Enhancing Quality and Safety of Garlic Pulp through Ohmic Heating: A Comprehensive Study on Physicochemical, Microbiological, and Bioactive Content

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Abstract: This research paper investigates the application of ohmic heating as an innovative method to improve the quality and safety of garlic pulp. Garlic is a widely consumed vegetable renowned for its unique flavor and potent bioactive compounds, but traditional processing methods often degrade its bioactive constituents and pose microbial safety concerns. In this study, the researchers explore the potential of ohmic heating to address these issues. The study begins by examining the physicochemical properties of garlic pulp subjected to ohmic heating, including changes in pH, color, texture, and moisture content. The results reveal that ohmic heating effectively preserves overall quality attributes, with notable improvements in color and texture compared to conventional processing methods. Additionally, the impact of ohmic heating on the bioactive content of garlic pulp is investigated. High-performance liquid chromatography (HPLC) analysis reveals that ohmic heating leads to superior retention of key bioactive compound diallyl disulfide. By preserving physicochemical properties, enhancing microbial safety, and retaining bioactive content, ohmic heating offers a novel approach to elevate the nutritional and safety standards of garlic-based products. These findings have significant implications for the food industry, providing valuable insights into the potential benefits of adopting ohmic heating technology.

Keywords: Garlic Pulp, Ohmic Heating, High-performance liquid chromatography (HPLC)

1. INTRODUCTION

Garlic (Allium sativum) has been a cherished ingredient in culinary traditions worldwide, appreciated not only for its distinct flavor but also for its numerous health-promoting properties. Rich in bioactive compounds such as allicin, sulfur compounds, and antioxidants, garlic has been associated with various health benefits, including antioxidant, antimicrobial, and anticancer effects. However, the post-harvest storage of garlic presents significant challenges due to its susceptibility to spoilage, which can lead to quality deterioration and economic losses. Traditional preservation methods, such as drying and refrigeration, are commonly employed but may have limitations in retaining the physicochemical and bioactive attributes of garlic [1].

Garlic comprises a plethora of bioactive compounds, encompassing flavonoids, organo-sulphur compounds, phenolic acids, vitamins, among others. The biological effects attributed to garlic are primarily rooted in its organosulphur compounds. Among these, notable organosulphur compounds include diallyl-disulphide, diallyl-sulphide, allyl methyl trisulphide, diallyl-trisulphide, and dithiins. The activation of these organosulphur compounds occurs upon the disruption of a garlic clove, leading to the release of the allinase enzyme. This enzymatic reaction plays a pivotal role in the synthesis of thiosulphinates [2]. Notably, it is these organosulphur compounds that impart the distinctive flavor associated with garlic [3]. Diallyl disulphide, a prominent volatile compound found in garlic essential oil and crushed garlic, significantly contributes to the characteristic odor and flavor of this versatile bulb.

In recent years, ohmic heating has emerged as a promising thermal processing technology for food preservation. Ohmic heating, also known as Joule heating or electrical resistance heating, involves the passage of an alternating electric current through a food product, resulting in rapid and uniform heating. Unlike conventional heating methods, ohmic heating directly heats the food material by utilizing its electrical resistance, minimizing heat transfer limitations and ensuring uniform temperature distribution. This unique characteristic makes ohmic heating an attractive option for preserving the quality and safety of heat-sensitive foods, such as garlic pulp [4].

The application of ohmic heating to offers several potential advantages. Firstly, ohmic heating can facilitate the inactivation of spoilage microorganisms and pathogens, thereby extending the shelf life of garlic pulp. It is essential to ensure the microbiological safety of food products as microbial contamination can lead to adverse health effects and spoilage. Several researches concerning the pasteurization of orange juice, the effectiveness of ohmic heating was substantiated [5]. Orange juice was subjected to ohmic heating at temperatures of 90ºC, 120ºC, and 150ºC for durations of 1.13, 0.85, and 0.68 seconds, respectively. The results showcased that ohmic pasteurization successfully inhibited microbial growth for an extended period, lasting up to 105 days, and maintained sensory attributes for over 100 days when compared to conventionally pasteurized juice. Similarly a study into the quality assessment of ohmic-pasteurized fermented red pepper paste, a traditional Korean food item [6]. Pasteurization was carried out using ohmic heating at various frequencies ranging from 40 to 20000 Hz and voltages ranging from 20 to 60 V. The findings revealed a remarkable 99.7% reduction in microbial growth in the ohmic-pasteurized paste, underscoring the efficacy of this method in enhancing food safety and quality. Furthermore, the impact of ohmic heating on the pasteurization of liquid whole egg, egg white, and yolk was thoroughly assessed [7]. Using a consistent heating rate, both ohmic and conventional heating were conducted at 60ºC for 6.5 minutes. Impressively, ohmic pasteurization yielded superior color values compared to conventional heating, with no modification to the free fatty acid content.

Secondly, ohmic heating has the potential to maintain or even enhance the bioactive content of garlic due to its rapid and controlled heating process. Allicin, for example, is a highly valuable bioactive compound in garlic that can be susceptible to degradation during traditional heat processing methods. The precise control over temperature and heating duration provided by ohmic heating can minimize the loss of such compounds. Studies have been conducted influence of both conventional and ohmic pasteurization methods on the aminoacid content of vegetable based baby food [8], total phenol content in aloe vera gel juice [9]. Remarkably, the ohmic heating technique has a discernible impact on the protein content and there was a significant increase in total phenol content of the ohmic heated aloe vera gel juice.

Ohmic heating offers the advantage of preserving these attributes by minimizing the exposure of garlic pulp to prolonged high temperatures, which can result in undesirable changes. Therefore, this study aims to comprehensively evaluate the impact of ohmic heating on the physicochemical, microbiological, and bioactive content of garlic pulp.

2. MATERIALS AND METHODS

2.1. Sample Preparation and Processing

Garlic cloves of the Ooty 1 variety, sourced from local markets in Chennai, underwent an initial preparation phase involving peeling and subsequent homogenization in a blender. Following this preparation, the garlic cloves were partitioned into two discrete sets, one designated for ohmic processing and the other for conventional processing.

In the case of conventional processing, the garlic pulp was carefully transferred into a laboratory beaker and subjected to heating using three distinct temperature gradients: low heat (35°C - 82°C), medium heat (38°C - 82°C), and high heat (47°C - 82°C). Conversely, within the ohmic heating procedure, the garlic pulp was positioned between titanium electrodes and processed at three specific voltage gradients: 13.33 V/cm, 20 V/cm, and 26.66 V/cm. Throughout both the ohmic and conventional heating processes, the temperature of the garlic pulp was meticulously recorded at 30-minute intervals. A time-temperature plot was generated to examine the impact of time and voltage gradient on both ohmically and conventionally heated samples [10].

2.2. Electrical conductivity

The electrical conductivity (σ) was determined based on the resistivity of the sample and the dimensions of the ohmic heating cell, utilizing the following equation [11].

$$\sigma = \frac{LI}{AV} \ldots \quad (1)$$

Where,

σ- Electrical conductivity (S/m); A - Area of the cell (m^2); L -Distance between two electrodes; I - Current (A); V - Voltage (V).

A plot depicting the variation in electrical conductivity with respect to temperature was generated to elucidate the relationship between voltage gradient, electrical conductivity, and temperature.

2.3. Performance evaluation of Ohmic heating system

The efficiency of the ohmic heater's performance was evaluated through an examination of the system performance coefficient, a metric utilized to gauge the heating system's effectiveness. This coefficient is computed by assessing the heat energy utilized in relation to the electrical energy applied [12].

System Performance Coefficient (SPC) is defined as:

$$\text{System Performance Coefficient, SPC} = \frac{Q}{P} \quad (2)$$

$$P = Q + E_{loss} \quad (3)$$

$$P = \sum (VIt) \quad (4)$$

$$Q = mC_p(T_f - T_i) \quad (5)$$

$$\sum (VIt) = mC_p(T_f - T_i) + E_{loss} \quad (6)$$

Where,

P= Electrical energy given to the system (J); Q= Energy required to heat the sample (J);

V= Voltage applied (V); I= Current (A); t=Time (s); m= Mass of the sample (kg); C_P=Specific heat capacity (J/kgºC); T_f= Final temperature (ºC); T_i =Initial temperature (ºC)

2.4. Colour analysis

Color measurements of the garlic samples, which underwent differential processing, were conducted using the Hunter Lab (Colour Quest) equipment. Calibration of the equipment was performed using a white reference tile. The change in the color of the sample before and after processing was quantified using the Total Colour Difference (TCD) metric [13].

The total colour difference was calculated using the Scofield equation

$$\text{TCD} = \sqrt{(\text{Lo} - \text{L})^2 + (ao - a)^2 + (bo - b)^2} \quad (7)$$

where,

L_0= Lightness of garlic before treatment

L= Lightness of garlic after treatment

a_0= Redness/ greenness of garlic before treatment

a= Redness/ greenness of garlic after treatment

b_0= Blueness/yellowness of garlic before treatment

b= Blueness/yellowness of garlic after treatment

2.5. pH and Titratable Acidity

Differentially processed garlic pulp underwent analytical assessments for pH and titratable acidity. In this process, 50 ml of garlic pulp obtained from the differential processing procedure was subjected to filtration using a Whatman's filter. The resulting filtrate served as the analytical sample for pH and titratable acidity determinations. To measure pH, the pH electrode was immersed in the prepared garlic pulp and gently agitated until a stable reading was achieved. For the titratable acidity analysis, the filtrate was titrated with a 0.1 N sodium hydroxide solution. The calculation of acidity was performed using a specified formula, and the results were expressed as a percentage of pyruvic acid content [14].

$$\text{Acidity, \%} = \frac{\text{Titre value * Normality of alkali * Volume made up * Equivalent weight of acid}}{\text{Volume of sample taken for estimation *Weight of sample taken * 1000}} * 100 \qquad (8)$$

2.9. HPLC analysis of Diallyl disulphide content

The analysis of the bioactive compound Diallyl Disulphide (DADS) in garlic products was done using High-Performance Liquid Chromatography (HPLC). Following a meticulous procedure, garlic powder obtained through different processing methods was prepared for analysis. The Shimadzu UFLC system (LC-20AD, Japan) with a C18 column was utilized under specific conditions. The experimental parameters encompassed: i) column temperature set to 25 ºC, ii) employment of a mobile phase comprising methanol and water (86:14 v/v), iii) injection volume of 20 µL, iv) maintenance of a flow rate of 1 ml/min, and v) a total running time of 14 minutes. The detection of the chromatogram transpired at a wavelength of approximately 210 nm. The quantification of DADS was based on peak area calculations. The experiment aimed to assess DADS content and its preservation in garlic samples subjected to distinct processing techniques. The procedure involved the extraction of DADS through solvent mixtures, centrifugation, and subsequent HPLC analysis [15].

2.10. Estimation of Ascorbic acid

A volume of 10 ml of garlic pulp obtained from differential pasteurization was combined with 100 ml of a 3% metaphosphoric acid solution and subsequently subjected to filtration. From the resulting filtrate, a 10 ml portion was meticulously titrated against a dye solution containing a mixture of sodium bicarbonate and dichlorophenol indophenols. The quantification of ascorbic acid content within the garlic pulp was conducted utilizing the subsequent formula, and the results were expressed in milligrams per 100 grams of the sample [15].

$$\text{Ascorbic acid content, } \left(\frac{\text{mg}}{\text{100g of sample}}\right) = \frac{\text{Titre value*Dye factor*Volume made up}}{\text{Volume of filtrate taken*weight of sample}} * 100 \qquad (9)$$

2.11. Microbial analysis

Microbial analysis of garlic was performed for optimization of process parameters and for shelf life analysis. For optimization studies, the microbial growth studies were done immediately after processing, while the samples were tested for every 15 days during the shelf life studies. Microbial analyses was carried out by following the protocol of Collins [16].

2.12. Statistical analysis

The entirety of the data pertaining to the assessment of the effects of diverse processing techniques on physicochemical characteristics and functional properties underwent statistical analysis, employing one-way analysis of variance (ANOVA), followed by subsequent post hoc multiple pairwise Tukey testing. The one-way ANOVA analysis was executed utilizing MINITAB version 17.0 statistical software. Furthermore, both linear and non-linear regression analyses were conducted utilizing GRAPH PAD PRISM version 5.0 statistical software.

3. RESULTS AND DISCUSSION

3.1. Effect on temperature of garlic pulp

The rise in temperature exhibited a linear correlation with the extension of treatment duration, culminating in the attainment of a bubbling point at 82ºC for garlic pulp. As evidenced in Figure 4.26, an augmentation in the voltage gradient expedited the interval required to reach the boiling threshold, thus establishing a conspicuous reduction in time. The temporal disparities observed in inducing bubbling at distinct voltage gradients bore statistical significance.

Notably, garlic pulp necessitated 480 seconds to commence bubbling under the influence of an ohmic treatment at 13.33 V/cm, whereas the corresponding durations dwindled to 270 seconds and 90 seconds when subjected to treatments at 20 and 26.66 V/cm, respectively. This phenomenon finds its explanation in the relationship between temperature and the concurrent voltage and current coursing through the specimen. The electrical conductivity factor markedly influenced the heating rate of the sample, with the application of a heightened voltage gradient facilitating an accelerated generation of heat, thereby intensifying the current passing through the specimen. Irrespective of the variance in applied voltage gradients, the temperature exhibited a consistent linear ascent from 30 to 82ºC. The ohmic heating rates, specifically recorded at voltage gradients of 13.33, 20, and 26.66 V/cm, were discerned to be 0.104, 0.185, and 0.555ºC/s, respectively. In contrast, conventional heating of garlic pulp under low, medium, and high heat settings yielded heating rates of 0.103, 0.183, and 0.577ºC/s, respectively. The inception of bubble formation was notably marked when the temperature reached 82ºC, and the heating process was subsequently terminated. This occurrence could be attributed to the liberation of gas within the liquid medium, prompted by electrochemical reactions. The formation of gas bubbles likely ensued as a consequence of a myriad of redox reactions, ultimately resulting in the generation of by-products.

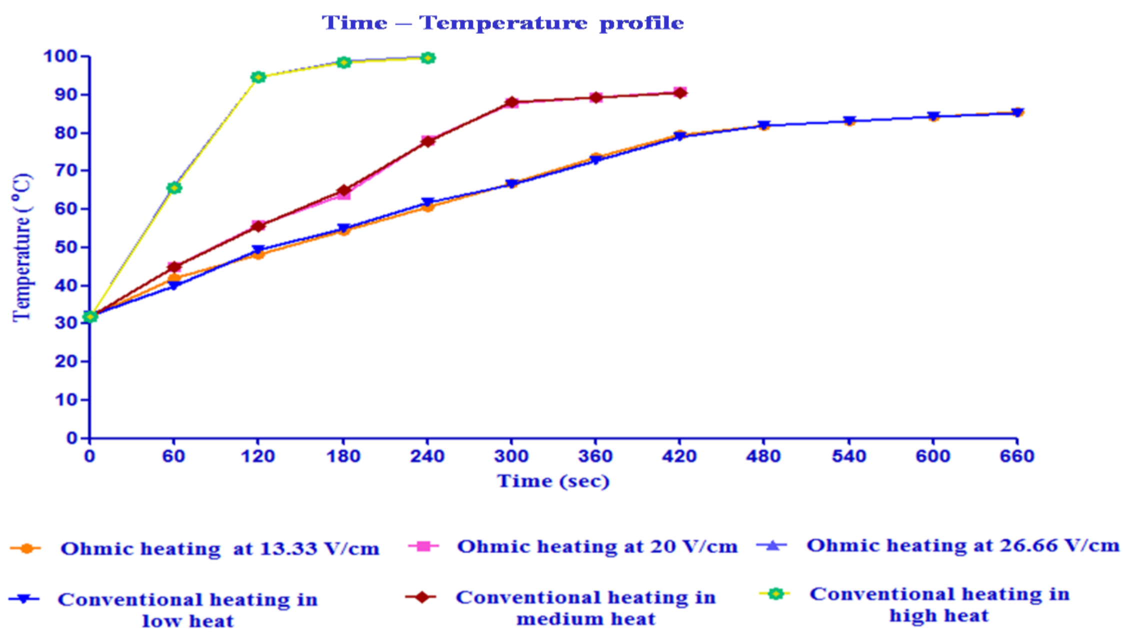


Figure 1. Change in temperature during pasteurization.

In a similar way, when lemon juice underwent ohmic heating within the voltage range of 30-55V/cm for a duration of 45 seconds, it manifested a bubbling point of 74ºC [17]. Analogously, in the case of tomato juice subjected to ohmic heating within the voltage range of 50-70 V/cm for a span of 48 seconds, the bubbling temperature was recorded at 80ºC [18]. The discernible pattern of escalated voltage gradients correspondingly translated into heightened electrical currents traversing the sample, thus fostering an accelerated heat generation and a commensurate reduction in the time required to attain the boiling point. Notably, the processing of tomato paste at voltage gradients of 6-14 V/cm necessitated an interval ranging from 235 to 38 seconds to attain a temperature of 96ºC [17]. In a similar vein, the application of voltage within the range of 20-40V/cm led to the grape juice achieving a temperature of 90ºC [19].

3.2. Effect of voltage gradient on electrical conductivity

The increase in temperature was accompanied by a corresponding elevation in electrical conductivity, a phenomenon in consonance with previously documented literature. Notably, when subjecting garlic pulp to ohmic heating at 13.33 V/cm, the electrical conductivity exhibited a substantial increase, escalating from 0.04 to 0.3 S/cm. Similarly, under treatments at 20 and 26.66 V/cm, the electrical conductivity displayed discernible increments, surging from 0.05 to 0.28 S/cm and 0.05 to 0.25 S/cm, respectively, as vividly depicted in Figure 4.27. This observable transformation may be ascribed to alterations in the structural composition of the biological tissue, including modifications in protopectin, the collapse of cell walls, the expulsion of gas bubbles, and a reduction in the viscosity of the sample. It is of note that the boiling point was ascertained to be 82ºC, and subsequent to the attainment of this bubbling temperature, a decline in the electrical conductivity of garlic pulp ensued. This decline could plausibly be attributed to the formation of electrolytic hydrogen bubbles, as posited by prior research [20].

The observed increase in electrical conductivity as a function of rising temperature finds explanation in the context of reduced drag movement. Moreover, a noteworthy disparity in electrical conductivities emerged across various voltage gradients, a fact that was substantiated by rigorous statistical analysis. Throughout the experimental trials, an unwavering linear trend in the ascent of electrical conductivity was consistently observed, compelling the utilization of a linear regression model to effectively model the trial data.

$$EC=MT+C \quad (10)$$

In the aforementioned equations, the constants M and C assume pivotal roles, while T signifies the temperature in degrees Celsius (ºC). The paramount significance of the linear model's appropriateness for elucidating the relationship between conductivity and temperature is exemplified by the attainment of the highest regression coefficient value (R^2>0.99). This metric serves as a discerning criterion for the selection of the most fitting model to encapsulate the intricacies of ohmic heating curves.

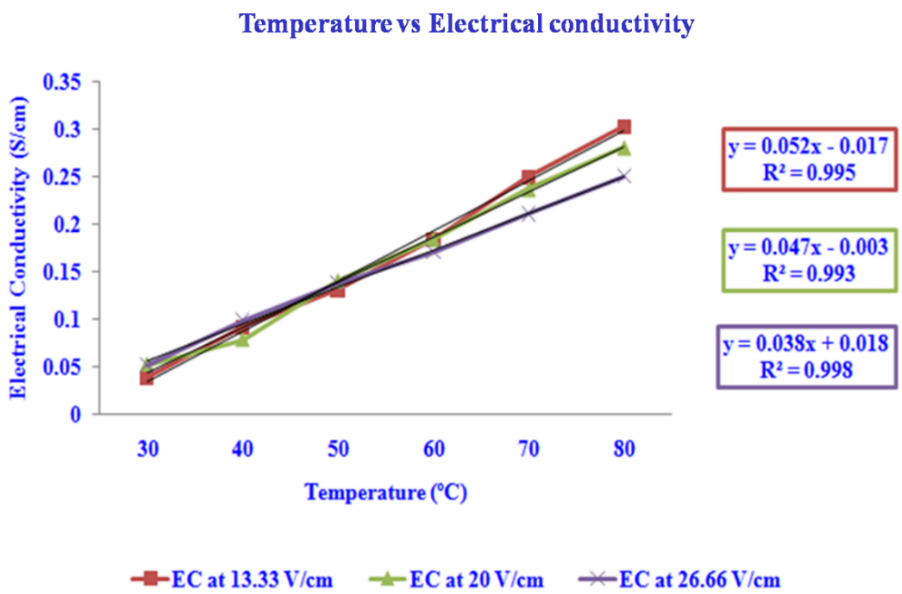


Figure 2. Effect of Electrical conductivity on temperature

Notably, the regression coefficient reached its zenith when garlic underwent ohmic heating at a substantial voltage gradient, specifically yielding an R^2 value of 0.998 at 26.66 V/cm. It is imperative to elucidate that the R^2 value, serving as the coefficient of determination, assumes an indispensable role in the discernment of the optimal model to delineate the nuances inherent in ohmic heating processes.

In the realm of food products, a diverse spectrum of electrical conductivity values ranging from 0.01 to 10 S/m has been documented [21]. For instance, when subjected to ohmic heating within the range of 20-60 V/cm, sour cherry juice exhibited electrical conductivity values spanning from 0.1 to 1.6 S/m [22]. Similarly, lemon juice, when subjected to ohmic heating at 30-55 V/cm, manifested conductivity values within the range of 0.4 to 1.0 S/m [23]. The conductivity of grape juice, when treated at voltage gradients spanning 20-40 V/cm, ranged from 0.38 to 0.78 S/m [19]. Furthermore, the electrical conductivity values for peach puree, apricot puree, and orange juice, when subjected to ohmic heating within the voltage range of 20-70 V/cm, exhibited variability in the range of 0.15 to 1.2 S/m. Notably, pomegranate, when subjected to ohmic heating, yielded an electrical conductivity ranging from 0.058 to 0.51 S/m [23].

3.3. Influence of different voltage gradients on System Performance Coefficient (SPC)

The System Performance Coefficient (SPC) was meticulously computed for each experimental trial by assessing the electrical energy injected into the system against the heat absorbed by the garlic sample. It is worth emphasizing that the applied voltage gradient emerged as a pivotal determinant significantly impacting both the energy input and output of the system, a relationship thoughtfully detailed in Table 4.5.

Evidently, there is a progressive amplification in the electrical energy supplied to the system as the voltage gradient increases, as corroborated by the tabulated data. Notably, when the sample underwent heating at 20 and 26.66 V/cm, the resulting SPCs were calculated at 0.418 and 0.415, respectively. Intriguingly, these values signify that approximately 60% of the electrical energy injected into the system remained untapped during the sample processing. In stark contrast, when ohmic heating was conducted at 13.33 V/cm, the SPC surged to 0.90. One plausible explanation for this variation is that the protracted heating time associated with the lower voltage gradient of 13.33 V/cm contributed to an increased accumulation of electrical energy.

In a broader context, liquid samples in general exhibit a spectrum of system performance coefficients, spanning from 0.4 to 1 [24]. This discernible shift between electrical energy and heat energy, aptly termed "energy loss" (Eloss), becomes more pronounced when a lower voltage gradient is applied. Impressively, when ohmic heating was carried out at 13.33 V/cm, the heat loss to the surroundings was found to be minimal, underscoring the profound influence of the sample's inherent properties on energy utilization. This observation carries significant implications for equipment design in the context of ohmic heating processes involving solid samples, as it suggests that not the entirety of the electrical energy is converted into thermal energy. Instead, a portion of the electrical energy appears to be allocated to physical, electrochemical, and chemical transformations within the food sample.

Consistently, the SPC values align closely with earlier findings, as evidenced by reported SPC ranges of 0.49-1, 0.62-1, and 0.52-0.92 when apricot puree, peach puree, and orange juice underwent ohmic heating within the voltage range of 20-70 V/cm [25]. Similarly, when subjecting lemon juice to ohmic heating at voltage gradients spanning 30-55 V/cm, SPC values within the range of 0.54-0.92 were documented [17].

System performance coefficient (SPC) is defined as:

$$SPC= Q/P$$

Mass of sample, m = 400 g
Specific heat of garlic, C_P = 3.31 J/gºC
Initial temperature of sample, T_i = 30 ºC
Final temperature of sample, T_f = 85 ºC

- $P=Q+ E_{loss}$
  - P= Electrical energy given to the system (J)
  - Q= Energy required to heat the sample (J)
- $P= \sum(VIt)$
  - V= Voltage applied (V)
  - I= Current (A)
  - t=Time (s)
- $Q=mC_P(T_f-T_i)$
  - M= Mass of the sample (kg)
  - C_P=Specific heat capacity (J/kgºC)
  - T_f = Final temperature (ºC)
  - T_i =Initial temperature (ºC)
- $\sum(VIt)= mC_P(T_f-T_i) + E_{loss}$

Table 1. Effect of different voltage gradients on system performance coefficient

Voltage gradient (V/cm)	Electrical energy given to the system, P (J)	Energy required to heat the system, Q (J)	Energy loss, E_{loss} (J)	System performance coefficient, SPC
13.33	80640	72820	7820	0.903
20	173880	72820	101060	0.418
26.66	175200	72820	102380	0.415

3.4. Optimization study on process parameter for differential pasteurization.

An exhaustive exploration into the optimization of process conditions for the pasteurization of garlic pulp has been undertaken. This comprehensive study encompassed the examination of various physicochemical properties, including pH, acidity, total color difference, and ascorbic acid content, both prior to and following pasteurization, employing both ohmic and conventional techniques.

Remarkably, the pH of the garlic pulp exhibited discernible variations based on the applied voltage gradient, as meticulously tabulated in Table 4.6. Notably, the pH value exhibited a direct correlation with treatment duration, displaying an upward trajectory as the voltage gradient diminished. This phenomenon can be attributed to the prolonged residence time, which engenders the hydrolysis of garlic pulp and concurrent corrosion of the electrodes, inherent to the ohmic heating process. To illustrate, under conditions of a high voltage gradient (26.66 V/cm), the relatively brief residence time resulted in a marginal pH increase of 0.48%. Conversely, when subjected to ohmic heating at 13.33 V/cm, the considerably protracted residence time yielded a more substantial pH increase, amounting to 2.79%. The consequential elevation in pH was concomitant with a reduction in the acidity of the garlic pulp.

Table 2. Optimization of process parameter for pasteurization

Treatments	pH	Acidity %	TCD	Ascorbic acid (mg/100g)
Unpasteurized garlic pulp	$5.49±0.01^{h}$	$1.25±0.03^{a}$	-	$26.55±0.39^{a}$
OH at 13.33 V/cm, 1 min	$5.64±0.02^{c,d}$	$1.10±0.01^{d,e,f,g}$	3.51	$10.59±0.34^{f}$
OH at 13.33 V/cm, 2 min	$5.69±0.01^{b}$	$1.06±0.02^{g,h}$	3.65	$09.45±0.19^{g}$
OH at 13.33 V/cm, 3 min	$5.79±0.01^{a}$	$1.04±0.02^{h}$	4.43	$07.74±0.19^{h}$
OH at 20 V/cm 1 min	$5.60±0.02^{d,e,f}$	$1.13±0.01^{c,d,e}$	3.36	$13.10±0.39^{c}$
OH at 20 V/cm, 2 min	$5.63±0.01^{c,d}$	$1.10±0.01^{d,e,f,g}$	3.40	$11.85±0.19^{d}$
OH at 20 V/cm, 3 min	$5.77±0.02^{a}$	$0.94±0.01^{i}$	4.08	$10.71±0.19^{e,f}$
OH at 26.66 V/cm, 1 min	$5.52±0.03^{h}$	$1.15±0.02^{c,d}$	2.45	$15.61±0.19^{b}$
OH at 26.66 V/cm, 2 min	$5.56±0.01^{f,g}$	$1.17±0.01^{b,c}$	3.20	$13.21±0.19^{c}$
OH at 26.66 V/cm, 3 min	$5.61±0.01^{d,e}$	$1.12±0.01^{c,d,e}$	3.37	$11.51±0.52^{d,e}$
CH in low heat, 1 min	$5.65±0.01^{b,c}$	$1.09±0.02^{e,f,g,h}$	3.57	$09.34±0.39^{g}$
CH in low heat, 2 min	$5.69±0.01^{b}$	$1.07±0.02^{f,g,h}$	3.85	$07.74±0.19^{h}$
CH in low heat, 3 min	$5.80±0.01^{a}$	$0.91±0.02^{i}$	4.74	$06.26±0.19^{i}$
CH in medium heat, 1 min	$5.61±0.01^{d,e}$	$1.12±0.01^{c,d,e,f}$	3.37	$12.76±0.19^{c}$
CH in medium heat, 2 min	$5.66±0.02^{b,c}$	$1.09±0.01^{d,e,f,g}$	3.48	$11.16±0.19^{d,e}$
CH in medium heat, 3 min	$5.78±0.01^{a}$	$0.92±0.02^{i}$	4.28	$09.57±0.34^{g}$
CH in high heat, 1 min	$5.52±0.01^{g,h}$	$1.22±0.01^{a,b}$	2.84	$14.81±0.19^{b}$
CH in high heat, 2 min	$5.57±0.01^{e,f}$	$1.16±0.01^{c}$	3.21	$11.73±0.19^{d}$
CH in high heat, 3 min	$5.64±0.01^{d,e}$	$1.11±0.01^{d,e,f,g}$	3.7	$10.48±0.19^{f}$

Furthermore, the evaluation of the total color difference before and after processing revealed a notably diminished alteration when ohmic heating was conducted at 26.66 V/cm (for a duration of 2 minutes), as well as during conventional heating at high heat settings (for a duration of 2 minutes). The observed degradation in ascorbic acid content during pasteurization can be attributed to a multifaceted interplay of factors, including the applied heat treatment, chemical oxidation, degradation via anaerobic pathways, and electrochemical degradation arising from electrode reactions. These intricate processes collectively contribute to the alteration of the ascorbic acid content in garlic pulp during the pasteurization process [26].

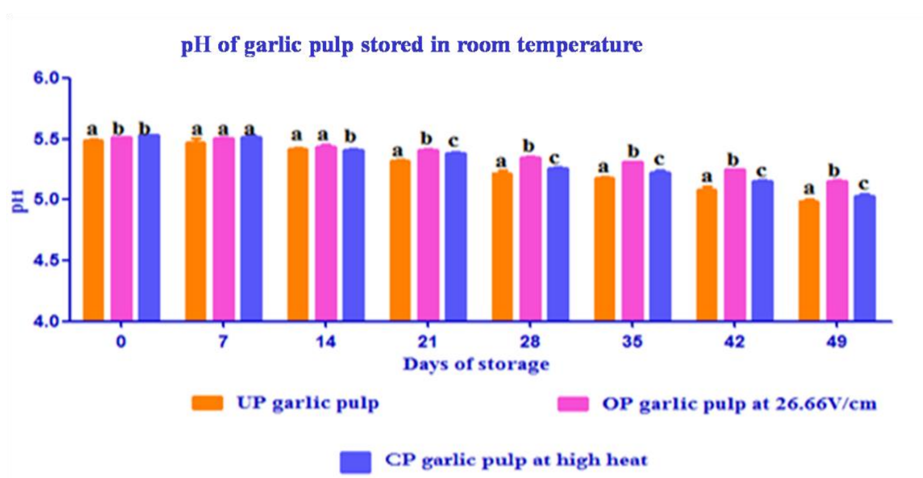
3.5. Change in pH

In the pursuit of optimizing process conditions, the pH of garlic pulp both before and after pasteurization was subjected to rigorous analysis. Initially, the pH of the unprocessed garlic pulp was determined to be 5.49±0.011. Following pasteurization, whether through ohmic heating (at voltage gradients of 13.33, 20, and 26.66 V/cm) or conventional heating (at low, medium, and high heat settings) for varying durations of 1, 2, and 3 minutes, an observable increase in pH was consistently noted. This shift in pH was observed to intensify with prolonged treatment time and a corresponding decrease in voltage gradient. This phenomenon can be attributed to the breakdown of hydrogen bonds and the accumulation of ions around the iso-electric point. It is particularly pronounced in treatments with extended residence times, such as garlic pulp pasteurized through conventional heating at low heat and ohmic heating at 13.33 V/cm for 3 minutes, which exhibited the most substantial pH changes, with increases of 5.4% (5.7±0.005) and 5.6% (5.8±0.01), respectively. In contrast, the least pronounced pH alterations were observed in garlic pulp ohmically pasteurized at 26.66 V/cm for 2 minutes (5.56±0.02, a change of 1.3%) and conventionally pasteurized at high heat for 2 minutes (5.57±0.015, a change of 1.5%). Hence, these two treatments were identified as the optimized parameters for pasteurization.

In subsequent storage studies, unpasteurized garlic pulp and garlic pulp subjected to pasteurization via ohmic heating (26.66 V/cm, 2 minutes) and conventional heating (high heat, 2 minutes) were packaged in glass bottles and stored at both room temperature and refrigeration temperature. Over the storage period, a consistent decrease in pH was observed for both pasteurized and unpasteurized garlic pulp, as depicted in Figure 4.28. Notably, the rate of pH decline was more pronounced at room temperature compared to refrigeration temperature. Under refrigeration conditions, the pH of unpasteurized and conventionally pasteurized garlic pulp remained stable for up to 7 days before gradually decreasing. In contrast, the pH of ohmically pasteurized garlic pulp remained unchanged for up to 14 days. Unpasteurized garlic pulp displayed a more rapid rate of pH change compared to pasteurized garlic pulp.

For instance, when stored at room temperature, unpasteurized garlic pulp exhibited a percentage reduction in pH of 9.1% (4.9±0.01) after 49 days. Under refrigeration, the pH showed a decrease of 5.5% (5.19±0.01) after 49 days and a further decrease of 18.9% (4.45±0.025) after 77 days. Similarly, ohmically pasteurized garlic pulp, when stored at room temperature, showed a decrease of 6.7% (5.15±0.017) after 49 days. In refrigeration conditions, the pH exhibited a decrease of 4.1% (5.29±0.01) after 49 days and a further decrease of 12.3% (4.84±0.015) after 77 days. In line with the room temperature storage, conventionally pasteurized garlic pulp displayed a decrease of 8.9% (5.03±0.015) in pH after 49 days. When refrigerated, the pH exhibited a decrease of 5.6% (5.22±0.01) after 49 days and a further decrease of 14.8% (4.71±0.005) after 77 days.

The observed pH changes can be attributed to electrochemical reactions between the electrode and garlic pulp, involving processes such as hydrolysis and corrosion. Electrochemical reactions lead to the loss of buffering capacity, with electrode corrosion being a result of electro-dissolution caused by low-frequency alternating current. Importantly, it was noted that when ohmic heating was applied to tomato paste within the voltage range of 6-14 V/cm, the pH change was significantly less [27]. This trend aligns with findings in pomegranate juice during ohmic heating [28].



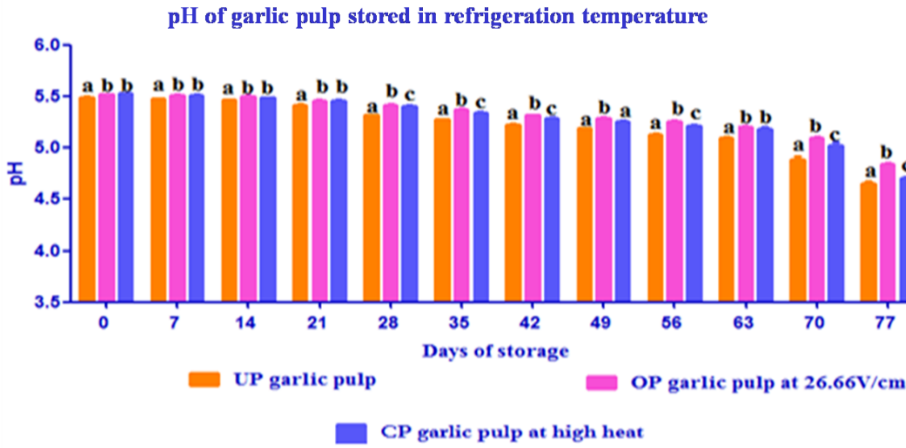


Figure 3. Change in pH of garlic pulp during storage

3.6. Effect on acidity

In the quest to optimize process parameters, the acidity of garlic pulp was meticulously examined both before and after treatment. It was discerned that alterations in pH directly influenced the acidity of garlic pulp, with the acidity demonstrating a decreasing trend with increasing process time. The initial acidity percentage of unpasteurized garlic pulp stood at 1.25±0.01%. Notably, garlic pulp subjected to prolonged treatment times, such as conventional heating at low heat and ohmic heating at 13.33 V/cm for 3 minutes, exhibited more pronounced changes in acidity, amounting to 0.91±0.005% and 1.04±0.005%, respectively. Conversely, garlic pulp ohmically pasteurized at 26.66 V/cm for 2 minutes and conventionally pasteurized at high heat for 2 minutes displayed minimal percentage changes in acidity, with values of 1.17±0.02% and 1.16±0.05%, respectively. These two treatments were subsequently identified as the optimal parameters for pasteurization.

In the context of storage studies, garlic pulp differentially pasteurized under these optimized conditions was hermetically sealed in glass bottles and stored at both room temperature and refrigeration temperature. Over the course of the storage period, the acidity of both pasteurized and unpasteurized garlic pulp displayed an upward trajectory, regardless of the storage conditions.

Specifically, unpasteurized garlic pulp, when stored at room temperature, exhibited a percentage increase in acidity of 17.9% (1.5±0.006%) after 49 days, as depicted in Figure 4.29. In the case of refrigeration storage, the acidity showed a percentage increase of 9% (1.34±0.012%) after 49 days and a more substantial increase of 23.3% (1.65±0.06%) after 77 days.

Similarly, for garlic pulp ohmically pasteurized and stored at room temperature, the acidity presented an increase of 15.3% (1.45±0.012%) after 49 days, while conventionally pasteurized pulp displayed an increase of 17% (1.47±0.02%) during the same timeframe. Conversely, in refrigeration storage conditions, ohmically pasteurized garlic pulp showed a percentage increase in acidity of 9.8% (1.36±0.006%) after 49 days, with an additional increase of 17.3% (1.49±0.006%) observed on the 77th day. Conventionally pasteurized garlic pulp, when stored in similar refrigeration conditions, exhibited a relatively rapid increase in acidity during the storage period, recording a percentage increase of 10.8% (1.37±0.006%) after 49 days and a further increase of 20% (1.57±0.012%) on the 77th day.

These shifts in acidity may be attributed to the utilization of organic acids for energy synthesis, alongside hydrolysis of pulp and electrode corrosion, all of which can contribute to fluctuations in the acidity of garlic pulp during storage. Notably, similar findings have been reported in studies involving sweet lime juice [29], sapota juice [30], watermelon juice, and processed tomato paste [31].

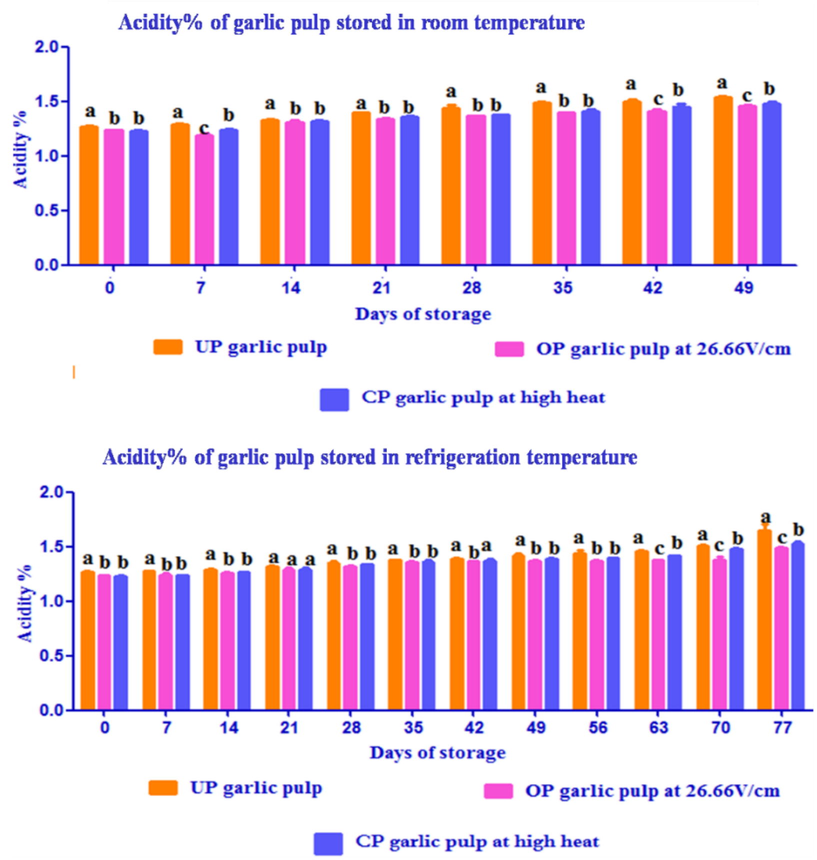


Figure 4. Change in acidity of garlic pulp during storage

3.7. Change in Total Colour Difference (TCD)

Color is a pivotal sensory attribute that profoundly influences consumer acceptance of a product. Notably, the applied voltage gradient in the pasteurization process exerts a discernible influence on color change. In the pursuit of process parameter optimization, the Total Color Difference (TCD) of garlic pulp was diligently assessed both before and after treatment. It was observed that an increase in process time, coupled with a decrease in voltage gradient, resulted in an escalation of the total color difference. This phenomenon is primarily attributed to the shortened residence time associated with higher voltage gradients, notably 26.66 V/cm.

Furthermore, during the storage period, the TCD exhibited a more pronounced progression in unpasteurized garlic pulp compared to pasteurized pulp, as vividly illustrated in Figure 4.30. Unpasteurized garlic pulp displayed a marked increase in TCD, rising from 0 to 38 after 49 days of storage at room temperature. When stored in refrigeration conditions, the TCD surged from 0 to 45.3 after 77 days.

For garlic pulp subjected to pasteurization via both ohmic and conventional heating, the TCD increased to 2.45 and 2.84, respectively. During storage at room temperature, the color of ohmic pasteurized garlic pulp exhibited an increase of 89% (23.9), while conventional pasteurized garlic pulp displayed a 92% increase (35.5) after 49 days. In refrigeration conditions, ohmic pasteurized garlic pulp displayed a TCD increase of 63.3% (6.69) and 82% (13.9) on the 49th and 77th day of storage, respectively. Conversely, conventionally pasteurized garlic pulp demonstrated a more rapid progression in color change, manifesting a percentage increase of 72% (10.1) and 90% (28) on the 49th and 77th day of storage under refrigeration conditions.

The visual representation of the color change in differentially pasteurized garlic pulp is vividly depicted in Figure 4.31. It becomes evident that the color of garlic pulp degraded over 49 days of storage at room temperature, while in refrigeration conditions, the color of pasteurized garlic pulp remained relatively stable for approximately 77 days. This phenomenon is attributed to degradation, particularly linked to the browning of garlic pulp, a process influenced by the presence of oxygen and metal ions. The pasteurized garlic pulp's color change is further exacerbated by electrode corrosion associated with ohmic heating.

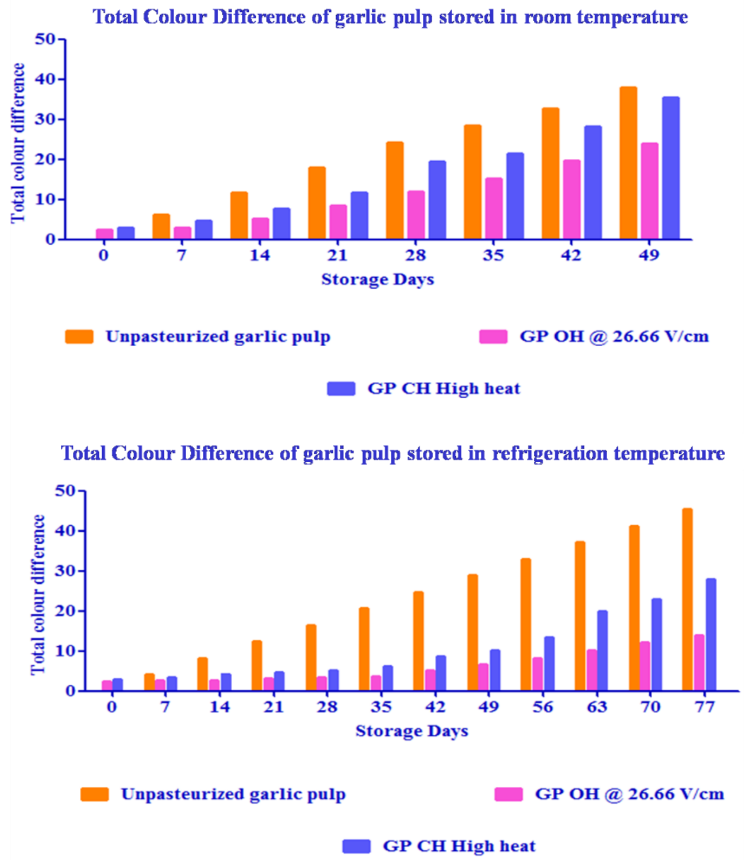


Figure 5. Change in total colour difference of garlic pulp during storage#

All the values are means of triplicate determination

UP: Unprocessed; OP: Ohmic Processed; CP: Conventionally Processed

In the broader context, food substances are replete with ligands, and during ohmic heating, the transition of metal ions occurs, leading to the formation of various coordination complexes, essential minerals for processed foods, which inherently possess colors that alter the overall appearance of the processed food product. The application of a low electric field in this context results in heightened color changes, often attributed to the occurrence of electrochemical reactions. However, it is worth noting that no significant color change was observed when ready-to-eat pineapple samples were subjected to ohmic heating at voltage gradients of 20 and 30 V/cm, coinciding with a reduction in polyphenol oxidase activity [32]. Analogously, similar findings were reported in studies involving sapota juice subjected to ohmic heating at voltage gradients ranging from 15 to 30 V/cm [30] and pea puree ohmically heated at 20 V/cm [33].

3.8. Change in ascorbic acid content of garlic pulp during storage

Ascorbic acid, a delicate and heat-sensitive nutrient, is known to undergo degradation through both aerobic and anaerobic mechanisms. Aerobic degradation occurs in the presence of oxygen, metal ions, enzymes, and sugars, while anaerobic degradation is induced by thermal heating [34]. Due to the anaerobic mechanism, the ascorbic acid content in garlic pulp experienced a decline following pasteurization via both ohmic and conventional methods. This decline in ascorbic acid content can be attributed to factors such as the solid content of the pulp and the applied voltage gradients [35]. Initially, the ascorbic acid content of unpasteurized garlic pulp stood at 26.5±0.31 mg/100 ml, which subsequently decreased to 15.6±0.2 mg/100 ml and 14.8±0.2 mg/100 ml after pasteurization via ohmic and conventional methods, respectively, as illustrated in Figure 4.32.

During storage, the degradation of ascorbic acid content was even more pronounced. Notably, the rate of degradation was more substantial in unpasteurized and conventionally pasteurized garlic pulp compared to ohmically heated pulp. Unpasteurized garlic pulp, for instance, exhibited a significant decline, with an initial ascorbic acid content of

3.26±0.017 mg/100 ml, indicating a degradation percentage of 87.7% after a 49-day storage period at room temperature. In contrast, ohmically and conventionally pasteurized garlic pulp experienced significant degradation, reducing to 5.1±0.032 mg/100 ml (a decrease of 67%) and 4.2±0.005 mg/100 ml (a decrease of 71%), respectively, when stored at room temperature for 49 days.

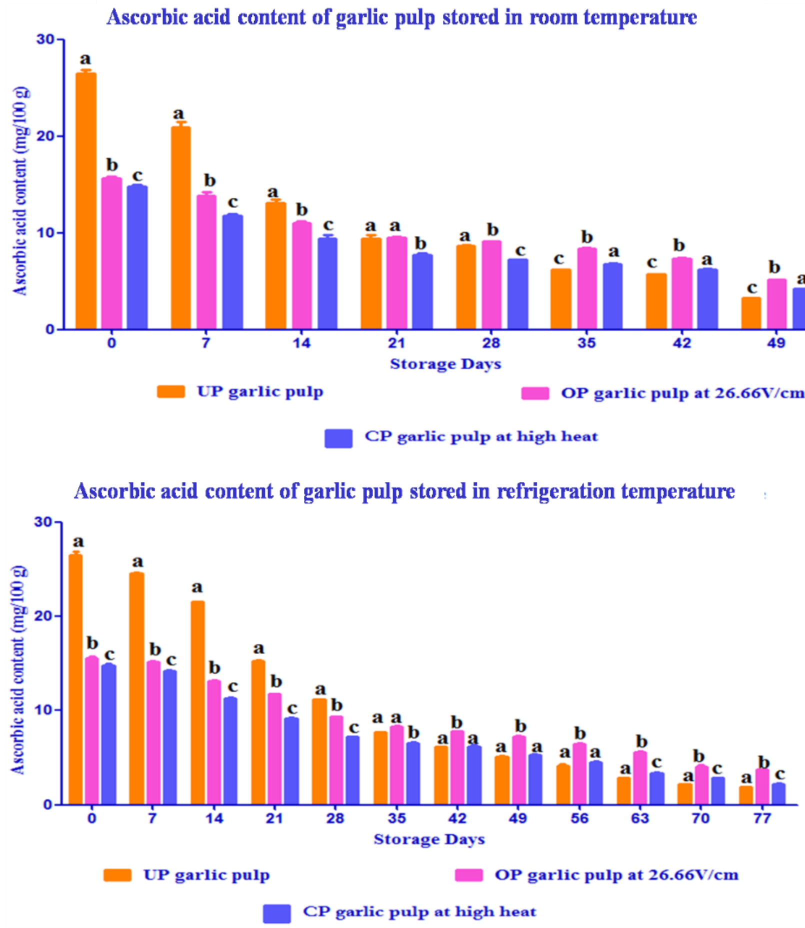


Figure 6. Change in ascorbic acid content of garlic pulp during storage

Similarly, in refrigeration conditions, the ascorbic acid content of unpasteurized garlic pulp decreased to 5.14±0.07 mg/100 ml (an 80.6% decrease) and 1.93±0.02 mg/100 ml (a 92.7% decrease) after 49 and 77 days of storage, respectively. Meanwhile, ohmic pasteurized garlic pulp decreased to 7.26±0.05 mg/100 ml (a 53.4% decrease) and 5.37±0.03 mg/100 ml (a 76% decrease) after 49 and 77 days of storage. For conventionally pasteurized garlic pulp stored in refrigeration conditions, a decrease of 5.33±0.05 mg/100 ml (a 64% decrease) and 2.19±0.19 mg/100 ml (an 85% decrease) was observed after 49 and 77 days.

During ohmic heating, aside from degradation due to heat, additional deterioration occurs due to electrode reactions and the chemical decomposition of the solution by electric current. Furthermore, degradation can be influenced by the interactions between the chemically decomposed material and the electrode. The loss of ascorbic acid content in acerola pulp is attributed to reactions induced by the applied electric field. Similar findings have been reported in studies involving ohmically heated sapota juice [30] and ohmically heated sweet lime juice [29].

3.9. Impact on Diallyl disulphide content

The sustainability of diallyl disulphide in garlic pulp following differential processing and during the storage period was meticulously analyzed using High-Performance Liquid Chromatography (HPLC). To facilitate this analysis, a reference standard of diallyl disulphide was meticulously prepared at varying concentrations using a methanol and hydrochloric acid solution. Subsequently, HPLC was conducted using a mobile phase comprising methanol and water, and the resulting chromatogram was detected at a wavelength of 210 nm. The retention time for diallyl disulphide was precisely determined to be 2.9 minutes. Utilizing the area and standard concentrations, a calibration curve was thoughtfully constructed, yielding the linear regression equation Y=10.9X+1905, with an R2 value of 0.992.

Differentially processed garlic pulp samples were then prepared for HPLC analysis and subsequently injected into the system. The diallyl disulphide content was effectively separated using a C18 column, and the resulting chromatograms are thoughtfully presented in Figures 4.33 and 4.34. Initial analysis indicated that unpasteurized garlic pulp contained 0.051 g/100g of diallyl disulphide content. However, over the storage period, this quantity notably decreased, reaching 0.006 g/100g after 77 days, marking an 87.2% reduction in the bioactive compound content. Notably, this change was influenced by the pasteurization technique employed.

Following differential pasteurization, garlic pulp was observed to contain diallyl disulphide content of approximately 0.021 g/100g and 0.02 g/100g, respectively. However, after a shelf life period of 77 days, these values decreased to 0.013 g/100g and 0.01 g/100g, as depicted in Figure 4.35. It's worth noting that ohmic pasteurized garlic pulp exhibited less degradation (38%) compared to conventionally pasteurized garlic pulp (48.2%). This decrease can be attributed to the heat treatment applied during processing and the subsequent storage conditions.

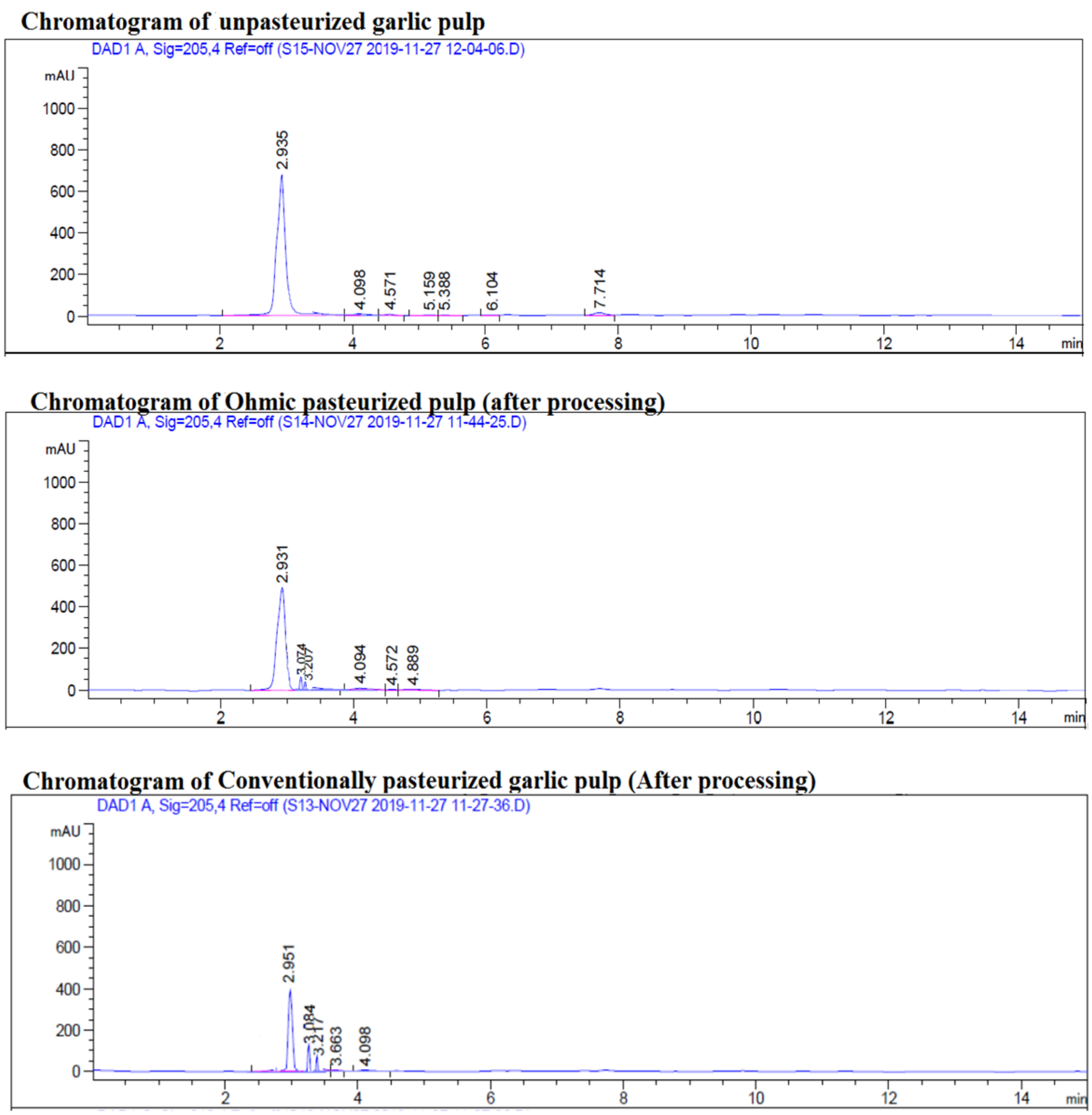


Figure 7a. Chromatogram of diallyl disulphide content in garlic pulp after differential processing

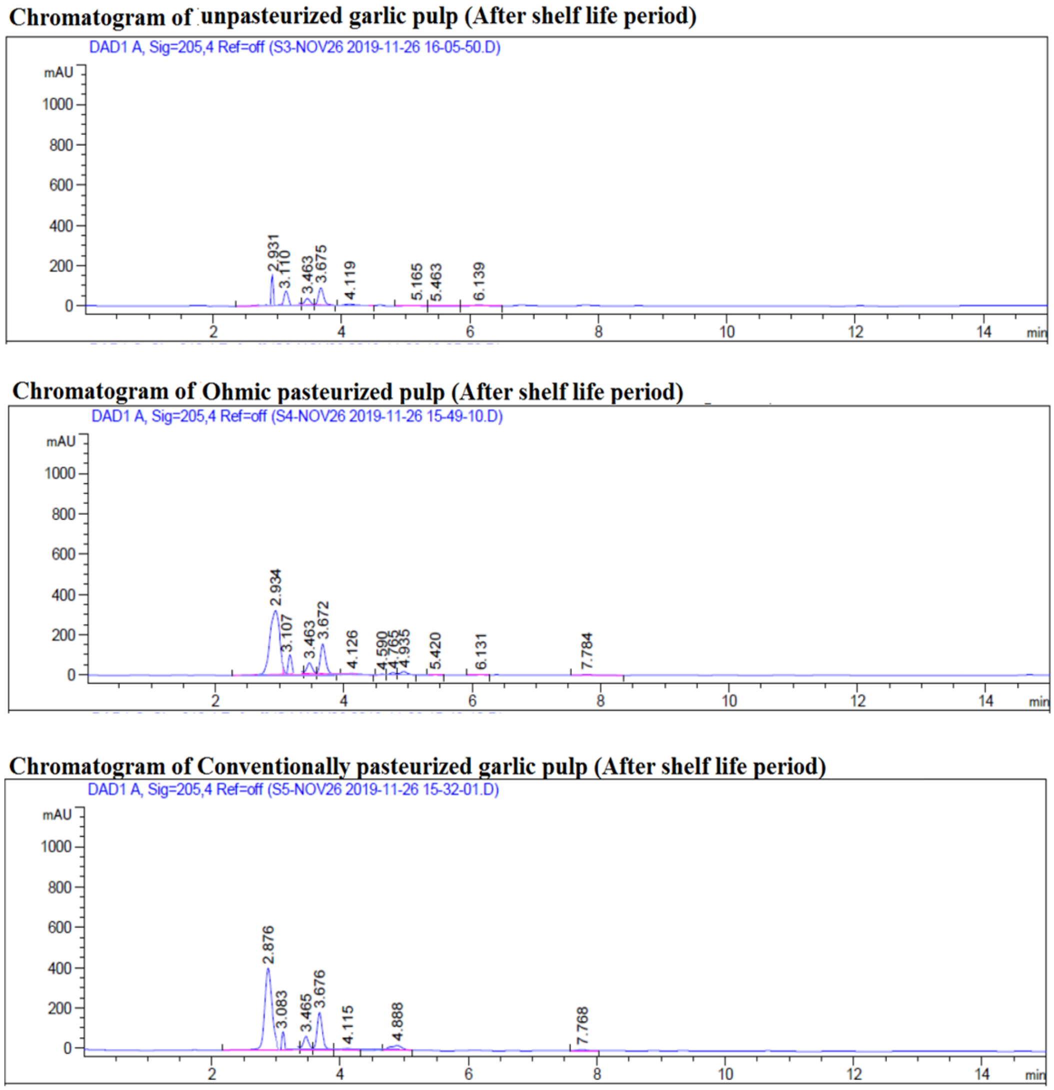


Figure 7b. Chromatogram of diallyl disulphide content in garlic pulp after storage period of 77 days

In a related study, the retention of glucomannan content by ohmic pasteurization was investigated in aloe vera gel juice [36]. Additionally, research on pink grapefruits and oranges subjected to ohmic heating was conducted to analyze the retention of their carotenoid profile, which includes lycopene, lutein, cis-violaxanthin, zeaxanthin, cis-antheraxanthin, and beta-cryptoxanthin [37].

3.10. Influence of Variable Pasteurization Methods on Microbial Proliferation in Stored Garlic Pulp

In accordance with FSSAI regulations, the permissible total plate count for thermally processed vegetable pulp is limited to 50 CFU/ml. Observations regarding microbial growth in ohmic and conventionally pasteurized garlic pulp, as well as unpasteurized pulp, were made under different storage conditions.

When stored at room temperature, both ohmic pasteurized and conventionally pasteurized garlic pulp began showing traces of microbial growth after 15 days of storage. In contrast, unpasteurized pulp became spoiled within the same 15-day period. Under refrigeration conditions, unpasteurized garlic pulp exhibited microbial degradation after 20 days. Conventionally pasteurized garlic pulp, on the other hand, indicated bacterial growth after 45 days of storage in refrigeration temperature, while ohmic-heated garlic pulp managed to prevent microbial growth for up to 75 days, as detailed in Table 4.7. A visual representation of microbial growth in differentially processed garlic pulp is presented in Figure 4.36. The observed increase in microbial load can be attributed to variations in pH during the storage period. Therefore, it can be concluded that ohmic heating at 26.66 V/cm is effective in preventing spoilage in garlic pulp.

Table 3. Microbial growth in differential processed garlic pulp stored in room temperature

Storage days	Unpasteurized	Ohmic pasteurized at 26.66 v/cm	Conventionally pasteurized at high heat
Storage at room Temperature			
0	46.6 ± 5.7	-	-
15	53.3 ± 5.7[a]	10.0[b]	10.0[b]
30	76.6 ± 5.8[a]	23.3 ± 5.8[b]	36.6 ± 5.7[b]
45	123.3 ± 11.5[a]	43.3 ± 5.7[b]	63.3 ± 5.7[b]
Storage at refrigeration temperature			
0	46.6 ± 5.7	-	-
15	46.6 ± 5.7	-	-
30	66.6 ± 5.7[a]	-	13.3 ± 5.7[b]
45	103.3 ± 11.5[a]	13.3 ± 5.7[b]	36.6 ± 5.7[c]
60	133.3 ± 5.7[a]	30.0 ± 10.0[b]	66.7 ± 5.7[c]
75	176.6 ± 5.7[a]	46.6 ± 5.7[b]	93.3 ± 5.7[c]

This microbial inhibition through ohmic heating is consistent with findings in other studies. For instance, when orange juice is ohmically heated, complete bacterial inactivation was achieved [38]. Similarly, reduced D values (a measure of microbial lethality) were observed in ohmically heated milk compared to conventionally heated milk [39]. A similar pattern was observed in aonla pulp [40], and comparable results were reported in a study investigating the positive effect of ohmic heating on preventing the growth of yeasts, molds, and mesophiles in strawberries [41]. The inhibition of microbial growth in ohmic heating may be attributed to the low-frequency nature of this technique, which can cause pore formation in the cell wall, leading to cellular damage [42] and subsequently hindering microbial proliferation [43].

4. CONCLUSION

In conclusion, this study underscores the significant potential of ohmic heating as a transformative technology for enhancing the quality and safety of garlic pulp. Through meticulous examination of physicochemical, microbiological, and bioactive content parameters, we have demonstrated that ohmic heating surpasses conventional processing methods in preserving the integrity of this valuable agricultural product.

The observed improvements in color retention and texture, coupled with the stable pH levels, affirm ohmic heating as a superior alternative to traditional methods. This technology not only maintains the sensory attributes of garlic pulp but also ensures its intrinsic acidity remains unaltered, a critical aspect for culinary applications.

Furthermore, the study has illuminated the profound impact of ohmic heating on microbial safety. The uniform heat distribution achieved by this method leads to a substantial reduction in microbial load, effectively surpassing the efficacy of conventional approaches. This enhancement in safety standards is of paramount importance, particularly in the context of ensuring food safety for consumers.

Perhaps most promising is the remarkable preservation of bioactive compounds, including allicin, alliin, and diallyl disulfide, as revealed through HPLC analysis. This retention of essential phytochemicals underscores ohmic heating as a means to enhance the nutritional and health benefits associated with garlic consumption.

The implications of this research extend beyond garlic processing, offering a paradigm shift in the approach to handling and preserving agricultural produce. The adoption of ohmic heating technology stands poised to revolutionize not only the garlic industry but also broader segments of the food processing sector.

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