DOI: http://dx.doi.org 10.22104/ift.2025.7710.2222

Innovative Food Technologies

Innovative Food Technologies, 12(3), 305-319, Spring 2025

Iranian Research Organization for Science and Technology (IROST)

Comparative analysis of ohmic heating and conventional evaporation for milk concentration: Quality parameters, energy and exergy efficiencies, GHG emission, and sensory evaluation

Hosain Darvishi[1*], Mobin Mohammadi[1], Nasser Behroozi-Khazaei[1], Hossein Jahani-Azizabadi[2], Moslem Solaimani[1]

[1] Department of Biosystems Engineering; Faculty of Agriculture; University of Kurdistan, Sanandaj, Kurdistan, Iran
[2] Department of Animal Science; Faculty of Agriculture; University of Kurdistan, Sanandaj, Kurdistan, Iran

ARTICLE INFO

Keywords:
Ohmic evaporation,
sustainable dairy processing,
exergy analysis,
carbon footprint,
milk quality

ABSTRACT

This study presents a comparative analysis of ohmic and conventional heating methods for milk concentration, evaluating processing kinetics, energy-exergy efficiency, quality parameters, environmental footprint, and sensory attributes. Ohmic heating outperformed conventional methods, slashing processing time by 1.88–4.33 times and reducing energy consumption by 10.5–17 times, while achieving remarkably higher energy and exergy efficiencies (42.71–57.79% and 9.48–12.75%, respectively) compared to conventional heating (5.42% and 1.18%). Notably, ohmic heating led to less significant pH alterations (3.87 - 6.97%) compared to conventional heating method (10.37%). However, it induced more noticeable in color. Sensory attributes indicated that a voltage gradient of 20 V/cm provided the optimal balance of taste, texture, and aroma. Crucially, ohmic heating reduced CO2 emissions by 90.3–95.6% compared to conventional heating. These results establish ohmic heating as a sustainable, energy-efficient alternative for industrial milk concentration, addressing critical challenges in food processing sustainability while maintaining product quality.

How to cite this article:
Darvishi, H., Mohammadi, M., Behroozi-Khazaei, N., Jahani-Azizabadi, H., Solaimani, M. (2025). Comparative analysis of ohmic heating and conventional evaporation for milk concentration: Quality parameters, energy and exergy efficiencies, GHG emission, and sensory evaluation. *Innov. Food Technol., 12(3), 305-319*
DOI: http://dx.doi.org 10.22104/ift.2025.7710.2222

* Corresponding author:
E-mail addresses: h.darvishi@uok.ac.ir
(Received Date: 28 June 2025, Revised Date: 19 July 2025, Accepted Date: 20 July 2025)

1. Introduction

Milk, a globally consumed nutrient-rich food, provides essential proteins, vitamins, and minerals vital for human health. However, its high moisture content and perishability necessitate advanced processing technologies to ensure safety, extend shelf life, and preserve intrinsic quality. Conventional thermal processing methods, including pasteurization, sterilization, and evaporation, remain staples in the dairy industry. While effective for microbial inactivation, these methods often compromise nutritional and sensory qualities due to prolonged exposure to high temperatures, leading to Maillard reactions, protein denaturation, and vitamin degradation (Coutinho et al., 2018). Furthermore, conventional evaporation—a key step in producing concentrated dairy products like milk powder and condensed milk—is energy-intensive, contributing to high operational costs and significant environmental footprints due to greenhouse gas emissions and reliance on non-renewable energy sources.

In response to growing demands for sustainable and quality-focused food processing, innovative thermal technologies have emerged. Ohmic heating (OH), also known as Joule heating, is a transformative technique in which alternating electrical currents pass directly through a food matrix, producing rapid and volumetric heating as a result of the product's electrical resistance. Unlike conventional heating, which relies on indirect heat transfer via surfaces, OH minimizes thermal gradients, ensuring uniform temperature distribution while drastically reducing processing times (Alkanan et al., 2021; Sun et al., 2024). This method has demonstrated exceptional potential in preserving heat-sensitive nutrients, bioactive compounds, and sensory attributes in dairy products, attributed to its ability to achieve target temperatures faster than traditional methods (Norouzi et al., 2021; Cappato et al., 2017).

The advantages of OH extend beyond quality preservation. Its inherent energy efficiency—stemming from direct heat generation within the product—significantly reduces energy losses to the environment, making it a promising candidate for sustainable industrial scaling (Fadavi et al., 2018). However, optimizing OH systems requires rigorous analysis of operational parameters such as voltage gradient, electrical conductivity, and product geometry, which influence heating uniformity and energy utilization (Varghese et al., 2014; Alkanan et al., 2021). For milk concentration, a process critical to reducing transportation costs and enhancing product versatility, OH has the potential to revolutionize conventional evaporation. Traditional methods, such as multi-stage vacuum evaporation, demand substantial energy inputs and often compromise functional properties like solubility and flavor (Rocha et al., 2020; Sürme and Sabancı, 2021). In contrast, preliminary studies suggest that OH achieves comparable concentration efficiencies while preserving the nutritional and sensory profiles of the samples more effectively (Balthazar et al., 2022; Darvishi et al., 2020b).

Despite these promising insights, the application of OH in milk concentration remains underexplored. Existing studies, such as those by Parmar et al. (2018), and Sürme and Sabancı (2021), offer limited scope, focusing narrowly on single voltage gradients (7–13 V/cm) and basic quality metrics (e.g., free fatty acid content). A systematic evaluation of OH's engineering performance (e.g., energy/exergy efficiency, thermal losses), environmental impact (e.g., carbon footprint reduction), and comprehensive product quality (e.g., pH, color, microbial safety, and sensory acceptability) is absent. Furthermore, no prior research has holistically compared OH with conventional evaporation across these multidimensional criteria, leaving critical gaps in understanding its industrial viability.

This study pioneers a comparative analysis of ohmic (OH) and conventional methods for milk concentration, highlighting four innovations: analyzing voltage gradients (15–22.5 V/cm) and their synergistic effects on energy consumption, processing kinetics, and energy efficiency; quality profiling (pH, color, sensory properties); life cycle assessment (CO2 emissions); and exergy analysis to identify sources of irreversibility.

2. Materials and methods

2.1. Fresh milk preparation

Fresh cow milk was obtained from the educational farm of Kurdistan University located in Sanandaj, Kurdistan. The milk samples were immediately transferred to the laboratory, where processing experiments were conducted. To minimize compositional changes, the samples were stored at 8 °C throughout the experimental procedures. The initial moisture content of the milk was determined as 7.44 kg- water/kg-dry matter using calculations based on the standard oven-drying method.

2.2. Ohmic heating system

The schematic diagram and photographic image of the ohmic heating system are shown in Fig.1. The ohmic heating system consisted of a Pyrex glass cell (10 × 10 × 20 cm), two 316L stainless steel electrodes (2 mm thickness, 10 cm apart), a variable voltage transformer (2 kW, Omega, Korea), a power analyzer (DW-6090A, Lutron, Thailand), two Teflon-coated temperature sensors for monitoring product temperature with an accuracy of 0.01 °C, a digital scale (GF-3002A, A&D, Japan) with a precision of ±0.01 g for measuring mass changes, an electronic data transfer board for real-time recording, and a computer. Ohmic heating experiments were conducted at four voltage levels: 15, 17.5, 20, and 22.5 V/cm with three replications. The sinusoidal alternating current from the city power supply (60 Hz) was used to generate the electric fields. For each trial, 250 mL of fresh milk was utilized. The experiments were carried out until the moisture content of the milk decreased to 2.38 kg-water/kg-dry matter. The parameters of temperature, voltage, current, and milk mass were measured and recorded at 1s intervals. After each experiment, the cell and electrodes were washed with tap water.

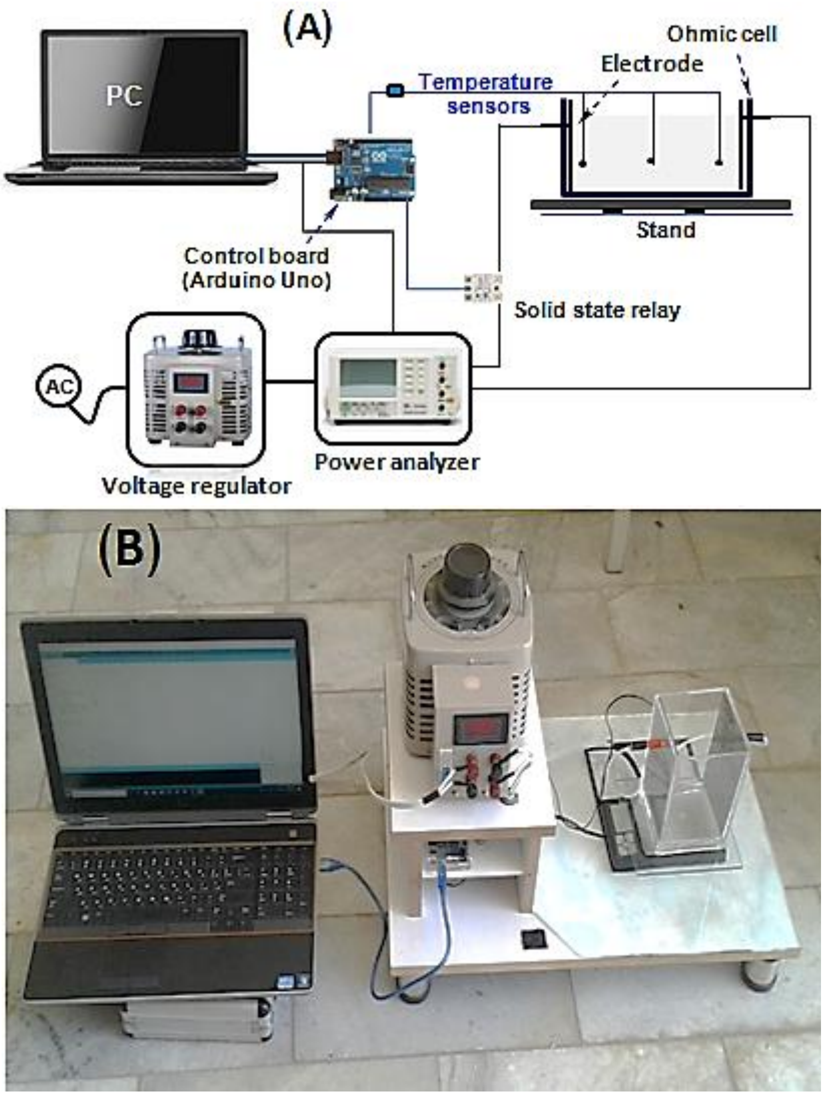

Fig 1. (A) Schematic diagram and (B) picture of ohmic heating system

2.3. Conventional heating system

The Pyrex glass chamber was placed on a laboratory hot plate (Iran Azma, Iran) with a power consumption of 1000 watts. The product temperature was measured using NTC temperature sensors at 1 s intervals. A digital scale was used to measure the variations in sample mass and determine the completion of the heating process. In each experiment, 250 mL of fresh milk was used. The heating process was stopped when the moisture content of the milk reached 2.38 kg-water/kg-dry matter.

2.4. pH measurement

pH of fresh and processed samples was measured using a pH-meter (Atron Co., Iran). The pH change was calculated as follows:

$$\Delta pH = \left(\frac{pH_0 - pH_f}{pH_0}\right) \times 100 \quad (1)$$

Where, pH_0 is the pH of the fresh sample, pH_f is the pH of the processed sample, and ΔpH is the pH change (%).

2.5. Color evaluation

The color parameters (L*a*b*) of processed and fresh milk were measured using an image processing system. The total color change of the sample was calculated as follows:

$$\Delta E = \sqrt{(a_f - a_0)^2 + (b_f - b_0)^2 + (L_f - L_0)^2} \quad (2)$$

Where ΔE is the total color change (-), L is the brightness, a is the red-green component, b is the yellow-blue component, and the subscripts f and 0 represent the final and initial products, respectively.

2.6. Sensory evaluation

The sensory properties of milk samples were performed by a semi-trained sensory panel. Sensory analysis of milk samples was performed 3 h after concentration. Five panelists (n = 5) were asked to evaluate the odor, taste, and color of concentrated milk. A 5-hedonic scale (Scale: 1-dislike extremely; 2-dislike slightly; 3-neither like nor dislike; 4-like slightly; 5-like extremely) was used by panelists to evaluate the sensory attributes of experimental samples. To assess more accurately, the range of scores was selected between 1 and 100, as shown in Table 1. The mean of evaluated sensory parameters was determined as the overall acceptance.

Table 1. Five hedonic scale with ranges of scores for sensory evaluation

Scale	Ranges of scores	Level of acceptability
1	0-19.99	Dislike extremely
2	20-39.99	Dislike slightly
3	40-59.99	Neither like nor dislike
4	60-79.99	Like slightly
5	80-100	Like very much

2.7. Energy consumption and efficiency

The energy consumption of the ohmic and conventional heating systems was calculated as follows (Aydin et al., 2020):

$$E_{OH} = \sum VI\Delta t \quad (3)$$

$$E_{Conv} = P \times t \quad (4)$$

where, V is the electrical voltage (V), I is the electrical current (A), Δt is the time step (s) for measuring voltage and current parameters, P is the power consumption of the laboratory hot plate (W), t is the duration of the conventional heating process (s), E_{OH} and E_{Con} are the energy consumption by the ohmic and conventional system (J), respectively.

The specific energy consumption was calculated as follows:

$$SEC = \frac{E}{m_w} \quad (5)$$

where, E is the energy consumption by heating system (J), Mw is the water mass evaporated from sample (kg), and SEC is the specific energy consumption by the heating system (J/kg water).

The energy efficiency was calculated as follows (Darvishi et al., 2015):

$$\eta_{en} = \left(\frac{m_0 C_p \Delta T + m_w h_{fg}}{E}\right) \times 100 \quad (6)$$

where, m_0 is the initial mass of sample (kg), C_p is the specific heat capacity of sample (J/kg K), ΔT is the difference between initial and final temperatures of sample during sensible heating period (°C), h_{fg} is the latent heat (J/kg water), and η_{en} is the energy efficiency of heating systems (%).

The specific energy loss was calculated as follows:

$$SEL = \left(1 - \frac{\eta_{en}}{100}\right) \times \frac{E}{m_w} \quad (7)$$

Where SEL is the specific energy loss (MJ/kg water).

2.8. Exergy efficiency and improvement potential

The exergy efficiency of heating system was calculated as follows (Darvishi et al., 2015):

$$\eta_{ex} = \left(\frac{EX_{out}}{EX_{in}}\right) \times 100 = \left(\frac{m_p ex_p + m_w \left(1 - \frac{T_\infty}{T_m}\right) h_{fg}}{m_f ex_f + 0.99 \times E}\right) \times 100 \quad (8)$$

where, EX_{in} and EX_{out} are the input and output exergy from cell heating (J), m_f and m_p are the initial and final masses of sample (kg), ex_f and ex_p is the specific exergy of initial and final sample (J/kg), T_m is the sample temperature during evaporation process (K), T_∞ is ambient temperature (K), and η_{ex} is the exergy efficiency (%).
The specific exergy of initial and final sample was calculated as follows:

$$ex_f = C_p\left[T_f - T_\infty - T_\infty \times \ln\left(\frac{T_f}{T_\infty}\right)\right] \quad (9)$$

$$ex_p = C_p\left[T_m - T_\infty - T_\infty \times \ln\left(\frac{T_m}{T_\infty}\right)\right] \quad (10)$$

Where, T_f is the initial temperature of sample (K).

The specific exergetic improvement potential can be calculated as follows (Sürme and l Sabancı, 2021):

$$IP = (1 - \eta_{ex})\left(\frac{EX_{in} - EX_{out}}{m_w}\right) \quad (11)$$

Where, IP is the specific exergetic improvement potential (J/kg water). The ambient temperature was considered to be 20 °C.

2.9. Environmental impact

The environmental analysis of any system is carried out to analyze its impact on the environment in terms of greenhouse gas (GHG) emissions. The GHG emissions from the heating system were calculated using an indirect method based on electricity consumption during the heating process. The specific CO2 emission calculated as follows (Motevali and Tabatabaei, 2017):

$$S_{GHG} = K_i \times \frac{SEC}{\eta_P \times \eta_D} \times OF \quad (12)$$

Where S_{GHG} is the specific CO_2 emission (kg CO_2/kg water), k_i is the emission factor (kg/J), η_p is the distribution lines efficiency (0.90), η_p is the efficiency of power plant (0.80), OF is the oxidation factor (-). The GHG emission factor is influenced by the energy mix used for power generation. In Iran's western province, power plants primarily operate on a combined-cycle system. According to Nazari et al. (2010), the emission factors from fossil fuels, specifically gas oil, used in combined-cycle power plants in Iran is 172.77 g/MJ for CO_2. An oxidation factor (OF) with a value of one was employed in the calculations (Calvo and Domingo, 2017).

2.10. Statistical analysis

The results were reported in the form of mean values ± standard error. The experiments were conducted in three replications. ANOVA and Duncan's mean comparison test at a significance level of 5% were used to examine the effect of voltage gradient on the measured parameters. SPSS software was used for statistical analyses.

3. Results and discussion

3.1. Heating rate and processing time

The changes in milk temperature during the concentration process are shown in Fig. 2. The temperature of the milk samples reached 89.5 ± 1°C and then remained constant until the end of the heating process. It is noted that the laboratory is situated at an altitude of approximately 1459 meters above sea level. At this elevation, the boiling point of water is 90.7 ± 0.5 °C. The sample temperature increased more rapidly during the ohmic heating process compared to conventional heating. As depicted in Fig. 3, the heating rate by the ohmic heating method was 2.6 to 6 times higher than that of conventional heating. By increasing the voltage gradient from 15 to 22.5 V/cm, the heating rate increased from 10.63°C/min to 24.68°C/min. The heating rate increased due to the higher applied voltage gradient, as a greater voltage results in more electrical energy being dissipated within the sample, ultimately causing a faster temperature rise (Darvishi et al., 2015; Duguay et al., 2016).

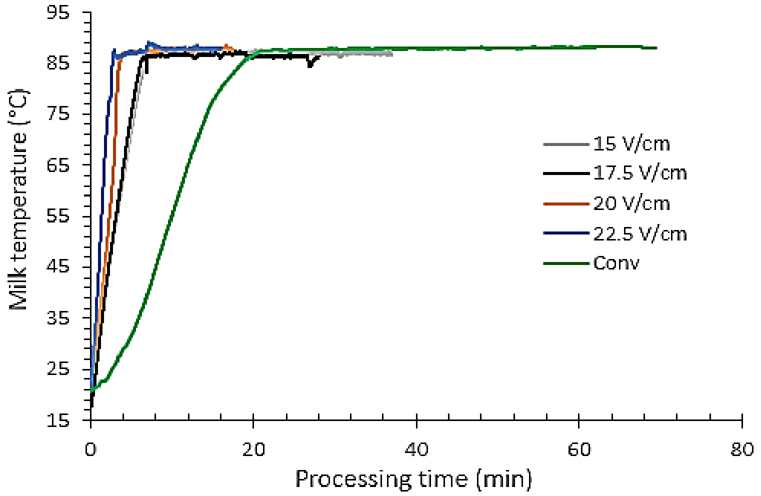

Fig 2. Temperature of milk during concentration process at different heating conditions

The processing time for milk concentration using ohmic heating and conventional heating methods is shown in Fig. 3. The processing time at ohmic heating method decreased with increasing applied voltage gradient. Concentration process took 37.01 min when using a voltage gradient of 15 V/cm, 28.10 min for 17.5 V/cm, 17.50 min for 20 V/cm, and 16.05 min for 22.5 V/cm. Furthermore, the processing time for the conventional heating method was 69.40 min. The processing time in the ohmic heating method was 1.88 to 4.33 times shorter than conventional heating. In the conventional heating method, due to the low heat transfer coefficients of the substance, the thermal energy is transferred to the milk samples at a lower rate, which ultimately leads to a decrease in the evaporation rate and an increase in processing time (Hosainpour et al., 2015; Fadavi et al., 2018). Meanwhile, in the ohmic heating method, thermal energy is directly generated inside the material and is affected by changes in the thermal properties of the food materials to a lesser extent than the conventional heating method (Cokgeme et al., 2017; Panirani et al., 2023). Sürme and Sabancı (2021) reported that the processing time for milk at a voltage gradient of 11 V/cm in the ohmic heating method was 1.33 times shorter compared to the processing time in the conventional heating method.

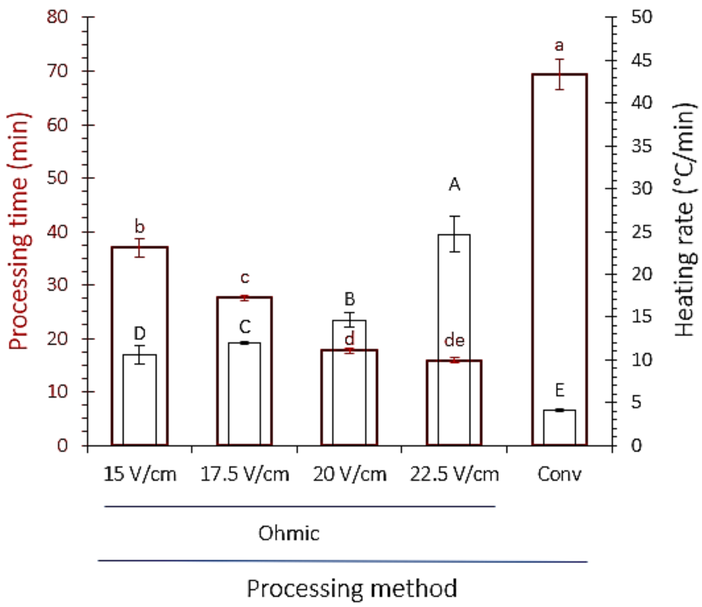

Fig 3. Processing time and heating rate of ohmic and conventional milk concentration technologies
Different superscripts in the same parameter indicate significant differences ($p < 0.05$).

3.2. pH changes

The effects of processing method and voltage gradient on changes in pH of concentrated milk samples are shown in Fig. 4. Statistical analysis indicates that the pH values of processed samples are significantly influenced by the voltage gradient and the processing method employed ($p < 0.05$). The pH values of samples processed by the ohmic heating method ranged from 6.01 to 6.21 on average, whereas the average pH value of samples processed by the conventional heating method was 5.79. The pH values of processed samples were lower than those of fresh samples in both methods. In other words, the pH values of processed samples were 3.87% to 6.97% lower than that of the fresh sample, while in the conventional heating method, the pH value was 10.37% lower than that of the fresh sample. The decrease in milk pH can be attributed to changes in the chemical composition of milk and an increased concentration of organic compounds and acids (Aydogdu et al., 2023). During the concentration process, water in the milk evaporates, resulting in a decrease in the milk volume. As the milk volume decreases, the concentration of acids and other organic compounds in the milk increases, leading to a decrease in pH. Aydogdu et al. (2021) reported that the increase in ionic strength directly influences the hydrogen ion activity and, consequently, the pH. Therefore, during evaporation, the pH of milk decreases and ionic strength increases, causing a reduction in the activity coefficient of soluble calcium and phosphate. According to literature the literature, high-temperature milk processing decreases the soluble calcium and phosphate content, accompanied by hydrogen release, resulting in a pH reduction (Lucey et al., 2009; Aydogdu et al., 2023; and Schmitt et al., 1993).

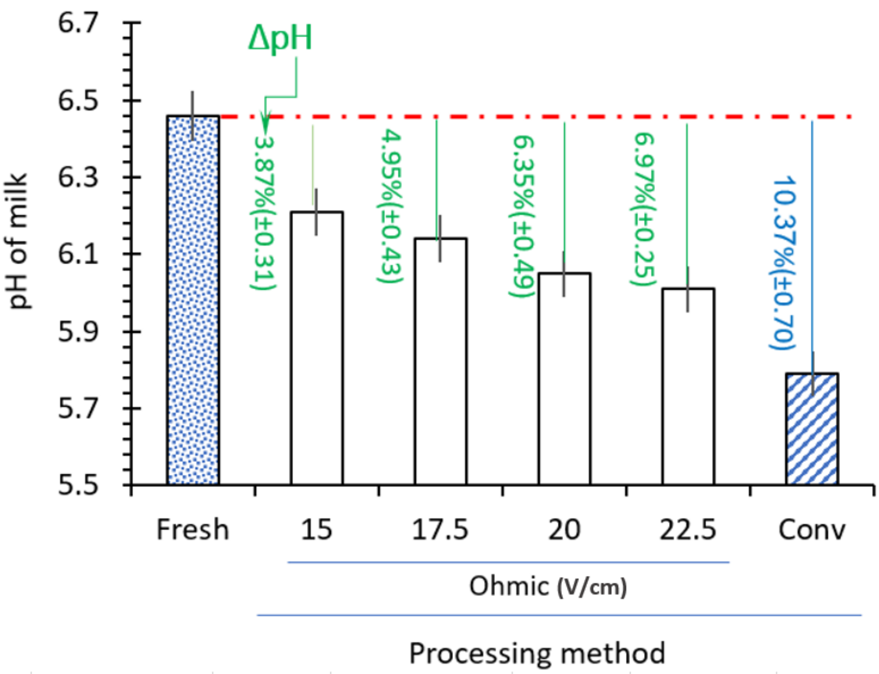

Fig 4. Effect of heating conditions on pH of concentrated milk

The pH change of samples processed by the conventional heating method was greater than that of the samples processed by ohmic heating. Additionally, increasing the voltage gradient resulted in a further decrease in the pH value of the processed samples compared to those treated with ohmic heating at lower voltages. Processing time, heating rate, and chemical reactions during milk concentration affect the pH values of processed samples (Fadavi et al., 2018). An increased heating rate may cause degradation or transformation of organic compounds in milk, such as acids, which can be converted into sugars or used in energy synthesis. These changes may reduce the acid content and acidity of the sample, which in turn results in an increase in pH. The results obtained in this study are consistent with the findings presented by Fadavi et al. (2018) and Darvishi et al. (2020a).

3.3. Color changes

Fig. 5 depicts fresh milk alongside samples processed using different heating methods, while Table 2 summarizes the color parameters and total color changes of the processed samples. According to results, the L value of the samples processed by the conventional heating method (85.96) was higher than that of the samples processed by the ohmic heating method (79.59 to 80.92). Additionally, the a and b values for the samples processed by the conventional heating method were lower than those obtained for the samples processed by the ohmic heating method. The concentration process caused a decrease in the L and a values of the processed samples compared to fresh milk, while the b value increased. During the concentration process, water present in the milk evaporates to a significant extent. This leads to an increase in the concentration of color compounds such as casein, caramelized lactose, and fat-soluble vitamins. The increased concentration of these compounds results in a darker milk color and consequently a decrease in the L value (brightness) (Lime et al., 2022). On the other hand, during the concentration process, some compounds like chlorophyll and riboflavin may degrade or their concentration may decrease, leading to a decrease in the *a* value. Additionally, the concentration of yellow-colored compounds such as carotenoids, riboflavin, and some browning products increases during the concentration process. This leads to an increase in the b value and a shift towards a yellower color. The results indicate that the ohmic heating method causes greater color changes in the processed samples than the conventional heating. Electrode-substance reactions, browning reactions, and degradation of pigments in the ohmic heating method can contribute to increased color changes in processed milk products compared to the conventional heating method. The highest color changes were observed in the processed samples at a voltage gradient of 15 V/cm. Parmar et al. (2018) investigated the effect of the ohmic heating processing method on color changes in milk. They demonstrated that the ohmic heating method resulted in an increased yellow color parameter and decreased whiteness compared to conventional heating.

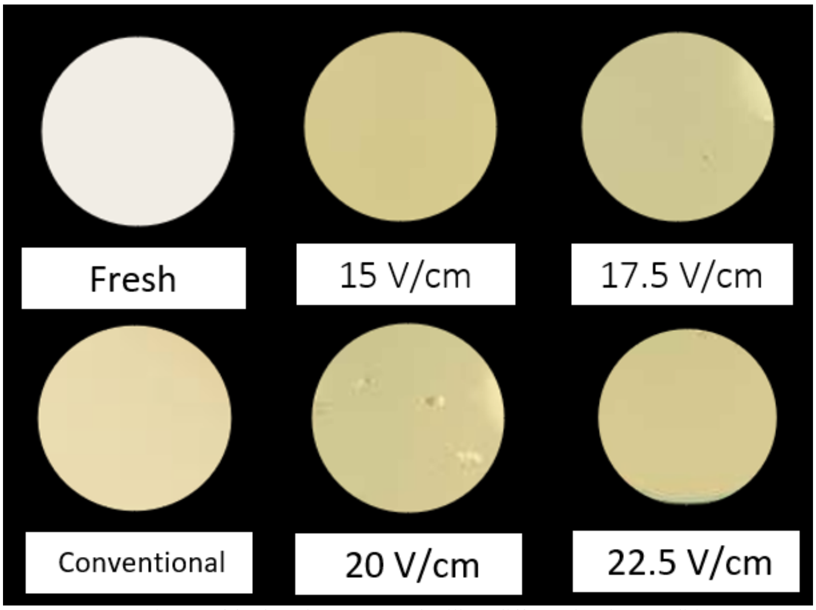

Fig 5. Picture of fresh and concentrated milk at different heating conditions

Table 2. Average values of L-a-b color parameters and total color change of concentrated milk samples, and specific exergetic improvement potential of different concentration methods

Processing method	Voltage gradient (V/cm)	L	a	b	ΔE	IPs (MJ/kg water)
Ohmic	15	80.28±0.41[c]	-4.25±0.66[ab]	30.81±0.91[a]	29.22±0.76[a]	4.70±0.24[b]
	17.5	79.59±0.56[c]	-5.03±0.71[a]	26.37±1.07[bc]	25.74±0.85[c]	4.19±0.17[c]
	20	80.92±1.29[c]	-4.57±1.26[ab]	28.45±1.22[b]	26.95±1.02[c]	3.47±0.07[d]
	22.5	80.05±0.56[c]	-4.39±0.97[ab]	28.49±1.46[b]	27.10±1.34[bc]	3.33±0.01[e]
Conventional	-	85.96±0.43[b]	-0.97 ± 1.15[c]	23.52 ± 0.91[d]	20.22 ± 0.82[d]	40.73±1.22[a]
Fresh milk	-	91.07±0.70[a]	-0.44±0.20[d]	4.19±0.31[e]	-	-

Different superscripts in the same parameter indicate significant differences ($p < 0.05$).

3.4. Sensory evaluation

According to Figure (6), the sensory attribute of odor shows an increasing trend (from a score of 42.5 to 80) with an increase in voltage gradient from 15 to 22.5 V/cm. The odor score for the sample processed by the conventional heating method was 65, which is higher than the score of 15 V/cm voltage gradient. The taste scores at voltage gradients of 15, 17.5, and 20 V/cm were relatively stable and evaluated within the range of 62.5 to 67. The conventional treatment has a taste score of 60, which was similar to the ohmic heating method. The lowest color score (62.5) was recorded for the samples processed by the ohmic heating method at a voltage gradient of 22.5 V/cm, while the color score for the samples processed by the conventional heating method was similar to that of the samples processed at other voltage gradients. The examination of the overall acceptance scores indicates that a voltage gradient of 20 V/cm can have a positive effect on odor, taste, and color.

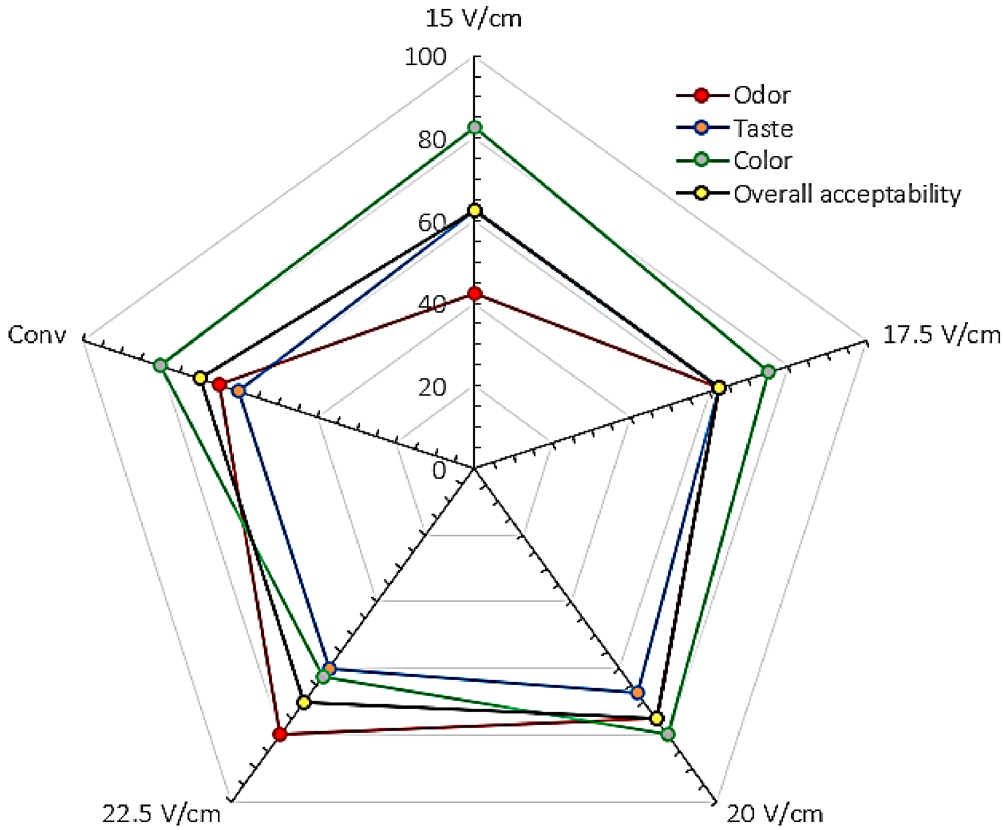

Fig 6. Results of sensory evaluation for the parameters of odor, taste, color, and overall acceptability

3.5. Energy consumption and efficiency

Fig. 7 illustrates the impact of the processing method and voltage gradient on the specific energy consumption and energy loss of the milk concentration process. The statistical results indicate a significant effect of the voltage gradient and processing method on specific energy consumption ($p < 0.05$). As the voltage gradient increased from 15 to 22.5 V/cm, the specific energy consumption decreased from 5.29 to 3.91 MJ/kg of water removed. The processing time decreased as the voltage gradient increased, leading to a reduction in specific energy consumption (Cevik, 2021; Darvishi et al., 2020b). The specific energy consumption for conventional heating was 41.68 MJ/kg of water removed. The specific energy consumption by ohmic heating method was 36.8 - 37.8 MJ/kg water lower than conventional heating. The longer processing time and lower heat transfer coefficients of the milk in the conventional heating method contribute to the higher specific energy consumption (Cokgezme et al., 2017; Darvishi et al., 2015). Balthazar et al. (2022) demonstrated that ohmic heating pasteurization of fresh sheep milk reduced energy consumption by 72% compared to conventional heating.

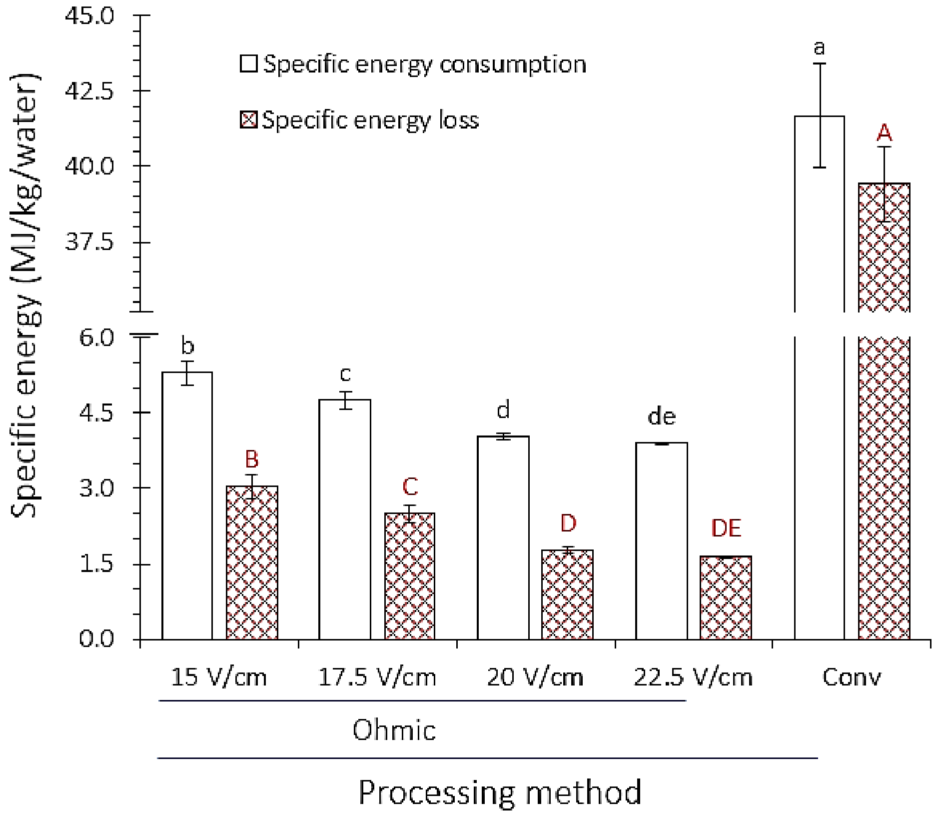

Fig 7. Specific energy consumption and energy loss of ohmic and conventional milk concentration technologies
Different superscripts in the same parameter indicate significant differences ($p < 0.05$).

According to Fig. 8, the energy efficiency increased from 42.71% to 57.79% as the voltage gradient increased from 15 to 22.5 V/cm. Icier et al. (2003) reported that the energy efficiency of the ohmic heating system in liquid food processing ranges from 47% to 92%. The energy efficiency of the ohmic concentration process was reported to be in the ranges of 67.07% to 85.50% for tomato juice (Darvishi et al., 2015), 23.94% to 55.12% for pomegranate juice (Cokgezme et al., 2017), 66.61% to 74.27% for grape juice (Darvishi et al., 2020a), and 56.3% to 67.1% for cow milk (Sürme and Sabancı, 2021).

The energy efficiency of the conventional heating method was calculated as 5.42% (Fig. 8), indicating considerable energy losses during the process. The energy efficiency of ohmic heating was 51% to 87% higher than that of conventional heating, as heat is generated directly within the material, minimizing energy losses compared to external heating methods. According to Fig. 7, between 1.65 and 3.04 MJ/kg of water removed was lost as wasted energy during the ohmic heating process. A significant amount of energy is lost through heat transfer from the ohmic cell body to the environment, heating of the electrodes and the ohmic cell body itself, and electrochemical side reactions occurring during the process. The specific energy loss by conventional concentration method was 39.42 MJ/kg water. These energy losses are primarily due to inefficiencies inherent in the system, such as resistive heating, thermal dissipation, and parasitic chemical reactions. To reduce energy losses and enhance overall efficiency, design and operation of ohmic heating systems should account for factors such as insulation, electrode material selection, and optimized operating conditions.

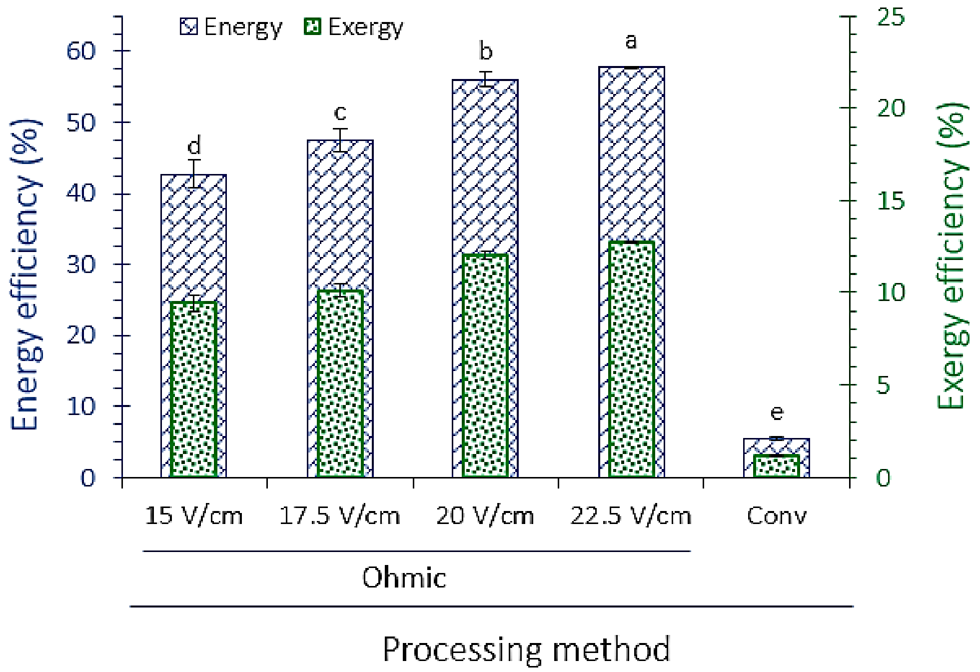

Fig 8. Energy and exergy efficiencies of ohmic and conventional milk concentration technologies
Different superscripts in the same parameter indicate significant differences ($p < 0.05$).

3.6. Exergy efficiency and improvement potential

According to Fig. 6, the exergy efficiency ranged from 9.48% to 12.75% for the ohmic heating method, compared to 1.18% for conventional heating. This represents an 8.38–11.57% higher exergy efficiency for ohmic heating. Results demonstrated that the exergy efficiency increased with rising voltage gradient ($p<0.05$), indicating that faster heating and water evaporation rates at higher voltage gradients (Norouzi et al., 2021). This increase is attributed to higher current passing through the sample, which elevates the heat generation rate and consequently improves exergy efficiency significantly. Previous studies reported that shorter processing times and more homogeneous heating reduce exergy losses, or equivalently entropy generation, resulting in increased exergetic efficiency of the system (Bozkurt and Icier, 2010; and Darvishi et al., 2015).

Exergy efficiency values were 33.2%-45% lower than energy efficiency for the ohmic heating method, and 4.3% lower for the conventional heating method. The obtained values of exergy efficiency clearly indicate that a large proportion of the supplied thermal exergy is lost. Previous studies indicate that exergy loss occurs when the heating system's temperature boundary exceeds ambient temperature (Aghbashlo et al., 2013; Corzo et al., 2008). Preventing heat transfer across system boundaries can reduce exergy loss. This can be achieved by insulating the ohmic cell, selecting appropriate components, and optimizing heating conditions. The exergy efficiency of ohmic heating process was reported in the range of 27.75–60.34% for tomato paste (Darvishi et al., 2015), 49.7-59.3% for cow milk (Sürme and Sabancı, 2021), 31.56 – 59.46% for sour orange juice (Torshizi et al., 2020), and 63.2–89.2% for ground beef (Bozkurt and Icier, 2010).

According to Table 2, the specific improvement potential ranged from 3.33 to 4.70 MJ/kg water for the ohmic heating method, and was 40.73 MJ/kg water for the conventional heating method. It was noted that improvement potential values decreased with increasing voltage gradient ($p \leq 0.05$). Similar findings were reported by Bozkurt and Icier (2010), and Darvishi et al. (2015).

3.7. Environmental impact

The effects of heating method on specific CO_2 emission are given in Fig. 9. The CO_2 dominates global GHG emissions, representing the most significant contributor to the greenhouse effect. The specific CO_2 emissions ranged from 937 to 1270 g/kg of water for the ohmic heating method compared to 10001 gCO_2/kg of water for the conventional heating method. In other words, the CO_2 emissions from the ohmic heating method were 7.9 to 10.7 times lower than those from the conventional method, primarily due to the lower energy consumption. Ghnimi et al. (2021) report that CO_2 emissions from the ohmic heating method were 1.7 times lower than those from the appertization method during chopped tomato processing, primarily due to a 65% energy saving achieved by ohmic heating. Ito et al. (2023) demonstrated that replacing retort heating with ohmic heating for chicken processing reduced CO_2 emissions by over 80%. However, Paini et al. (2023) report that the CO_2 emissions during the processing of diced tomatoes and peaches using ohmic heating are 1.8 and 2.7 times higher, respectively, than those from the conventional heating method. Also, specific CO_2 emissions from ohmic heating decreased with increasing voltage gradient due to reduced energy consumption, emphasizing the environmental benefits of advanced heating technologies such as ohmic heating. Similar findings were also reported by De Marco et al. (2016) for semi-finished apricots, Ghnimi et al. (2021) for chopped tomatoes with juice, and Ito et al. (2023) for chicken.

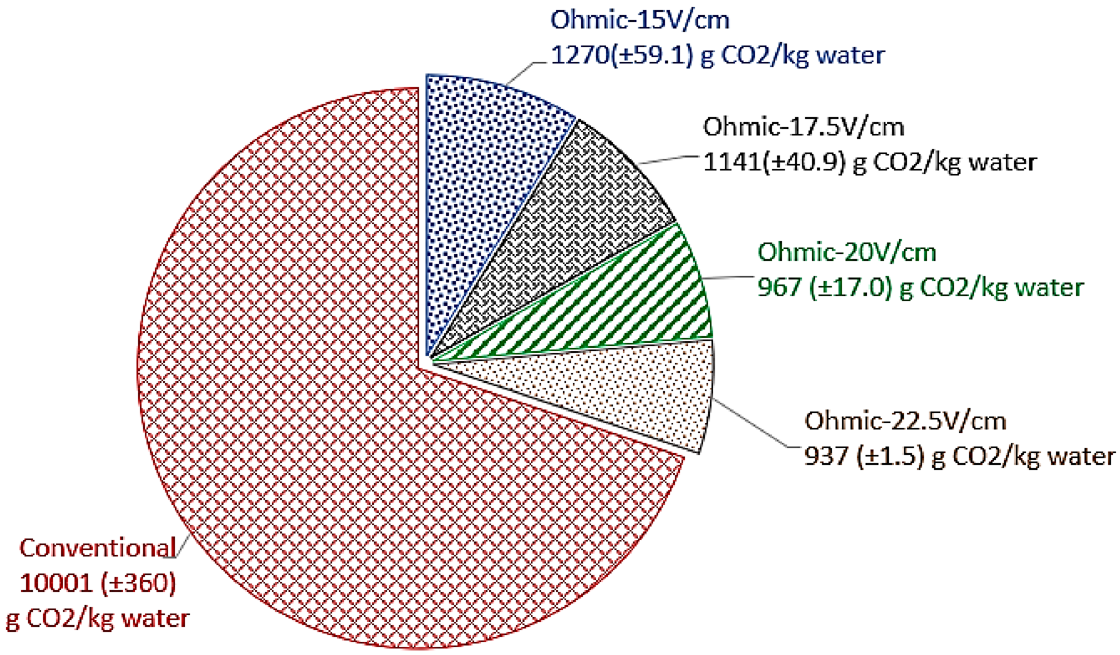

Fig 9. Values of the specific CO2 emission of the ohmic and conventional heating technologies

4. Conclusion

This study examines the comparative performance of ohmic and conventional heating methods for milk concentration, focusing on processing kinetics, energy consumption, efficiencies, quality properties, environmental impact, and sensory characteristics. The findings reveal that ohmic heating offers significant advantages, reducing processing time by 1.88 to 4.33 times and energy consumption by 10.5 to 17 times compared to conventional methods. Among the tested ohmic voltage gradients (15–22.5 V/cm), 20 V/cm emerged as the optimal condition for industrial implementation. This parameter delivered the highest sensory acceptability while maintaining critical quality advantages, including minimal pH reduction (ΔpH ≈4.5%), 4× faster processing than conventional heating, and 10.7× lower energy consumption. Though higher voltages (22.5 V/cm) further reduced processing time, they incurred greater color changes (ΔE = 27.10) and lower sensory scores—particularly in color perception. Thus, 20 V/cm represents the ideal compromise between efficiency, sustainability, and product quality. While ohmic heating resulted in minimal pH changes (3.87-6.97%) versus conventional heating (10.37%), it did produce more noticeable color alterations. Sensory evaluations indicated optimal product attributes at a voltage gradient of 20 V/cm using the ohmic method. The energy and exergy efficiencies for ohmic heating ranged from 9.48% to 12.75%, markedly higher than those for conventional heating (5.42% and 1.18%, respectively). Environmental analysis showed that specific CO_2 emissions decreased significantly from 1270 to 937 gCO_2/kg water as the voltage gradient increased from 15 to 22.5 V/cm in ohmic heating, while conventional heating resulted in much higher emissions of 10001 gCO_2/kg water. Despite the advantages, challenges such as color changes and sensory impacts at higher voltage gradients were noted. The study suggests that adopting ohmic heating technologies can enhance operational efficiency and product quality in the milk industry. Future research could focus on mitigating the sensory impacts associated with ohmic heating, potentially leading to further innovations in milk processing technologies. Overall, ohmic heating presents a promising approach for improving the efficiency and quality of milk products while reducing environmental impact.

References

[1] Aghbashlo, M., Mobli, H., Rafiee, S., & Madadlou, A. (2013). A review on exergy analysis of drying processes and systems. *Renew. Sustain. Energy Rev*., 22, 1–22. https://doi.org/10.1016/j.rser.2013.01.015

[2] Alkanan, Z.T., Altemimi, A.B., Al-Hilphy, A.R., Watson, D.G., & Pratap-Singh, A. (2021). Ohmic heating in the food industry: Developments in concepts and applications during 2013–2020. *Appl. Sci.,* 11(6), p.2507. https://doi.org/10.3390/app11062507

[3] Aydin, C., Kurt, Ü., & Kaya, Y. (2020). Comparison of the effects of ohmic and conventional heating methods on some quality parameters of the hot-smoked fish Pâté. *J. Aquat. Food Prod. Technol*., 29(4), 407-416. https://doi.org/10.1080/10498850.2020.1741752

[4] Aydogdu, T., O'Mahony, J.A., & McCarthy, N.A. (2023). pH, the fundamentals for milk and dairy processing: a review. *Dairy*, 4(3), 395-409. https://doi.org/10.3390/dairy4030026

[5] Balthazar, C.F., Cabral, L., Guimarães, J.T., Noronha, M.F., Cappato, L.P., Cruz, A.G., & Sant'Ana, A.S. (2022). Conventional and ohmic heating pasteurization of fresh and thawed sheep milk: Energy consumption and assessment of bacterial microbiota during refrigerated storage. *Innov. Food Sci. Emerg. Technol.*, 76, p.102947. https://doi.org/10.1016/j.ifset.2022.102947

[6] Bozkurt, H., & Icier, F. (2010). Exergetic performance analysis of ohmic cooking process. *J. Food Eng*., 100(4), 688-695. https://doi.org/10.1016/j.jfoodeng.2010.05.020

[7] Calvo, L. M., & Domingo, R. (2017). CO2 emissions reduction and energy efficiency improvements in paper making drying process control by sensors. *Sustainability*, 9(4), 514. https://doi.org/10.3390/su9040514

[8] Cappato, L.P., Ferreira, M.V., Guimaraes, J.T., Portela, J.B., Costa, A.L., Freitas, M.Q., Cunha, R.L., Oliveira, C.A., Mercali, G.D., Marzack, L.D.F., & Cruz, A.G. (2017). Ohmic heating in dairy processing: Relevant aspects for safety and quality. *Trends Food Sci. Technol*., 62, 104-112. https://doi.org/10.1016/j.tifs.2017.01.010

[9] Cevik, M. (2021). Electrical conductivity and performance evaluation of verjuice concentration process using ohmic heating method. *J. Food Process Eng*., 44(5), p.e13672. https://doi.org/10.1111/jfpe.13672

[10] Cokgezme, O.F., Sabanci, S., Cevik, M., Yildiz, H., & Icier, F. (2017). Performance analyses for evaporation of pomegranate juice in ohmic heating assisted vacuum system. *J. Food Eng*., 207, 1-9. https://doi.org/10.1016/j.jfoodeng.2017.03.015

[11] Corzo, O., Bracho, N., Vasquez, A., & Pereira, A. (2008). Energy and exergy analyses of thin layer drying of coroba slices. *J. Food Eng.,* 86, 151–161. https://doi.org/10.1016/j.jfoodeng.2007.05.008

[12] Coutinho, N.M., Silveira, M.R., Rocha, R.S., Moraes, J., Ferreira, M.V.S., Pimentel, T.C., Freitas, M.Q., Silva, M.C., Raices, R.S., Ranadheera, C.S., & Borges, F.O. (2018). Cold plasma processing of milk and dairy products. *Trends Food Sci. Technol*., 74, 56-68. https://doi.org/10.1016/j.tifs.2018.02.008

[13] Darvishi, H., Koushesh Saba, M., Behroozi-Khazaei, N., & Nourbakhsh, H. (2020a). Improving quality and quantity attributes of grape juice concentrate (molasses) using ohmic heating. *J. Food Sci. Technol*., 57, 1362-1370. https://doi.org/10.1007/s13197-019-04170-1

[14] Darvishi, H., Salami, P., Fadavi, A., & Saba, M.K. (2020b). Processing kinetics, quality and thermodynamic evaluation of mulberry juice concentration process using Ohmic heating. *Food Bioprod. Process*., 123, 102-110. https://doi.org/10.1016/j.fbp.2020.06.003

[15] Darvishi, H., Hosainpour, A., Nargesi, F., & Fadavi, A. (2015). Exergy and energy analyses of liquid food in an ohmic heating process: a case study of tomato production. *Innov. Food Sci. Emerg. Technol*., 31, 73-82. https://doi.org/10.1016/j.ifset.2015.06.012

[16] Darvishi, H., Khodaei, J., Behroozi-Khazaei, N., Salami, P., & Akhijahani, H. S. (2023). Greenhouse gas emission reduction potential, energy and exergy analysis of combined microwave-convective dryer. *Energy*, 285, 128772. https://doi.org/10.1016/j.energy.2023.128772

[17] De Marco, I., Miranda, S., Riemma, S., & Iannone, R. (2016). The impact of alternative apricot conservation techniques on global warming potential. *Chem. Eng. Trans.,* 49, 325-330. https://doi.org/10.3303/CET1649055

[18] Duguay, A.J., Ramaswamy, H.S., Zareifard, R., Zhu, S., Grabowski, S., & Marcotte, M. (2016). Ohmic heating behaviour of cabbage and daikon radish. *Food Bioprocess Technol.,* 9, 430-440. https://doi.org/10.1007/s11947-015-1622-9

[19] Fadavi, A., Yousefi, S., Darvishi, H., & Mirsaeedghazi, H. (2018). Comparative study of ohmic vacuum, ohmic, and conventional-vacuum heating methods on the quality of tomato concentrate. *Innov. Food Sci. Emerg. Technol.*, 47, 225-230. https://doi.org/10.1016/j.ifset.2018.03.004

[20] Ghnimi, S., Nikkhah, A., Dewulf, J., & Van Haute, S. (2021). Life cycle assessment and energy comparison of aseptic ohmic heating and appertization of chopped tomatoes with juice. *Sci Rep*., 11(1), p.13041. https://doi.org/10.1038/s41598-021-92211-1

[21] Gulati, A. (2019). Effect of dairy cow diets on the composition and processing characteristics of milk. national university of Ireland, Maynooth (Ireland), ID:10858. https://mural.maynoothuniversity.ie/id/eprint/10858

[22] Hosainpour, A., Darvishi, H., Nargesi, F., & Fadavi, A. (2014). Ohmic pre-drying of tomato paste. *Food Sci. Technol. Int.,* 20(3), 193-204. https://doi.org/10.1177/1082013213480360

[23] Ito, R., Yamanaka-Zamoto, N., Watanabe, M., & Hamada-Sato, N. (2023). Environmental impact assessment of aseptically packaged chicken using ohmic heating. *Food Sci. Technol Res.,* 29(6), 441-452. https://doi.org/10.3136/fstr.FSTR-D-22-00220

[24] Lim, S.H., Chin, N.L., Sulaiman, A., Tay, C.H., &

Wong, T.H. (2022). Sensory analysis for cow milk product development using high pressure processing (HPP) in the dairy industry. *Foods*, 11(9), p.1233. https://doi.org/10.3390/foods11091233

[25] Nazari, S., Shahhoseini, O., Sohrabi-Kashani, A., Davari, S., Paydar, R., & Delavar-Moghadam, Z. (2010). Experimental determination and analysis of CO2, SO2 and NOx emission factors in Iran's thermal power plants. *Energy*, 35(7), 2992-2998. https://doi.org/10.1016/j.energy.2010.03.035

[26] Norouzi, S., Fadavi, A., & Darvishi, H. (2021). The ohmic and conventional heating methods in concentration of sour cherry juice: Quality and engineering factors. *J. Food Eng.*, 291, p.110242. https://doi.org/10.1016/j.jfoodeng.2020.110242

[27] Paini, A., Romei, S., Stefanini, R., & Vignali, G. (2023). Comparative life cycle assessment of ohmic and conventional heating for fruit and vegetable products: The role of the mix of energy sources. *J. Food Eng.*, 350, p.111489. https://doi.org/10.1016/j.jfoodeng.2023.111489

[28] Panirani, P.N., Darvishi, H., Hosainpour, A., & Behroozi-Khazaei, N. (2023). Comparative study of different bread baking methods: Combined ohmic–infrared, ohmic–conventional, infrared–conventional, infrared, and conventional heating. *Innov. Food Sci. Emerg. Technol.*, 86, p.103349. https://doi.org/10.1016/j.ifset.2023.103349

[29] Parmar, P., Singh, A. K., Meena, G. S., Borad, S., & Raju, P. N. (2018). Application of ohmic heating for concentration of milk. *J. Food Sci. Technol.,* 55(12), 4956-4963. https://doi.org/10.1007/s13197-018-3431-4

[30] Rocha, R.S., Silva, R., Guimarães, J.T., Balthazar, C.F., Pimentel, T.C., Neto, R.P., Tavares, M.I.B., Esmerino, E.A., Freitas, M.Q., Cappato, L.P., & Calvacanti, R.N. (2020). Possibilities for using ohmic heating in Minas Frescal cheese production. *Food Res. Int*., 131, p.109027. https://doi.org/10.1016/j.foodres.2020.109027

[31] Sun, Y., Liu, Y., Zhou, W., Shao, L., Wang, H., Zhao, Y., Zou, B., Li, X., & Dai, R. 2024. Effects of ohmic heating with different voltages on the quality and microbial diversity of cow milk during thermal treatment and subsequent cold storage. *Int. J. Food Microbiol.*, 410, p.110483. https://doi.org/10.1016/j.ijfoodmicro.2023.110483

[32] Sürme, S, A., & Sabancı, S. (2021). The usage of Ohmic heating in milk evaporation and evaluation of electrical conductivity and performance analysis. *J. Food Process. Preserv*., 45(9), p.e15522. https://doi.org/10.1111/jfpp.15522

[33] Torshizi, M.V., Azadbakht, M., & Kashaninejad, M. (2020). Application of response surface method to energy and exergy analyses of the ohmic heating dryer for sour orange juice. *Fuel*, 278, p.118261. https://doi.org/10.1016/j.fuel.2020.118261

[34] Varghese, K.S., Pandey, M.C., Radhakrishna, K., & Bawa, A.S. (2014). Technology, applications and modelling of ohmic heating: a review. *J. Food Sci. Technol*., 51, 2304-2317. https://doi.org/10.1007/s13197-012-0710-3

DOI: http://dx.doi.org 10.22104/ift.2025.7710.2222

فصلنامه فناوری‌های جدید در صنعت غذا

دوره ۱۲، شماره ۳، صفحه ۳۱۹-۳۰۵، بهار ۱۴۰۴

مقاله پژوهشی

تحلیل مقایسه‌ای گرمایش اهمی و تبخیر متداول برای تغلیظ شیر: پارامترهای کیفی، راندمان انرژی و اکسرژی، انتشار گازهای گلخانه‌ای و ارزیابی حسی

حسین درویشی[۱*]، مبین محمدی[۱]، ناصر بهروزی خزائی[۱]، حسین جهانی عزیزآبادی[۲]، مسلم سلیمانی[۱]

۱. گروه مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه کردستان، سنندج، کردستان، ایران

۲. گروه علوم دامی، دانشکده کشاورزی، دانشگاه کردستان، سنندج، کردستان، ایران

(تاریخ ارسال: ۱۴۰۴/۰۴/۰۷، تاریخ آخرین بازنگری:۱۴۰۴/۰۴/۲۸، تاریخ پذیرش: ۱۴۰۴/۰۴/۲۹)

چکیده

این مطالعه به تحلیل مقایسه‌ای روش‌های گرمایش اهمی و متداول برای تغلیظ شیر پرداخته و سینتیک فرآیند، راندمان انرژی- اکسرژی، پارامترهای کیفی، اثرات محیط زیستی و ویژگی‌های حسی را ارزیابی می‌کند. نتایج نشان‌دهنده عملکرد بهتر گرمایش اهمی نسبت به گرمایش رایج بوده است. روش گرمایش اهمی سبب کاهش ۱/۸۸ الی ۴/۳۳ برابر برای زمان فرآوری و ۱۰/۵ الی ۱۷ برابر کاهش برای مصرف انرژی شده است. همچنین راندمان انرژی و اکسرژی روش گرمایش اهمی (به ترتیب ۴۲/۷۱-۵۷/۷۹٪ و ۹/۴۸-۱۲/۷۵٪) به‌طور چشمگیری بالاتر از گرمایش رایج (به ترتیب ۵/۴۲٪ و ۱/۱۸٪) بوده است. تغییرات pH نمونه فراوری شده با گرمایش رایج (۳/۸۷-۶/۹۷٪) کمتر از از روش رایج (۱۰/۳۷٪) بود. با این حال، گرمایش اهمی تغییرات رنگی محسوس‌تری داشت. ارزیابی حسی بیانگر آن بود که گرادیان ولتاژ ۲۰ ولت بر سانتی‌متر را به‌عنوان مقدار بهینه برای تعادل طعم، بافت و عطر می‌باشد. گرمایش اهمی، انتشار CO_2 را نسبت به گرمایش رایج، ۹۰/۳ – ۹۵/۶٪ کاهش داد. این نتایج، گرمایش اهمی را به‌عنوان جایگزینی پایدار و انرژی‌بَر برای تغلیظ صنعتی شیر تثبیت می‌کند که چالش‌های پایداری فرآوری غذا را بدون افت کیفیت محصول برطرف می‌سازد.

کلمات کلیدی: **تبخیر اهمی، فرآوری پایدار لبنیات، آنالیز اگزرژی، ردپای کربن، کیفیت شیر**

* نویسنده مسئول: h.darvishi@uok.ac.ir