Development and Assessment of a Batch Type Ohmic Heating System for Milk Processing

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ABSTRACT

This study aims to develop and assess the performance of a batch-type ohmic heating system for the thermal processing of cow and buffalo milk, particularly investigating whether the ohmic system affects the nutritional and microbial quality of the milk. An experimental setup was fabricated with a 7-liter capacity, utilizing an agitator as one electrode and the vessel surface as the other. The system was tested for heating milk from 32°C to target temperatures of 75°C and 92°C. Key processing parameters, including agitator speed and applied voltage, were optimized for both milk types. The physicochemical and microbial properties of the ohmically heated milk were evaluated, along with performance metrics such as heating rates, power consumption, and system efficiency. The developed ohmic heating system achieved heating rates of 4.29°C/min for cow milk and 2.85°C/min for buffalo milk. Cow milk demonstrated lower energy consumption, requiring less time and voltage compared to buffalo milk, with system performance coefficients of 58% for cow milk and 50% for buffalo milk. However, fouling on the agitator surface was identified as a challenge for industrial applications. Importantly, the ohmic heating process preserved the nutritional content while effectively reducing microbial load, confirming its potential for dairy processing. In conclusion, the batch-type ohmic heating system exhibited high efficiency and rapid heating capabilities for both cow and buffalo milk, indicating its viability for commercial use. Future research should focus on addressing fouling issues and further optimizing the system, enhancing the overall potential of ohmic heating technology in the dairy industry.

Keywords: Ohmic heating, milk processing, thermal efficiency, cow milk, buffalo milk, fouling, energy consumption, product quality

1. INTRODUCTION

In the food industry, the continuous evolution of novel technologies is pivotal for enhancing production processes, improving food safety, and developing innovative products. Among these technologies, thermal processing remains a fundamental application, particularly for perishable goods like milk. Thermal treatments are crucial for ensuring the safety and quality of milk, effectively eliminating pathogens and extending shelf life. However, traditional methods often suffer from disadvantages, such as uneven heating, which can lead to the degradation of nutritional and sensory qualities. This inconsistency can compromise the safety and quality of milk, underscoring the need for more efficient thermal processing techniques.

Conventional heating methods, while widely used, have significant limitations. These include fouling, a low overall heat transfer coefficient, inefficient use of heating media, and the potential loss of product quality. As consumer demand shifts toward minimally processed and fresh foods (Bolhuis et al., 2022), the food industry must seek innovative solutions. In this context, alternative technologies, such as pulsed electric field, high-pressure processing, and ohmic heating, are gaining prominence (Leong et al., 2022).

Ohmic heating—also known as electro-conductive heating or electrical resistance heating—stands out as a promising technique for food processing. This method utilizes electrical energy to generate heat directly within the food product, ensuring rapid and uniform heating with minimal deterioration of food quality (Kaur et al., 2016). It has been shown to preserve nutrients and flavors while reducing processing time and energy consumption. Current applications of ohmic heating include the processing of juices, soups, sauces, and dairy products, where its advantages over conventional methods can significantly enhance quality and safety.

Despite its potential, the application of ohmic heating in dairy processing remains underexplored, particularly regarding the challenges posed by milk's heterogeneous composition. For instance, studies by Ariç Sürme et al. (2021) demonstrated that increasing voltage gradients during the evaporation of cow's milk led to higher energy efficiency, while Norouzi et al. (2021) highlighted the superior heating rates of ohmic heating compared to conventional methods when concentrating sour cherry juice. Rocha et al. (2022) further illustrated the benefits of ohmic heating on high-protein flavored milk, noting reductions in energy expenditure and improved microbial inactivation.

Hence, an attempt has been made to design, develop, and optimize the parameters for heating milk without affecting its sensorial and microbial quality. This innovative system incorporates an agitator as one of the electrodes to enhance heat distribution and mitigate localized heating effects. By optimizing operational parameters, this research aims to improve the quality and safety of processed milk, addressing the pressing need for advanced thermal processing techniques that align with consumer expectations for high-quality dairy products.

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2. MATERIAL AND METHODS

This section outlines the materials and methods employed in the development and evaluation of a batch-type ohmic heating system for milk processing. The information provided herein aims to facilitate the reproducibility of the experiments conducted.

2.1 Experimental Setup

The conceptual design of the batch-type ohmic heater is illustrated in Figure 1. The setup consists of several integral components, including a milk vessel, an agitator, a motor, and a slip ring assembly, all mounted on a stainless-steel frame for stability. The agitator and milk vessel were used as electrodes to minimize fouling during the heating process.

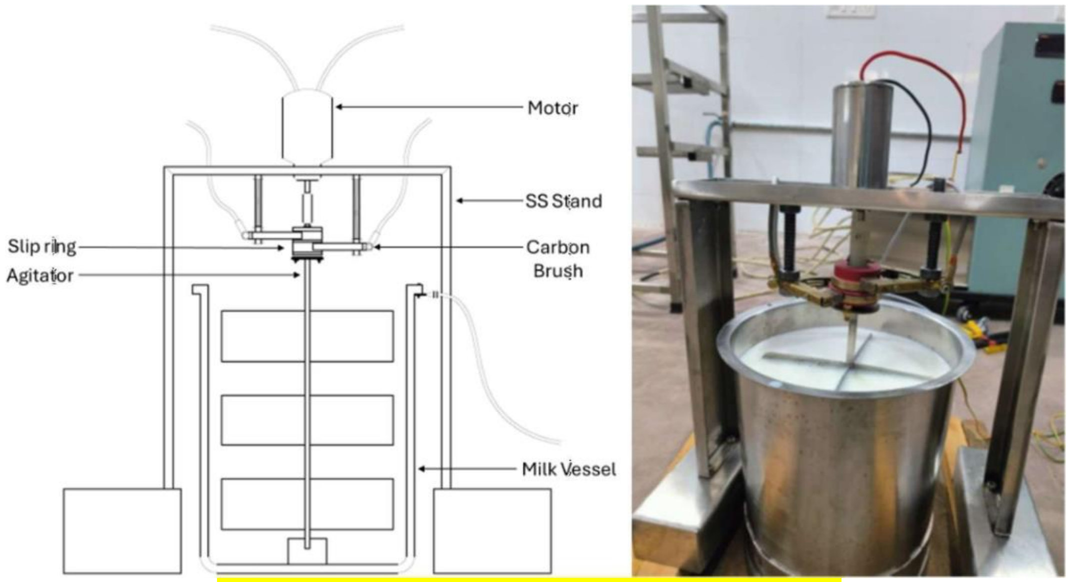

Figure 1: The conceptual diagram of an ohmic heater

2.2 Design and Fabrication of a Batch-Type Ohmic Heating System

The design of the small capacity ohmic heating vessel was based on a thorough review of existing literature. The final system includes Milk Vessel, Agitator & Motor assembly, and Slip Ring & Carbon Brush Assembly.

These components collectively facilitate efficient and controlled ohmic heating of milk

2.2.1 Design of Milk Vessel

The milk tank was fabricated from stainless steel, with a thickness of 2 mm and dimensions of 225 mm in diameter and 230 mm in height. The nominal capacity of the vessel was 7 liters, with a headspace of 50 mm to accommodate heating without overflow. Compliance with Bureau of Indian Standards (IS 2689) was ensured in its design.

2.2.2 Design of Agitator and Motor Assembly

The agitator featured a stainless-steel blade design with 12 blades positioned at three levels on the shaft, as shown in Figure 2. It was powered by a 12 V DC motor, capable of rotating at speeds between 10 and 100 RPM, with a torque of 5.7 kg-cm. A Teflon coupling was employed to electrically isolate the motor from the agitator while maximizing contact area for effective heat transfer.

Figure 2: Agitator, motor and slip ring assembly

2.2.3 Slip Ring and Carbon Brush Assembly

The slip ring and carbon brush assembly was crucial for current transmission to the rotating agitator, allowing it to serve as an electrode. A copper slip ring and carbon brushes were selected for their efficiency in transferring high amperage, as depicted in Figures 2. The entire assembly was secured to a stainless-steel frame, ensuring hygienic maintenance and ease of cleaning.

2.2.4 Electrical Panel

An electrical panel was used to manage all electrical components of the ohmic heating system, as shown in Figure 3. The electric panel consisted of variac (auto transformer), energy meter, step up transformer, voltmeter (0-500 V AC) and ammeter (0-100 ampere AC) for measuring the current and voltage supplied.

Figure 3: An electrical panel

2.2.5 Raw Milk

Two types of milk were utilized: raw cow milk, sourced from the Livestock Research Station (LRS) at Kamdhenu University, Anand, and raw buffalo milk, procured from a local vendor in Hadgud village of Anand District.

2.3 Experimental Design

The ohmic heating system underwent preliminary trials to establish operational parameters, specifically voltage settings for cow and buffalo milk. The parameters monitored included temperature profile, heating rate, and thermal efficiency.

2.4 Performance Evaluation of the Ohmic Heating System

To evaluate the performance, a series of experiments were conducted aiming for target temperatures of 75˚C and 92˚C. Response Surface Methodology (RSM) was employed for optimization, with various parameters assessed as outlined in Table 1.

Table 1: Experimental Parameters of ohmic heating system

Process Parameters		**Levels**
Variable Parameters	Voltage	Cow milk :18-35 V (90-180 V)
		Buffalo milk: 22-40V (110-200 V)
	Agitator speed	10 to 100 RPM
Fixed Parameters	Type of milk	Cow and Buffalo
	Initial Temperature	32˚C
	Final Temperature	75˚C & 92˚C

Performance Parameters (Responses)
• Temperature profile • Current profile • Heating time • Heating rate • Energy consumption • Sensory score • System performance coefficient

2.4.1 Performance Evaluation Parameters

Temperature profile: The temperature profile illustrates the pattern of temperature increase in milk during ohmic heating. Temperature changes were recorded using a digital thermometer at one-minute intervals.

Current profile: The current profile reflects the variation in electrical current during the ohmic heating of milk. Current measurements were obtained from the electrical panel, where an ammeter indicated the supplied current. These measurements were recorded at one-minute intervals.

Sensory Score: The Experimental milk processed at different processing parameters was evaluated by a panel of judges from Dairy engineering and Dairy technology department of Sheth M. C. College of Dairy Science, Anand, for sensory characteristics using 9-point Hedonic scale.

Heating time: The total heating time was defined as the duration required to increase the temperature of the milk from 32 °C to 75 °C and then to 92 °C. This time was manually recorded using a stopwatch

Heating Rate: The heating rate (HR) was calculated using the formula $HR = \frac{\Delta T}{t}$, where ΔT represents the temperature difference (°C) and t is the time taken (minutes) (Oluwole-Ojo et al., 2023)

Energy Consumption: Calculated using formula E = VIt. Where, E = Energy (Wh), V = voltage (V), I= current (A), t = time (min) (Pires et al., 2020). Voltage readings were obtained from a voltmeter placed in the electrical panel at one-minute intervals

System Performance Coefficient (SPC): The performance of the ohmic heating unit was evaluated by system performance coefficient (SPC) which is ratio of energy converted to useful work to energy provided to the system (Amitabh et al., 2019).

$$SPC = \frac{mC_p\Delta T}{\sum VIt}$$

Where, m = Mass of the sample (kg)(i.e. 7.224 kg approx), C_p = Specific heat capacity (3900 J/kg˚C), ΔT = Temperature difference (˚C), V = applied voltage (V), I = Ampere (A), t = Time of heating (minutes)

2.5 Chemical Analysis

Milk Composition Analysis: The determination of key components of milk, including fat, protein, and solid non-fat (SNF) content, was conducted using a Milkoscan instrument. This analytical tool is widely utilized in the dairy industry for its rapid and accurate analysis of milk composition.

Acidity: The acidity of all milk samples was measured following the standard procedure outlined in the Bureau of Indian Standards (BIS) Handbook (IS 1479-1961). The methodology described in this handbook was employed to ensure accurate and consistent measurements.

Alkaline Phosphatase: Alkaline phosphatase levels in the milk samples were determined in accordance with the procedure specified in ISO 11816:2013, which details the detection of alkaline phosphatase activity in milk and milk products. This method includes specific instructions for sample preparation, reaction conditions, and the measurement of alkaline phosphatase activity, ensuring the accuracy and reliability of the results obtained.

2.6 Microbial Analysis

Dilutions were prepared aseptically by transferring 1 ml of the milk sample into a test tube containing 9 ml of diluent, creating a 1:10 dilution, with further dilutions prepared sequentially.

Viable bacteria were enumerated following Houghtby et al. (1992), using Plate Count Agar and incubating at 37°C for 48 hours. For Yeast and Mold Count methodology from Marshall (1992) was used, employing Potato Dextrose Agar and incubating at 30°C for 5 days. Coliform enumeration utilized the pour plate method described by Houghtby et al. (1992), employing Violet Red Bile Agar and incubating at 37˚C for 48 hours.

2.7 Statistical Analysis

Response Surface Methodology (RSM) was utilized to optimize variables, specifically voltage and agitator speed. The experimental design was evaluated using Design Expert 13.0.5.0 software, which facilitated statistical analysis of response variables. A total of 52 runs were conducted, with 13 runs for each treatment at varying temperatures. Observed data were analyzed to derive polynomial regression equations, and their significance was assessed through ANOVA. Response surface diagrams were generated to visualize the interactions between independent and dependent variables.

3. RESULTS AND DISCUSSION

This section presents the results and discussion from a four-phase study investigating an ohmic heating setup for milk processing. Key phases included system design, optimization of heating parameters, quality assessment of treated milk, and performance evaluation.

Statistical analysis was conducted using Design Expert software to interpret the findings comprehensively.

3.1 Design and Fabrication of Batch Type Ohmic Heating System

The development of the batch-type ohmic heater involved creating a 7-liter stainless steel vessel, designed to optimize heating efficiency. The effective electrode surface area was determined to be 1670 cm², aligning with recommendations from Priyanka et al. (2018) to minimize fouling. The agitator, equipped with 12 blades arranged at three levels, had an effective surface area of 1427.55 cm², serving as a secondary electrode.

The effective rotation speed of the agitator was crucial for optimal performance, with literature suggesting a range of 10 to 100 rpm to avoid fat separation. A 12 V DC metal geared motor was selected, achieving a torque of 5.7 kg-cm, enabling effective mixing within the specified speed range.

Two methods for electrical current transfer to the rotating agitator were assessed. The first method, using an 8 mm bearing connected to a hook, resulted in sparking at elevated voltages and was discarded. The second method, employing a 2-copper ring slip ring and carbon brush assembly, was effective and reliable, enhancing the system's overall functionality.

Using stainless steel for all components was intentional, given its favorable properties in food processing. The complete assembly was mounted on a robust frame to ensure operational stability. The results indicate that the fabricated ohmic heating system is suitable for milk processing, confirming the effectiveness of the slip ring assembly in addressing electrical transfer challenges.

3.2 Response Surface Analysis of Heating Parameters

3.2.1 Heating time, energy consumption, and overall sensory score of cow Milk (at 75˚C)

The heating time for ohmically processed cow milk at 75˚C varied between 9.2 to 38 minutes. The shortest heating time of 9.2 minutes was recorded at a voltage of 35 V and agitator speed of 55 rpm. Analysis revealed significant effects of voltage ($P = .001$) and agitator speed ($P = .060$) on heating time, although no significant interaction effects were observed. The model's coefficient of determination (R^2) was 0.9923, indicating a strong fit.

Energy consumption ranged from 0.0551 to 0.1182 kWh. The lowest consumption was at 35 V and 55 rpm, while the highest was at 18 V and 55 rpm. Both voltage ($P = .001$) and agitator speed ($P = .004$) significantly influenced energy consumption. The model yielded an R^2 value of 0.9491, further establishing the significance of these factors.

The overall sensory score ranged from 6 to 8.5, with the highest score at 26.5 V and 55 rpm. Voltage significantly affected the sensory score ($P = .001$), while the effect of agitator speed was marginally significant ($P = .066$). The model's R^2 for sensory score was 0.8968, indicating reasonable fit.

The Response Surface Methodology (RSM) graphs illustrating the effects of voltage and agitator speed on the performance parameters can be seen in Figure 4.

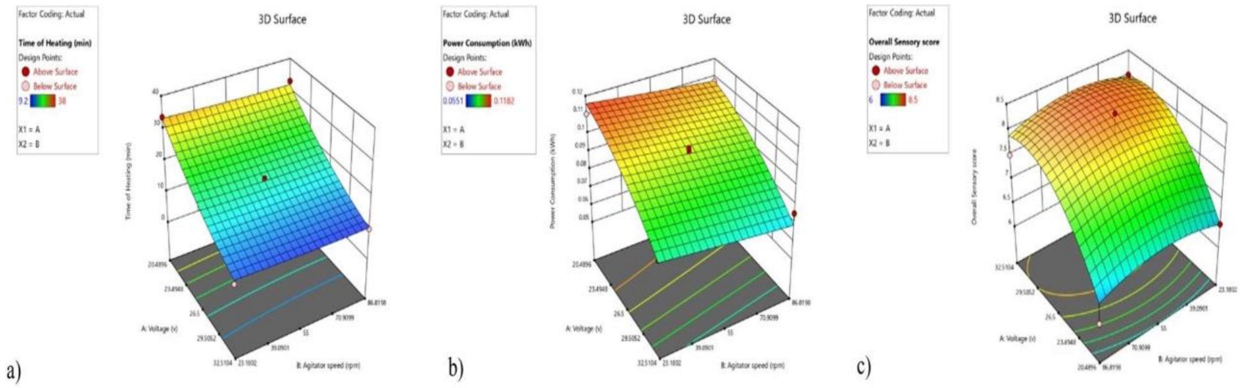

Figure 4.RSM Graphs of Effect of voltage and Agitator speed on a) Time of heating b) Energy Consumption C) Sensory score when cow Milk is heated to 75 ˚C

The rate of heating, energy consumption, and sensory quality are directly proportional and influenced by the speed of agitation and the applied voltage. Higher voltage and increased agitator speeds lead to shorter heating times due to enhanced heat transfer and greater current flow, resulting in lower energy consumption. The reduced heating time also minimizes the occurrence of burnt flavors, which contributes to higher sensory scores. Additionally, the composition of the milk significantly affects these parameters; Here, cow milk with lower fat content is utilized which reduces the insulating effect and further enhances heating efficiency.

Optimization identified settings of 32.5 V and 67 rpm, achieving a desirability of 0.847. Replication of the optimized process as per table 3 showed no significant differences for heating time ($P = .632$), energy consumption ($P = .609$), or overall sensory score ($P = .106$), confirming the reliability of the optimization.

Table 2: Validation of the optimized solution for heating Cow milk (at 75˚C)

Response	Predicted Value*	Actual Value@	Cal. t-Value#	P Value	Significance
Time of heating (minute)	10.126	10.071 ± 0.287	0.503	0.632	NS
Energy consumption (kWh)	0.072	0.071± 0.006	0.538	0.609	NS
Overall Sensory score	8.129	7.857 ± 0.378	1.903	0.106	NS

* Predicted values of Design Expert 13.0.1.0 package
@ Actual values are average of seven trials for optimized product
\# t-values found non-significant at 5 per cent level of significance
NS = non-significant
Tabulated t-value = 2.447 (cal. t-value less than tabulated value)

3.2.2 Heating time, energy consumption, and overall sensory score of cow Milk (at 92˚C)

At 92˚C, heating time varied from 12 to 55.4 minutes, with the minimum at 35 V and 55 rpm and the maximum at 18 V and 55 rpm. Both voltage ($P < .05$) and agitator speed ($P < .05$) significantly affected heating time, with an R^2 of 0.9923 and an F-value of 181.27 ($P < .001$).

Energy consumption at this temperature ranged from 0.1148 to 0.1928 kWh. Voltage and agitator speed both significantly influenced energy consumption ($P < .05$), yielding an R^2 of 0.9959.

The overall sensory score ranged from 5 to 8.5, with significant positive effects from voltage ($P < .05$). The optimization led to settings of 32.5 V and 63 rpm, with validation in table 3 confirming no significant differences ($P = .680$ for heating time, $P = .196$ for energy consumption, $P = .163$ for sensory score).

The Response Surface Methodology (RSM) graphs illustrating the effects of voltage and agitator speed on the performance parameters can be seen in Figure 5

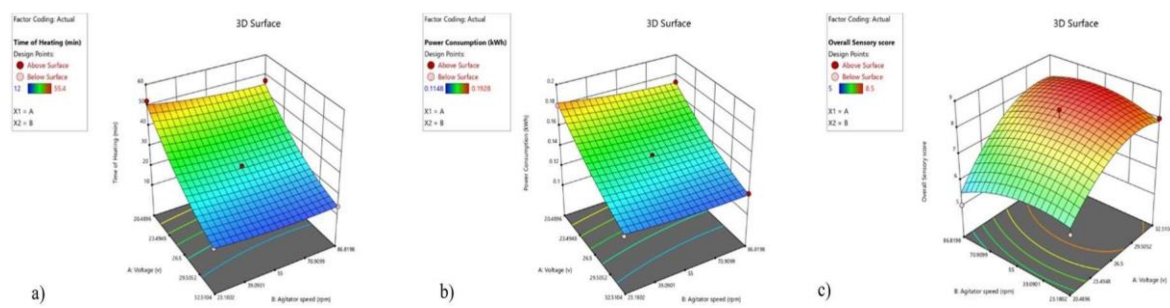

Figure 5: RSM Graphs of Effect of voltage and Agitator speed on a) Time of heating b) Energy Consumption C) Sensory score when cow Milk is heated to 92˚C

Table 3: Validation of the optimized solution for heating Cow milk (at 92˚C)

Response	Predicted Value*	Actual Value@	Cal. t-Value#	P Value	Significance
Time of heating (min)	13.711	13.657 ± 0.336	0.432	0.680	NS
Energy consumption (kWh)	0.12	0.118 ± 0.006	0.921	0.196	NS
Overall Sensory score	8.450	8.214 ± 0.393	1.585	0.163	NS

* Predicted values of Design Expert 13.0.1.0 package
@ Actual values are average of seven trials for optimized product
# t-values found non-significant at 5 per cent level of significance
NS = non-significant
Tabulated t-value = 2.447 (cal. t-value less than tabulated value)

3.2.3 Heating time, energy consumption, and overall sensory score of Buffalo Milk (at 75˚C)

For buffalo milk at 75˚C, heating time ranged from 12 to 38.4 minutes. The shortest time was at 40 V and 55 rpm, while the longest was at 20 V and 55 rpm. Voltage significantly influenced heating time ($P = .01$), with an R^2 of 0.990.

Energy consumption ranged from 0.0802 to 0.1458 kWh, significantly affected by voltage ($P = .01$) and agitator speed ($P = .05$). The model showed an excellent fit ($R^2 = 0.998$).

Sensory scores varied from 6 to 8.5, with voltage significantly influencing the scores (P = .02). The optimal conditions identified were 37 V and 43 rpm, achieving a desirability of 0.884. validation in table 4 confirming no significant differences

The rate of heating, energy consumption, and sensory quality are directly proportional and influenced by the speed of agitation and the applied voltage. Higher voltage and increased agitator speeds result in shorter heating times due to enhanced heat transfer and greater current flow, which in turn reduces energy consumption. The decreased heating duration also minimizes the development of burnt flavors, contributing to improved sensory scores. Conversely, the composition of the milk significantly impacts these parameters; in this, buffalo milk with higher fat content is utilized, which increases the insulating effect and reduces heating efficiency. This results in longer heating times and higher energy consumption.

The Response Surface Methodology (RSM) graphs illustrating the effects of voltage and agitator speed on the performance parameters can be seen in Figure 6.

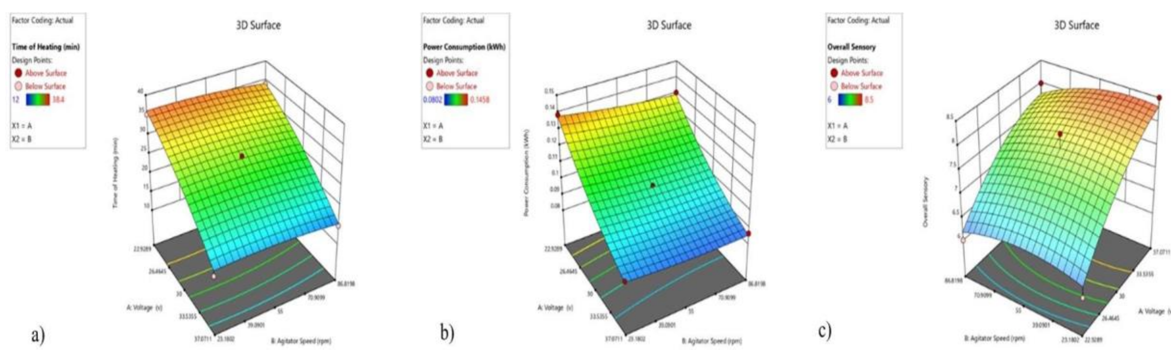

Figure 6: RSM Graphs of Effect of voltage and Agitator speed on a) Time of heating b) Energy Consumption C) Sensory score when Buffalo Milk is heated to 75˚C

Table 4: Validation of the optimized solution for heating Buffalo milk (at 75˚C)

Response	**Predicted Value***	**Actual Value@**	**Cal. t-Value#**	**P Value**	**Significance**
Time of heating (minute)	16.755	16.529 ± 0.359	1.668	0.146	NS
Energy consumption (kWh)	0.087	0.085± 0.005	1.109	0.309	NS
Overall Sensory score	8.337	8.071± 0.345	2.036	0.087	NS

* Predicted values of Design Expert 13.0.1.0 package
@ Actual values are average of seven trials for optimized product
# t-values found non-significant at 5 per cent level of significance
NS = non-significant
Tabulated t-value = 2.447 (cal. t-value less than tabulated value)

3.2.3 Heating time, energy consumption, and overall sensory score of Buffalo Milk (at 92˚C)

Heating time at 92˚C ranged from 15 to 58 minutes (Table 4.17), with both voltage (P = .01) and agitator speed (P = .01) significantly affecting the duration. The model had an R^2 of 0.9948 and an F-value of 266.64.

Energy consumption ranged from 0.1108 to 0.2018 kWh (Table 4.17), with significant effects from both voltage (P = .01) and agitator speed (P = .01). The model fit was strong (R^2 = 0.9877).

The Response Surface Methodology (RSM) graphs illustrating the effects of voltage and agitator speed on the performance parameters can be seen in Figure 7

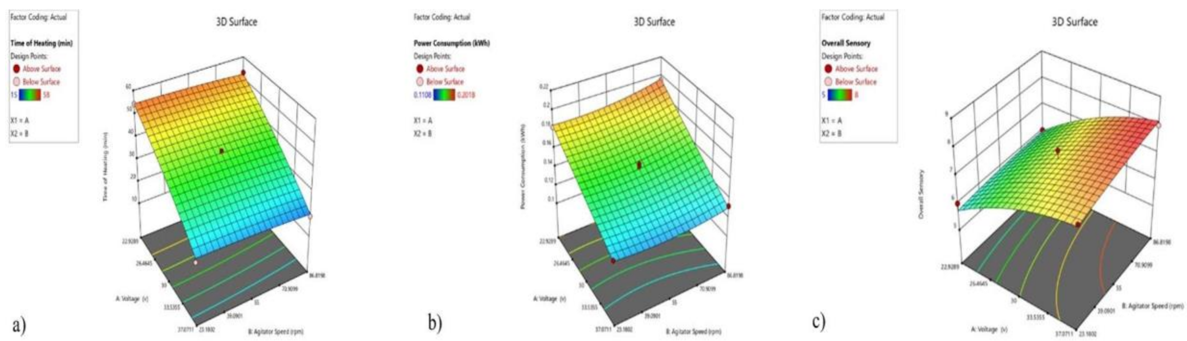

Figure 7: RSM Graphs of Effect of voltage and Agitator speed on a) Time of heating b) Energy Consumption C) Sensory score when Buffalo Milk is heated to 92˚C

The overall sensory scores varied from 5 to 8, influenced by both voltage (P = .01) and agitator speed (P = .01). The optimization process led to conditions of 37 V and 69 rpm, yielding a desirability of 0.894. Validation in table 5 confirmed no significant differences (P = .875 for heating time, P = .857 for energy consumption, P = .457 for sensory score)

Table 5: Validation of the optimized solution for heating Buffalo milk (at 92˚C)

Response	**Predicted Value***	**Actual Value@**	**Cal. t-Value#**	**P Value**	**Significance**
Time of heating (minute)	21.025	21.00 ± 0.404	0.164	0.875	NS
Energy consumption (kWh)	0.126	0.126 ± 0.004	0.188	0.857	NS
Overall Sensory score	8.0	7.857 ± 0.476	0.795	0.457	NS

* Predicted values of Design Expert 13.0.1.0 package
@ Actual values are average of seven trials for optimized product
# t-values found non-significant at 5 per cent level of significance
NS = non-significant
Tabulated t-value = 2.447 (cal. t-value less than tabulated value)

3.3 Quality Evaluation of Ohmically Heated Milk

3.3.1 Physico-Chemical Properties

Analysis of the physico-chemical properties of ohmically heated milk indicated slight variations compared to raw milk (Table 6). Cow milk's protein content decreased from 3.1% to 2.84% after heating, while buffalo milk showed a reduction from 3.81% to 3.72%. Fat content also decreased slightly, attributed to the lack of immediate cooling. Acidity increased from 0.133% in raw cow milk to 0.142% at 92˚C. Alkaline phosphatase tests confirmed effective pasteurization, indicating that the observed changes were primarily due to processing conditions.

Table 6: Comparison of the physico-chemical properties between raw and ohmically heated Cow and Buffalo milk

Particulars	**Raw Cow milk**	**Ohmic heated Cow milk (at 75˚C)**	**Ohmic heated Cow milk (at 92˚C)**	**Raw Buffalo milk**	**Ohmic heated Buffalo milk (at 75˚C)**	**Ohmic heated Buffalo milk (at 92˚C)**
Fat %	4.32 ± 0.187	4.30 ± 0.0173	4.29 ± 0.023	6.17 ± 0.015	6.15 ± 0.023	6.14 ± 0.021
Protein %	3.1 ± 0.034	2.91 ± 0.029	2.84 ± 0.36	3.81 ± 0.028	3.77 ± 0.029	3.72 ± 0.025
SNF %	8.55 ± 0.030	8.24 ± 0.023	8.1 ± 0.031	9.15 ± 0.040	9.12 ± 0.021	9.09 ± 0.037
Acidity %LA	0.133 ± 0.002	0.143 ± 0.001	0.142 ± 0.003	0.149 ± 0.003	0.152 ± 0.001	0.154 ± 0.002
Alkaline phosphatase test	Positive	Negative	Negative	Positive	Negative	Positive

3.3.2 Microbial Analysis

Microbial evaluations demonstrated significant reductions in microbial load. Aerobic Plate Counts for cow milk were recorded at 4.43 log CFU/ml at 75˚C, reducing to 4.31 log CFU/ml at 92˚C. Buffalo milk showed similar results, indicating effective microbial control. Coliform and yeast & mold counts were undetectable in heated samples, attributed to the electroporation effects during ohmic heating. Processing times for cow and buffalo milk ranged between 10 to 13 minutes and 16 to 21 minutes, respectively.

3.4 Performance Evaluation of The Developed Ohmic Heating System

3.4.1 Heating Times

The total heating time required for cow and buffalo milk at two different temperatures was systematically evaluated (Figure 8). The results indicated that buffalo milk necessitated a longer heating time compared to cow milk, primarily due to its higher fat content, which functions as an insulator during ohmic heating. Higher applied voltages correlated with the increased heating times for buffalo milk, underscoring the influence of milk composition on heating efficiency. In contrast, cow milk heated more rapidly owing to its lower fat content.

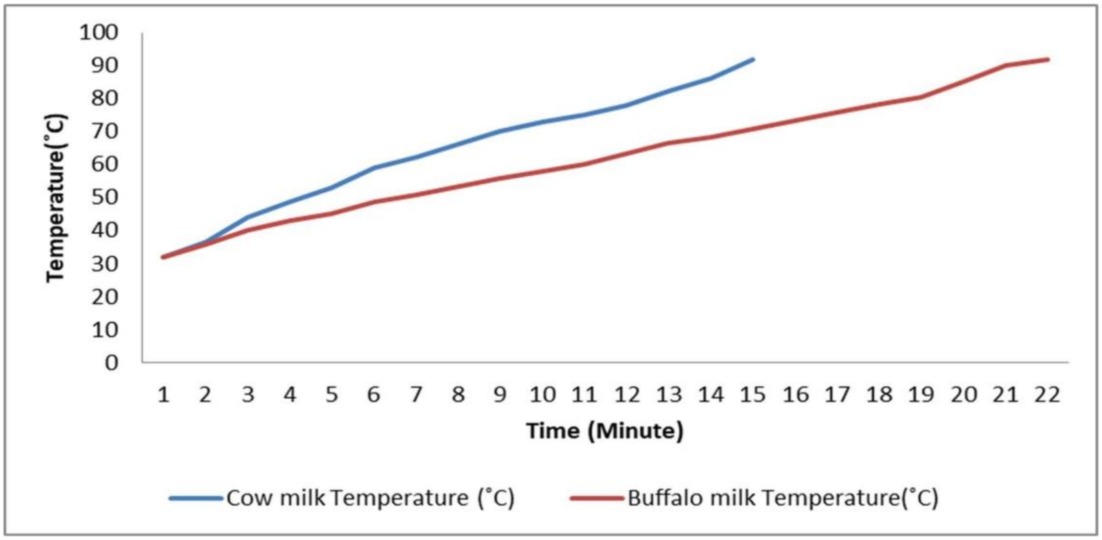

Figure 8: Temperature profile during ohmic heating

3.4.2 Temperature Profile

The temperature profiles of cow and buffalo milk during ohmic heating illustrated distinct behaviors (Figure 8). Cow milk demonstrated a faster initial temperature rise compared to buffalo milk, attributable to its lower fat and total solids content. As heating progressed, the rate of temperature increase for both types of milk gradually declined. This phenomenon can be explained by the transition of fat content into a liquid state, affecting the thermal conductivity of the milk. Additionally, higher applied voltages facilitated increased currents, enhancing the heating rates observed for both milk types.

3.4.3 Current Profile

The current profiles during the heating process exhibited notable differences between cow and buffalo milk (Figure 9). Cow milk showed a continuous increase in current with both time and temperature, reflecting a steady increase in electrical conductivity. In contrast, buffalo milk's current profile revealed an initial decrease within the temperature range of 32 to 60˚C. This reduction can be linked to the liquefaction of fat and the initial fouling of the agitator's surface. Both milk types of experienced fluctuations in current over time, indicating variations in electrical conductivity throughout the heating process.

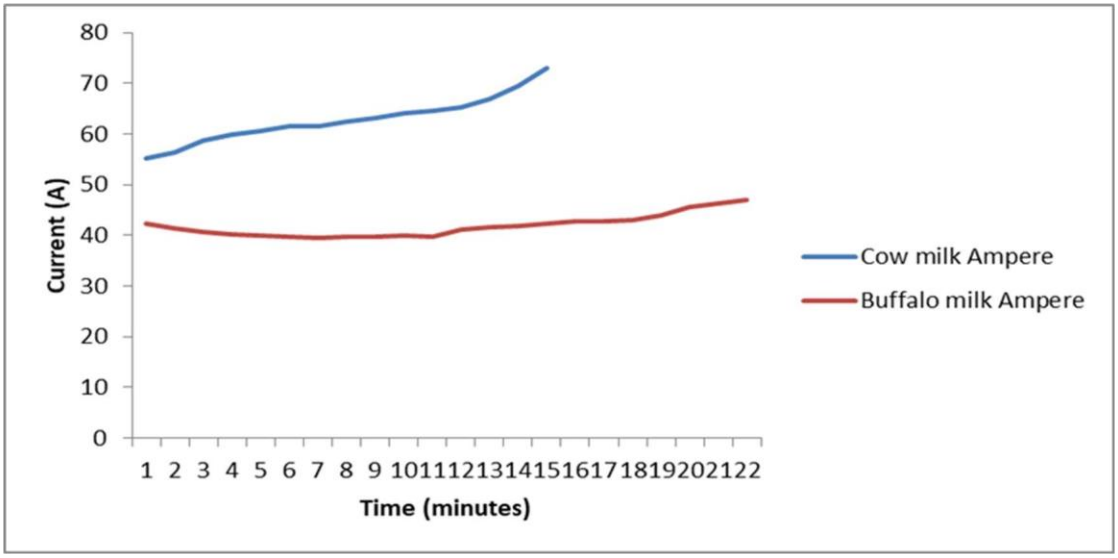

Figure 9: Current profile during ohmic heating

3.4.4 Heating Rate

The heating rate was significantly influenced by the interplay of current and resistance within the system. Electrical heating efficiency is proportional to both current and the square of resistance. Throughout the trials, it was evident that electrical resistance increased due to the effects of the agitator, leading to a reduction in current and a subsequently lower heating rate. The average heating rate was calculated at 4.29˚C/min for cow milk, while buffalo milk exhibited a reduced average heating rate of 2.85˚C/min. These findings highlight the critical role of current and resistance in determining the heating dynamics of the milk samples.

3.4.5 System Performance Coefficient

The system performance coefficient (SPC), representing the ratio of energy required for heating to the energy supplied, was calculated to evaluate system efficiency. Cow milk exhibited a higher SPC compared to buffalo milk, with values of 58.79 and 58.44 at temperatures of 75˚C and 92˚C, respectively. In contrast, buffalo milk showed lower SPC values of 46.71 at 75˚C and 50.10 at 92˚C. The disparity in SPC can be attributed to the insulating effects of the higher fat content in buffalo milk, which hampers efficient heat transfer during the ohmic heating process.

3.4.6 Fouling on the Agitator

Fouling on the agitator surface was a recurring observation during the heating process. The fouling primarily consisted of proteins and minerals from the milk, leading to a decrease in current supply and consequently affecting the heating rate. This reduction in current impaired the efficiency of the heating process and posed potential risks to the nutritional quality of the milk. The impact of fouling was significant, indicating the need for effective cleaning protocols to maintain optimal system performance.

3.4.7 Effect on the Surface of Agitator

Post-trial inspections consistently revealed the formation of fouling on the agitator surface (Figure 10). Cleaning procedures involving water and soap were employed to remove these deposits after each trial. Visual assessments of the agitator surface illustrated the extent of fouling resulting from the ohmic heating process. Furthermore, the presence of such fouling raises concerns regarding the potential transfer of stainless-steel material from the agitator into the processed milk, thus impacting product safety and quality.

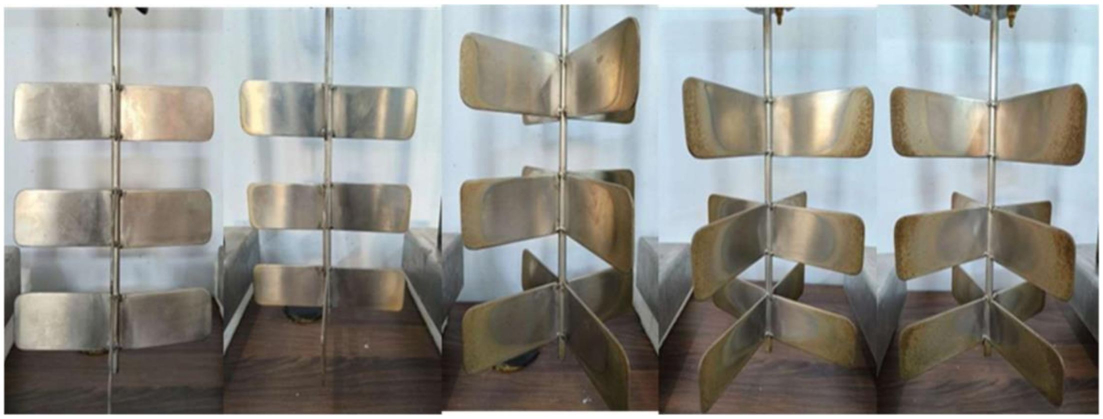

Figure 10: Effect on the surface of the agitator after ohmic heating of milk

4. CONCLUSION

The study successfully developed and assessed a batch-type ohmic heating system for the thermal processing of cow and buffalo milk, focusing on heating efficiency and product quality. The system achieved heating rates of 4.29°C/min for cow milk and 2.85°C/min for buffalo milk, demonstrating its capability for rapid heating. Notably, cow milk exhibited lower energy consumption and higher system performance coefficients (58% at 75°C and 50% at 92°C) compared to buffalo milk, indicating greater overall efficiency. In terms of quality, ohmic heating resulted in slight reductions in protein and fat content, with effective pasteurization confirmed by alkaline phosphatase tests. Significant reductions in microbial load were observed, with undetectable coliform and yeast counts in heated samples. However, the study identified fouling on the agitator as a significant challenge, impacting current supply and heating efficiency, primarily due to the deposition of proteins and minerals. This necessitates effective cleaning protocols to maintain optimal system performance and ensure product safety. Overall, the developed ohmic heating system exhibited high efficiency and rapid heating capabilities, indicating its potential for application in dairy processing. Future research should focus on addressing fouling issues and further optimizing the system for commercial viability.

5. FUTURE RESEARCH DIRECTIONS AND STUDY LIMITATIONS

The findings of this study on a batch-type ohmic heating system for milk processing open several avenues for future research and highlight important limitations. Future investigations should focus on developing effective strategies to minimize fouling on the agitator, exploring the scalability of the system for commercial applications, and assessing its performance with various milk types, such as goat or sheep milk. Further optimization of operating parameters and long-term quality studies will be crucial for ensuring product consistency and safety. However, the study is limited by its focus on a single batch system, which may not reflect the dynamics of continuous processing, and the use of only cow and buffalo milk, which could limit the applicability of the results to other milk types. Additionally, the evaluation was conducted under controlled conditions, which may not fully represent real-world scenarios, and some statistical analyses may require larger sample sizes for greater generalizability.

Addressing these limitations while pursuing the outlined future implications will enhance the effectiveness of ohmic heating technology in the dairy industry.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

Rohankumar Solanki (Author 1) conceptualized and executed the research, including the design and testing of the batch type ohmic heating system. He was supervised by Istiyakhusen Chauhan (Author 2), Suneeta Pinto (Author 3), and Sunil Patel (Author 4), who provided guidance on experimental design and facilitated access to necessary materials and facilities. Amit Patel (Author 5) conducted the statistical analysis of the data, ensuring the validity of the findings. Arpita Rathva (Author 6) assisted with the experimental trials and contributed to data collection. All authors participated in the interpretation of results and contributed to the manuscript preparation.

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