set of parameters. The multiple response values were measured and compared with the predicted values using the Model equation. Details of the experiments conducted and predicted and measured values of the output variables are expressed graphically.

Figure 3& 4 shows the graphical illustration of projected values using the model coupled with the corresponding computed values of all the responses. This finally gives a better picture and clear understanding. In Figure 5, lines are plotted to take the predicted and measured values to analyze the model's prediction accuracy. Predicted and experimental values often follow a close match, and the degree of deviation is negligible.

Determination of Load Capacity of PPS on Heating Efficiency and Heat Loss

An analysis was carried out to understand the effect of factors such as loading capacity and water temperature on the performance of the developed Pouch Pasteurizer, and the same was evaluated in terms of heat loss and heating efficiency.

Determination of Heat loss

Heat refers to the energy transferred from one body to another due to a temperature difference. Two objects with differing temperatures tend to reach thermal equilibrium during thermal processing. Heat loss from a thermal system to the atmosphere occurs via conduction, convection, and radiation (Horwell et al., 2020). This study calculated heat loss from the developed pouch pasteurizer using varying factors. A paired sample t-test was conducted to assess the effect of water temperature on heat loss, revealing that the difference in water temperature significantly influenced heat loss ($P<0.05$), as shown in Table 5 (Elatar, 2016).

As illustrated in Figure 6, heat loss increased with increased loading capacity. In this study, the effectiveness of the pouch pasteurization system was evaluated at a target temperature of 87°C. Notably, heat loss increased by 26% when the load capacity was at full compared to a quarter load capacity, likely due to the extended processing time required to reach the set temperature.

While previous studies suggest that optimal temperatures for producing 'good' quality crab (*Cancer pagurus*) range between 96°C and 100°C, with 'acceptable' quality achieved at temperatures between 104°C and 108°C for crabs weighing 400 g and 800 g, respectively (Condón-Abanto et al., 2019), our findings indicate that effective pasteurization can still be achieved at a lower temperature of 87°C for *Portunus pelagicus* species. This heat loss can be mitigated by providing thermal insulation, which reduces the overall heat transfer coefficient between the system and the surrounding atmosphere (Cengel & Ghajar, 2014), thus lowering the energy demands of heating and cooling systems.

Determination of Heating Efficiency

The study utilized hot water (87°C) and cold water (33°C) and tested three different loading capacities for the pouch holding basket: full load (60 pouches), half load (30 pouches), and quarter load (15 pouches). The results show that as the load on the Pouch Pasteurizer System (PPS) decreases, the system's heating efficiency increases. At full load, the heating efficiency of the hot side was 85% with a P-value of 0.03, while the cold side's heating efficiency was 63% with a P-value of 0.07. At half load, the hot side's heating efficiency increased to 91%, with an H/Q value of 0.09, while the cold side remained at 62% with an H/Q value of 0.04. Finally, at quarter load, the hot side's heating efficiency remained at 91% with a Q/F value of 0.06, and the cold side's efficiency increased to 69% with a Q/F value of 0.11.

The 65% to 89% heating efficiency implies that the water heater can convert a significant portion of the input energy into usable heat. The lower end of the range (60%) suggests that some energy is lost during the heating process, while the higher end (90%) reflects a higher efficiency level with fewer energy losses. The efficiency range of 60% to 90% exhibited by the water heater is considered favorable compared to typical market commodities. This suggests that the heater can convert a large portion of the input energy into usable heat, potentially leading to lower energy consumption and cost savings. According to the U.S. Department of Energy, electric water heaters typically have a maximum efficiency ranging from 93% to 98%, while gas water heaters generally achieve 80% to 85%. However, it should be noted that the actual efficiency of a water heater can be influenced by factors such as the unit's age, installation quality, and maintenance (Sidebotham, 2016).

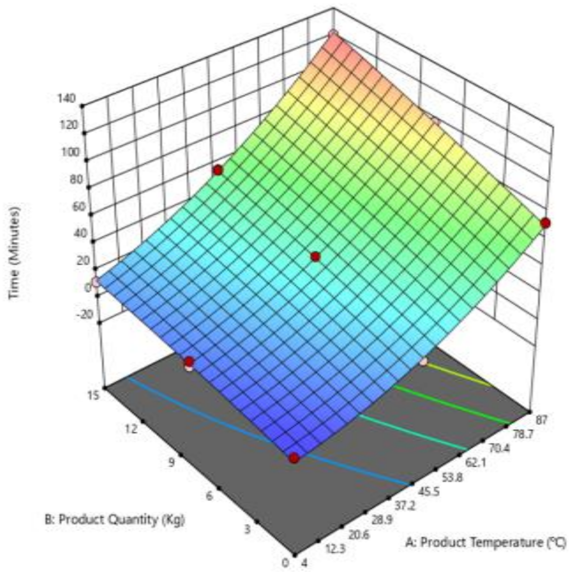
Optimizing the load capacity of a Pouch Pasteurizer (PP) can enhance heating efficiency and reduce heat loss, ultimately lowering energy costs. However, these findings are specific to the experimental setup and may not be generalized to other PP systems. Future studies could build on these findings to optimize the design and operation of PP systems further. A paired t-test was conducted to determine the significant difference between the hot and cold-water experiments, with N=3 for both samples. The hypothesis was fixed for the analysis.

Figure 6 demonstrates that the hot water method is more efficient than the cold-water method, likely due to the heating medium's preheating, which helps achieve the desired processing time more quickly. For the lab-scale application of the pouch pasteurizer, mild steel was used, considering the economic aspects of fabrication. However, it is important to note that mild steel is less corrosion-resistant than stainless steel and may require regular maintenance to prevent rust and deterioration. Considering the budget constraints, mild steel was chosen for its initial feasibility, workability, and cost-effectiveness. In the industry, mild steel is beneficial for its ability to be welded, malleability, and suitability for heat treatment processes, which can alter its mechanical properties (Badmos & Ajimotokan, 2009). Furthermore, mild steel is widely employed in metallic structures within the industry due to its affordability (Fuente et al., 2010).

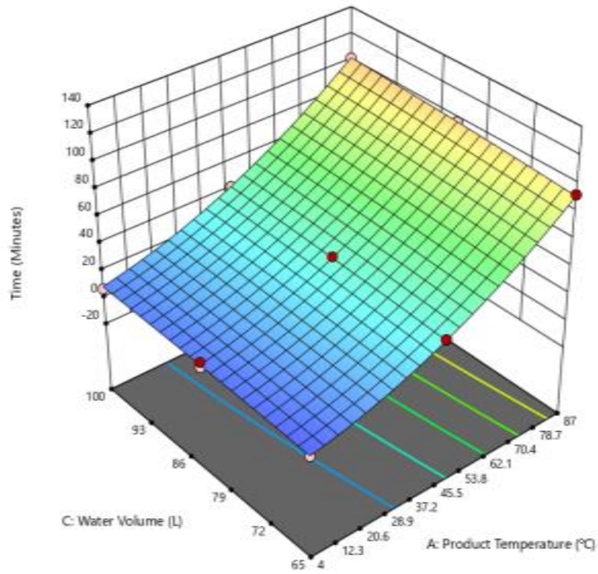
Conclusion

System Performance and Heat Loss

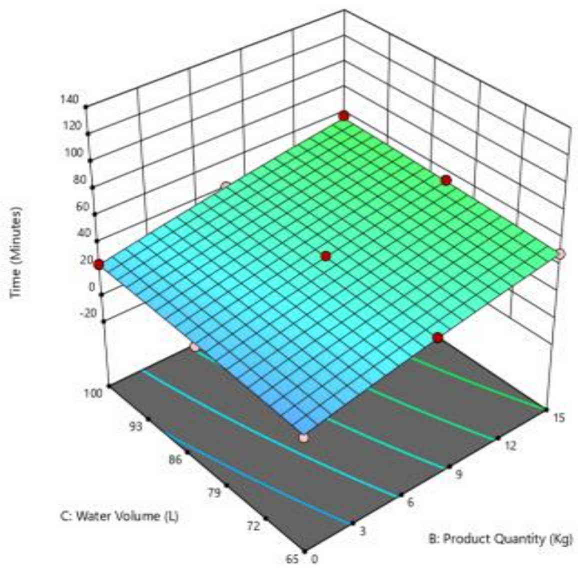
The time required to achieve the desired processing temperature closely aligns with both the calculated and actual experimental values, confirming the high efficiency and reliability of the fabricated Pouch Pasteurizer System (PPS). The observed heat loss is moderate, indicating that thermal losses are well-controlled and do not significantly impact the overall efficiency of the pasteurization process. The heating efficiency across both methods ranged from 60% to 90%, with minimal deviation from the expected performance metrics, suggesting optimal system functionality under the conditions tested.



(A/B)=Product Temperature vs. Product Quantity



(A/C)=Product Temperature vs. Water Volume



(B/C)=Product Quantity vs. Water Volume

Figure 3. Response surfaces of the interactive effects of input parameters on the process time of cold-water experiment.

Statistical Analysis and Model Validation

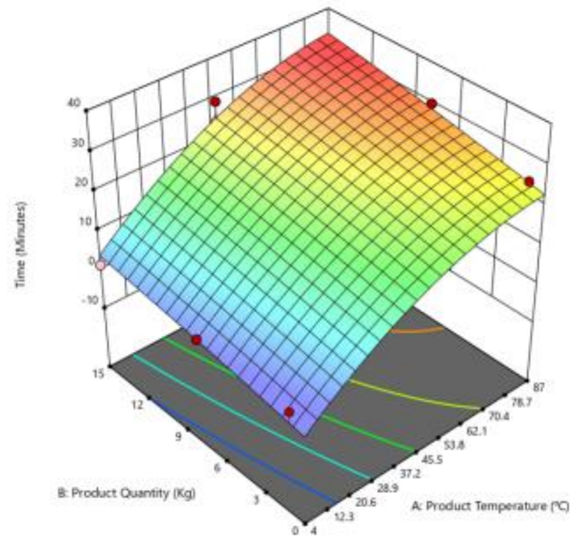
The results of the Box-Behnken Design, which were analyzed using regression methods, yielded an adjusted R^2 value of 0.9973 for the non-preheated method and 0.87 for the preheated method. These values indicate a highly satisfactory fit for the model, particularly for the non-preheated configuration, suggesting that the model can reliably predict system behavior under varying operational conditions. The slight reduction in the R^2 for the preheated method could be attributed to inherent system dynamics or the complexities of preheating processes that were not fully accounted for in the model.

Critical Parameters Influencing Processing Time

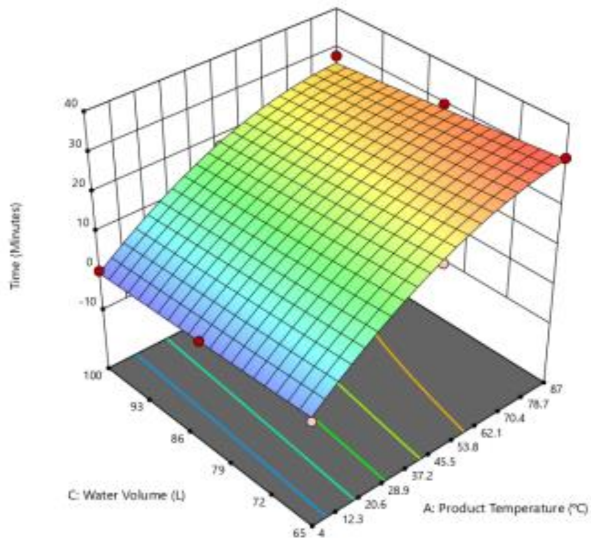
Through comprehensive experimental analysis, it was determined that the most significant factors influencing the processing time were the product temperature, the quantity of product being processed, and the volume of water used in the system. Among these, product temperature and water volume demonstrated the most substantial influence on the thermal dynamics, whereas the heater capacity exhibited the least effect on the overall processing time. This highlights the importance of optimizing the thermal environment within the pasteurizer to achieve maximum efficiency in pasteurization cycles.

Model Reliability and Experimental Validation

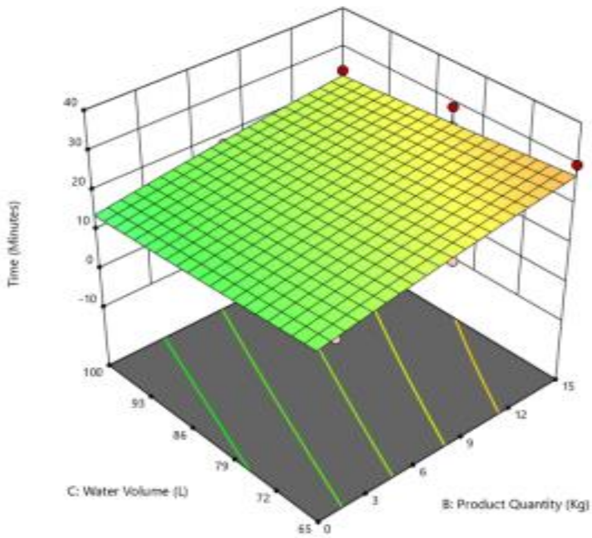
The predictive accuracy of the developed model was further validated through graphical representation of the predicted versus actual experimental data (Figure 5), where the negligible deviation between the two sets of values reaffirms the model's reliability in forecasting system behavior. This strong correlation underscores the model's potential for future optimization and scale-up of the pasteurization process, ensuring consistency and efficiency across different operational scenarios.



(A/B)=Product Temperature vs Product Quantity



(A/C)=Product Temperature vs Water Volume



(B/C)=Product Quantity

Figure 4. Response surfaces of the interactive effects of input parameters on the process time of hot water experiment.

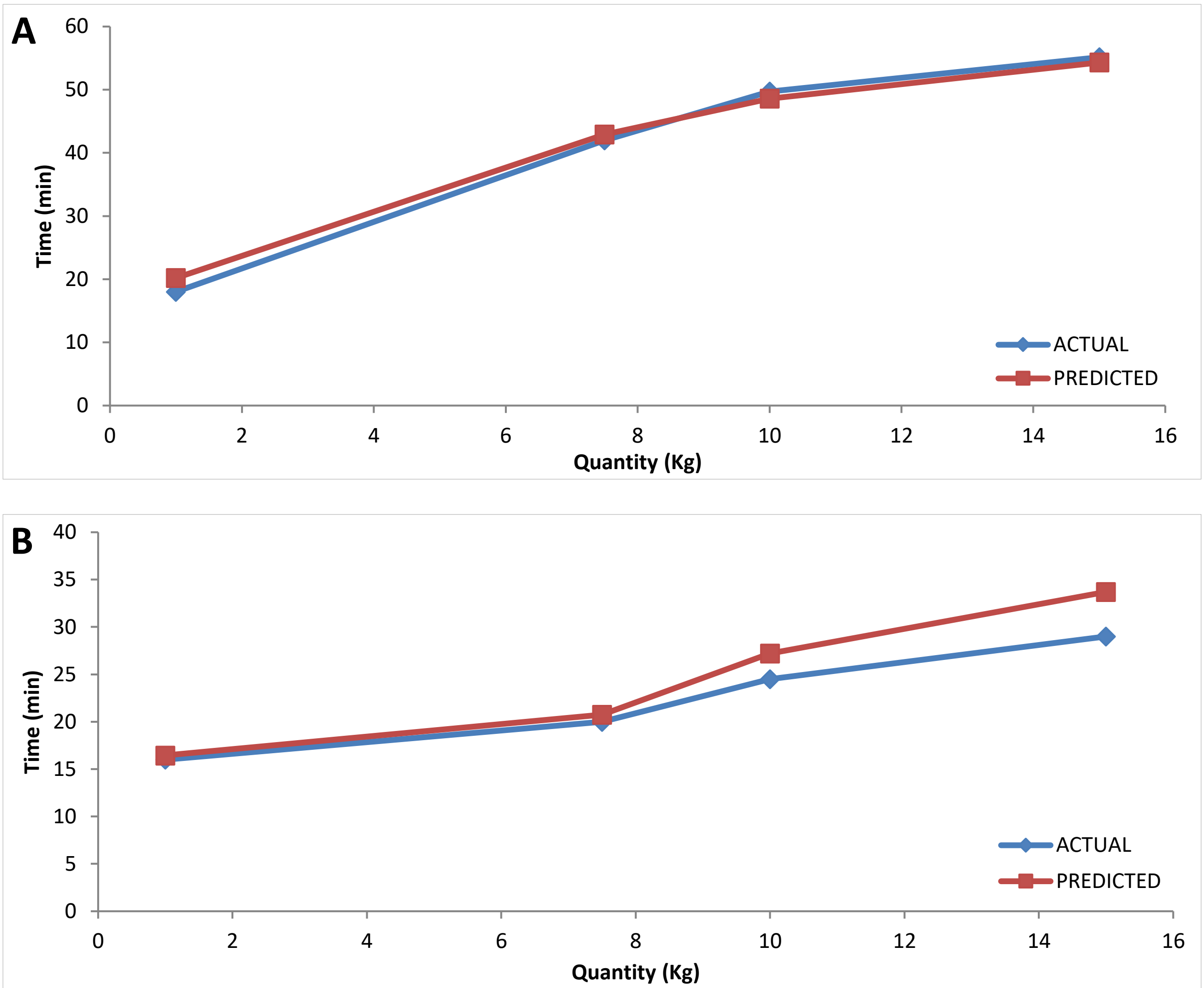


Figure 5. Predicted vs. actual graph of hot water (A) and cold-water experiments (B).

Table 5. Heat loss and efficiency values for cold and hot water

Details	Heat Loss (KW/hr)				
	Hot	P value	Cold	P value	P value
Full Load (60)	0.132±3	F/H=0.0002	0.145±3	F/H=0.0006	0.0003
Half Load (30)	0.116±3	H/Q=0.0001	0.127±3	H/Q=0.0002	0.0004
Quarter Load (15)	0.098±3	Q/F=0.0001	0.102±3	Q/F=0.000	0.006
			Efficiency (%)		
Full Load (60)	85 ± 3	F/H = 0.03	63 ± 3	F/H = 0.07	0.0009
Half Load (30)	91 ± 3	H/Q = 0.09	62 ± 3	H/Q = 0.04	0.001
Quarter Load (15)	91 ± 3	Q/F = 0.06	69 ± 3	Q/F = 0.11	0.0001

Implications for Industrial Scaling

The results of this study demonstrate that while pasteurization of crab meat is traditionally considered a large-scale industrial operation, the use of the developed small-scale pasteurization system offers significant advantages in terms of scalability and efficiency. The positive outcomes from the experimental trials suggest that the fabricated system could be effectively deployed in smaller-scale settings, providing a cost-effective and energy-efficient solution for the pasteurization of crab meat in retort pouches. The improved efficiency of the system, demonstrated in both preheated and non-preheated methods, provides valuable insight into optimizing pasteurization processes for both research and commercial applications.

Future Work

Future advancements in developing a mobile application or interactive chatbot interface could

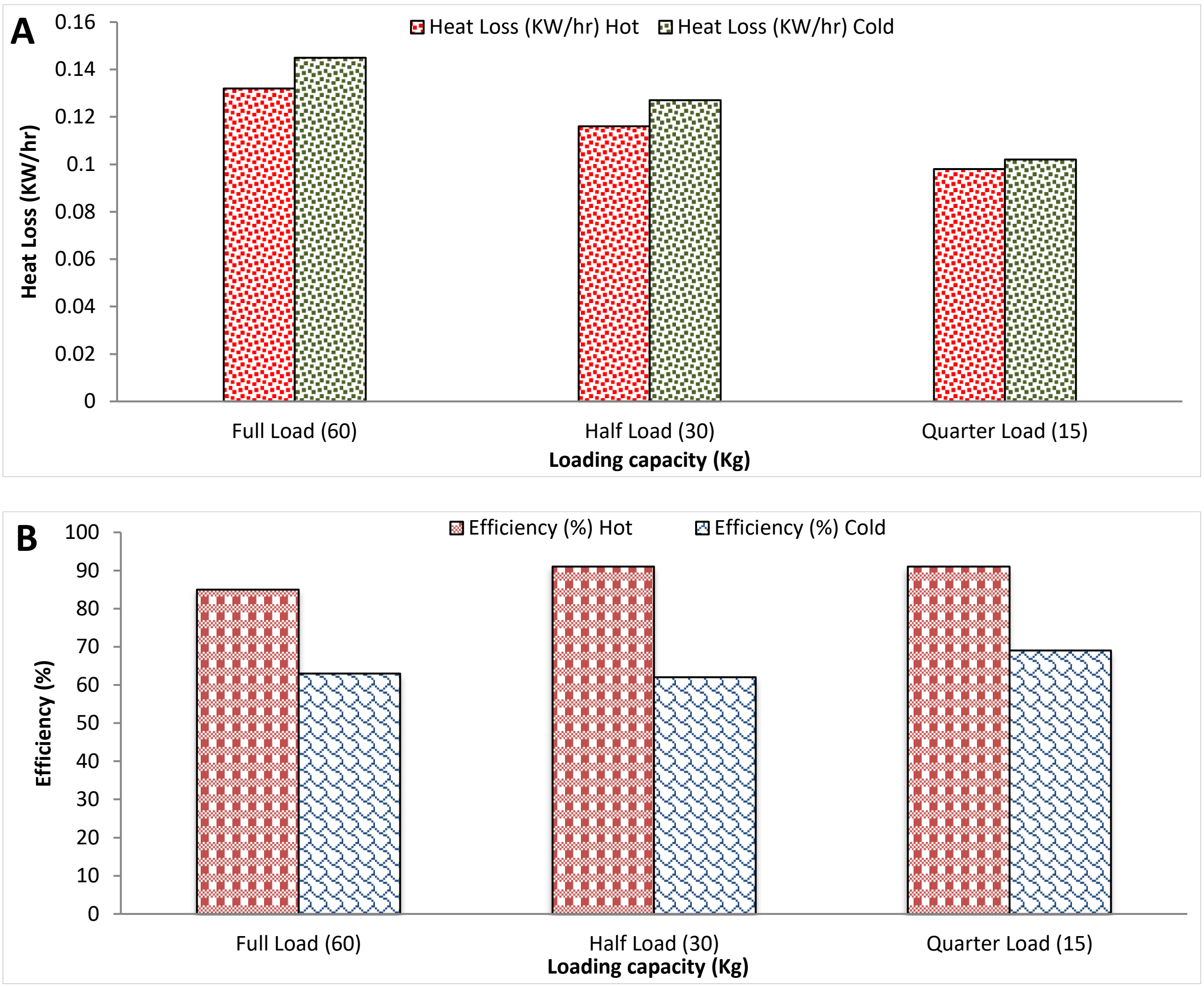


Figure 6. Effect of load capacity on heat loss (A) and heating efficiency (B).

significantly enhance the monitoring and control of the pasteurization process. By integrating the predictive equation into such platforms, real-time monitoring of process conditions could be facilitated, allowing users to access key parameters related to heating time quickly. This integration would enable small-scale crab processors to optimize operational efficiency by automatically adjusting process settings based on real-time data, ultimately improving the consistency and quality of the pasteurization process. Additionally, implementing such technologies could streamline the workflow and reduce the complexity associated with traditional pasteurization methods. Adopting advanced, user-friendly systems such as these would benefit small-scale processors and drive greater acceptance of innovative technological solutions within the industry, thereby enhancing productivity and encouraging the broader application of automated systems in food processing.

Ethical Statement

Not applicable.

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Author Contribution

Harini R: Conceptualization, Data collection & Writing, **N. Manimehalai:** Project supervision, Editing & Review, **R.U. Roshan:** Data analysis & Data interpretation, **R. Pradeep:** Critical revision & Design, **S. Kesavan:** Data curation & Editing.

Conflict of Interest

We declare that there are no conflicts of interest or competing interests associated with this manuscript.

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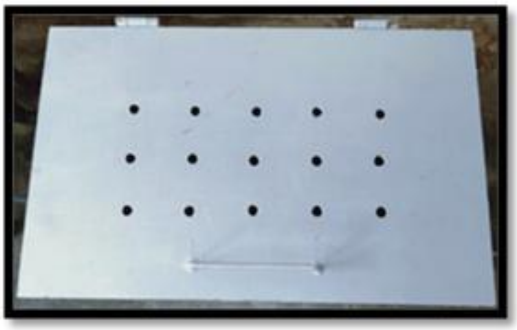
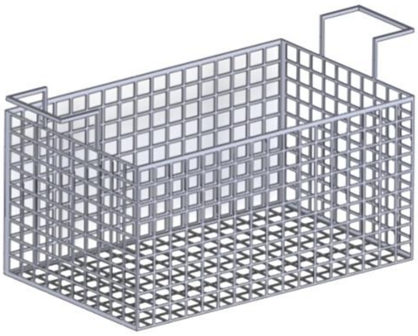
Supplementary Table 1. Analysis of Variance

	Cold water experiment			Hot water experiments		
Source	**F-value**	**p-value**		**F-value**	**p-value**	
Model	974.52	< 0.0001	Significant	60.14	< 0.0001	Significant
A - Product Temperature	7283.15	< 0.0001		446.67	< 0.0001	
B - Product Quantity	973.65	< 0.0001		38.49	< 0.0001	
C - Water Volume	53.77	< 0.0001		8.85	0.0094	
AB	94.64	< 0.0001		0.4712	0.5029	
AC	1.83	0.1967		0.4842	0.4971	
BC	0.2921	0.5968		0.0700	0.7949	
A^2	254.92	< 0.0001		32.84	< 0.0001	
B^2	3.07	0.1002		0.1319	0.7215	
C^2	1.01	0.3298		0.0165	0.8996	
Residual						
Lack of Fit	3.61	0.0660	Not Significant	3.56	0.0680	Not Significant
Pure Error						
Cor Total						
R^2		**99%**			**87%**	

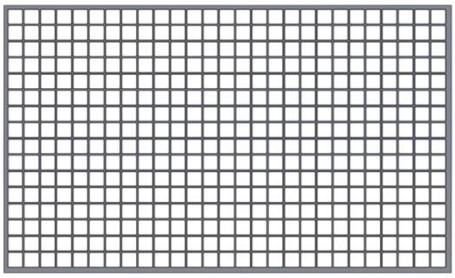
Supplementary Figure 1. Pouch Pasteurizer and its components with Control unit



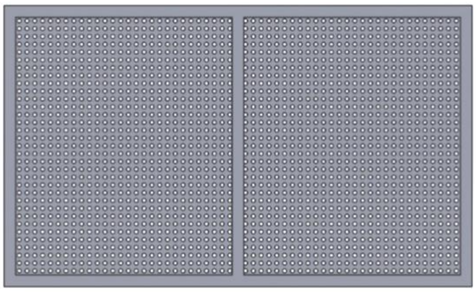
(A) Pasteurization tank with lid



(B) Holding basket



(C) Holding basket lid



(D) Grid

(E) Electrical Immersion Water Heater

(F) PID Controller with Cut-Off System

(G) Cut-Off Unit of PID