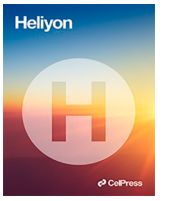
Heliyon 10 (2024) e25504

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Research article

Continuous decontamination of cumin seed by non-contact induction heating technology: Assessment of microbial load and quality changes

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ARTICLE INFO

Keywords:
Decontamination
Microbial load
Induction heating
Essential oil
Spices

ABSTRACT

Over the past few decades, the demand for high-quality food has increased steadily. Therefore, it is essential to develop innovative technologies that effectively reduce microbial load while minimizing any negative effect on the quality of spices. The objective of this study was to determine the efficacy of a self-designed non-contact induction heating system using contaminated cumin seeds. The non-contact induction heating decontamination process was performed at different temperatures of 115, 135 and 155°C and durations (45, 60 and 75 s) through continuous process (screw conveyor) in Pyrex cylinder chamber. Various parameters including microbial load, color characteristics, essential oil content, surface morphology, sample temperature, and energy consumption were analyzed as dependent variables in the study. The results showed that the treatment combination (155°C - 60 s) reduced the aerobic plate count from 6.21 to 2.97 CFU/g. Mold, yeast and coliforms in the treatment combination (155°C-45 s) were also reduced by 3.26 and 3.6 CFU/g, respectively. The total color difference of the samples increased due to the degradation and alteration of pigments at high temperatures. However, no statistically significant disparity in essential oil content was observed between the treatment groups and the control group. The quantities of essential oil components in the cumin seeds were determined to align with the ISO standard, with the primary constituents identified as follows: Terpinen-7-al γ (38.98%), Cumin aldehyde (20.75%), γ-Terpinene (18.81%), β-Pinene (13.66%), and p-Cymene (6.2%). In summary, non-contact induction heating system shows promise as an effective technology for surface decontamination of spices. The acquired findings contribute to a deeper understanding of the impact of the induction heating process on both the microbial contamination levels and the quality attributes of cumin seeds. This scientific knowledge serves as a foundational framework for the prospective adoption and integration of this technology on a larger industrial scale.

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https://doi.org/10.1016/j.heliyon.2024.e25504
Received 3 November 2022; Received in revised form 17 January 2024; Accepted 29 January 2024
Available online 4 February 2024

1. Introduction

Spices have high economic value due to their wide-ranging characteristics such as taste, color, aroma, and medicinal properties. Key spices that hold significant prominence in global trade encompass cardamom, vanilla, cinnamon, cassia, turmeric, and cloves in tropical regions, and cumin, bay, mustard, thyme, and mint in non-tropical regions. The quality of spices plays a significant role in determining their level of consumption and export value. The evaluation of spice quality involves a comprehensive examination of their physical, chemical, and microbiological characteristics. Chemical characteristics involves the assessment of essential oils and extracts (especially oleoresin). On the other hand, physical attributes entail evaluating texture, shape, impurities, and color [1,2].

Cumin (Cuminum cyminum L.) is a herbaceous annual plant belonging to the Apiaceae family. It is predominantly cultivated in countries such as India, Syria, Iran, Turkey, and China [3]. Cumin seeds are widely recognized and utilized as a popular spice globally valued for their distinctive flavor, and nutritional benefits [4–7]. Cumin seeds contain 3–4% essential oil, which can be extracted using steam or water distillation. Cumin aldehyde, β-Pinene, γ-Terpinene and p-Cymene are the key components of cumin seed essential oil used in the pharmaceutical, perfumery and food industries [8,9].

The microbial contamination of whole cumin is a matter of substantial concern, as it carries the potential to adversely impact consumer safety, result in the degradation of active compounds and nutritional attributes, and affect export trade while also influencing compliance with the quality standards established by importing nations. Moreover, in certain instances, the contamination of cumin can lead to a decrease in the product's shelf life and promote the accumulation of mycotoxins [10–13]. Hence, Efforts must be made to minimize or completely eradicate the microbial load on the product's surface. The decontamination of spices yields value-added products, reduces waste, extends shelf life, and enhances overall customer safety.

A range of equipment and techniques has been employed to address contamination issues in spices, herbs, and their derivative products. Traditional methods like gamma-irradiation and heat treatment, while effective to some extent, come with inherent limitations that have spurred the exploration of alternative approaches. These conventional methods have been associated with concerns such as the generation of potentially toxic and carcinogenic substances, as well as diminished consumer acceptance due to alterations in odor, color, flavor, and the reduction of volatile compounds [14–16]. Therefore, there is a growing demand for emerging technologies that can efficiently reduce microbial contamination while minimizing the negative effects on food quality.

In recent years, researchers have undertaken investigations into an array of innovative technologies, including ultraviolet, cold plasma, infrared, microwave, radio frequency and combinations thereof, to address the challenge of decontaminating spices [17]. Among these emerging technologies, induction heating has garnered significant attention and has been utilized in the decontamination and drying processes [18–21]. Non-contact induction heating is a method for heating a conductive material, typically a metal, through the application of electromagnetic induction. This process generates eddy currents within the metal, and the resulting resistance results in Joule heating. In cases involving non-conductive materials or samples with intricate geometries, a secondary susceptor can be used, although it's worth noting that its heat capacity might impose limitations on the heating and cooling rates. Eddy currents can be induced in any conductive material, but the magnetic hysteresis effect is unique to magnetic materials. The process of inductive heating boasts an impressive efficiency, with up to 95% of electrical energy being converted into heat. This allows for the conservation of at least 17% of the necessary energy in thermal processes for food materials, including the use of steam in pasteurization processes [22,23].

Lamo et al. (2019) developed an induction pasteurization method for guava juice. According to their results, treatment conditions at a temperature of 95 °C resulted in relative stability of the fruit juice for up to 40 days [24]. Wang et al. (2020) employed an induction-based method for pasteurization of liquid whole eggs. In this study, eggs were positioned within a glass container together with magnetic microbeads and subjected to a fluctuating magnetic field. Heat was generated in the microbeads through magnetic hysteresis and transferred to the product. The findings revealed that following a 60-s induction pasteurization process at 68°C, the Salmonella count was diminished by 6.7 CFU/g. This finding is comparable with the performance of the conventional heating method, which achieved a reduction of 6 CFU/g at 60°C for 210 s [20].

It is worth noting that there exists a notable dearth of research on the topic of induction heating, and our understanding of its impact on microorganisms and the quality characteristics of spices remains quite limited. Since most spice contaminants are found on the surface of the product and the internal parts are typically free of microorganisms, surface decontamination is sufficient to remove the contamination. The objective of this study was to assess the efficacy of non-contact induction heating treatment for surface decontamination of cumin seeds and evaluate its impact on a range of quality parameters associated with the seeds.

2. Material and methods

2.1. Materials

The cumin seeds in their whole form, which were employed in this research, were sourced from the central herbal market located in Tehran, Iran, in June 2022. Upon procurement, the seeds were promptly transferred to the Engineering Properties of Biological Materials Lab for subsequent examination. Post-acquisition, a meticulous screening process was conducted to eliminate any impurities or extraneous substances. Subsequently, the samples were placed in polyethylene bags and stored at a laboratory temperature of 23.0 $\pm$ 2.0°C until they were prepared for further analysis. The cumin seeds initially had a moisture content of 10.1% and a water activity of 0.67. Microbial culture media (Plate Count Agar, Potato Dextrose Agar and Violet Red Bile Agar) used in this study were purchased from Merck (Darmstadt, Germany).

2.2. Sample treatment

In the present study, a continuous non-contact induction heating system (lab-scale) was used for decontamination of cumin seeds. The schematic diagram of the induction heating system is shown in Fig (1). The system consisted of several components, including a screw conveyor (length: 120 cm, diameter: 7.5 cm, pitch: 3.5 cm), a Pyrex cylinder chamber with open ends (outer diameter: 8 cm, length: 70 cm), five induction coils (number of turns: 9, inner diameter: 8 cm), induction heating modules, a direct current (DC) power supply (24 V - 15 A), an electric motor (power: 30 W, speed: 63 rpm), a control circuit, a laptop, an inlet and outlet tube, a sample tank, and a seed outlet duct. The screw conveyor is positioned within a Pyrex cylinder chamber that is both heat-resistant and non-conductive. This chamber is enveloped by five induction coils. Each of these induction coils within the system can be controlled individually, providing the capability for on/off operations. The induction heating system has a maximum power output of 1500 W and operates at a frequency of 100 kHz. During the process, the screw conveyor was subjected to alternating electromagnetic field. The heat generated on the conveyor is transferred into the chamber through conduction and radiation mechanisms. Data observation and parameter control were accomplished using a control circuit. Temperature parameters were monitored using two K-type thermocouples placed inside the chamber, specifically at the inlet and outlet sections of the chamber. Before starting the process, an infrared thermometer was used to validate the temperature measured by the K-type thermocouple. The temperature difference between the infrared thermometer and the K-type thermocouple was taken into account in the calculations. This value varied in the range of $\pm 2^{\circ}C$. For each experiment, a mass flow rate of 5 g/s was maintained while loading the samples into the induction heating chamber. In each trial, 300 g of sterilized seeds were utilized. The conveyor system transported and rotated, facilitating the transfer of seeds from the heating zone to the outlet, where they were collected in sterile bags. In this study, the decontamination temperature was continuous. After adjusting the temperature (The temperature was regulated using the control circuit) and reaching a steady state, the decontamination process was started for each treatment. However, the gap between the induction coils did not disrupt the temperature continuity and it can be assumed that the temperature was continuous and uniform throughout the chamber. Following the decontamination process, the cumin samples were stored in bags at a temperature of $4^{\circ}C$.

2.3. Infrared thermal camera

In this study, a thermal imaging camera was employed to examine the surface temperature of the cumin seed samples treated with induction heating. Temperature measurements were promptly recorded once the samples were extracted from the heating chamber within the system. Thermal imaging is a rapid, non-destructive, and non-contact method used to ascertain the temperature of an object. This is achieved by sensing and quantifying the infrared radiation emitted from the object's surface. A thermal camera (A65, FLIR, Sweden) was utilized to measure the surface temperature of the cumin seed samples subjected to induction heating. The thermal camera was positioned parallel to the sample, maintaining a distance of 40 cm from the sample surface. The surface temperature of the product was measured at various points. In this study, a K-type thermocouple was used to adjust the emissivity. For this purpose, the temperature of the cumin seeds was then allowed to reach a steady state and then the emissivity setting on the infrared thermal camera was adjusted until it registered the same temperature as the thermocouple. The observed emissivity value was determined to be 0.95. Also, the following equation (Equation (1)) was used to compute values of CEM43°C. This method converts any time-temperature history into an equivalent number of minutes of heating at 43°C.

$$CEM43 = \int_0^t R^{43-T_i} dt \tag{1}$$

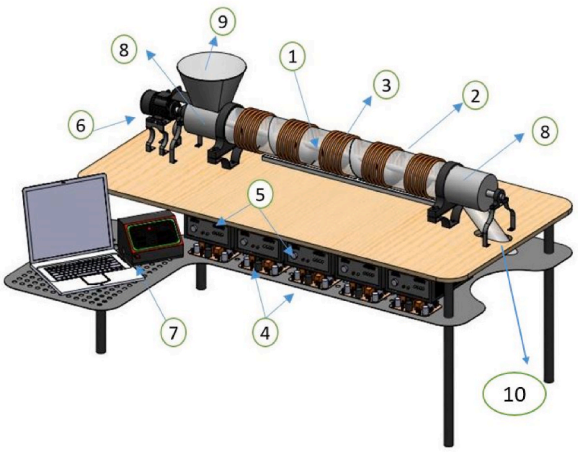

Fig. 1. Experimental set up of non-contact induction heating system: (Screw conveyor (1), Pyrex cylinder chamber (2), induction coils (3), induction heating modules (4), direction current power supply (5), electric motor (6), control circuit and laptop (7), inlet and outlet tube (8) and sample tank (9)).

where, CEM43 °C is the cumulative number of equivalent minutes at 43°C, t is the time interval, R is related to the temperature dependence of the rate of cell death (R (T < 43°C) = 0.25, R (T > 43°C) = 0.5) and T represents the actual applied temperature of the target tissue [25–27].

2.4. Microbiological analysis

Evaluation of survivability of aerobic plate count, mold and yeast, and coliforms of treatment and control sample (the samples that were not treated) were carried out in three replications for each treatment. In summary, 10 g of cumin seeds were randomly selected and combined with 90 mL of sterile saline solution. The mixture was then homogenized using a magnetic stirrer. In the next step, a tenfold serial dilution was prepared and plated on specific agar media: Plate Count Agar (incubated at 30 °C for 48 h) for aerobic plate count, Potato Dextrose Agar (incubated at 30°C for 72 h) for mold and yeast, and Violet Red Bile Agar (incubated at 37°C for 48 h) for coliforms. The results were reported as log colony forming units per gram (CFU/g) of the sample [28].

2.5. Color analysis

A colorimeter, specifically the HunterLab ColorFlex from the USA, was employed to gauge the color indices of the cumin surface. In this procedure, a layer of cumin seeds was placed into a Petri dish for each treatment, and the colorimeter provided values for CIE L*, a*, and b* color indices [29]. Also, the total color difference of the sample was calculated using Equation (2).

$$\Delta E = \left((\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\right)^{1/2} \tag{2}$$

$$\Delta L = (L_2^* - L_1^*); \Delta a = \left(a_2^* - a_1^*\right) and \Delta b = (b_2^* - b_1^*)$$

In the equation, L* color index represents the lightness of the cumin seeds, with higher values denoting lighter colors. The a* color index gauges the extent of greenness (with negative values) to redness (with positive values) in the color of the seeds. A positive value indicates a more reddish hue, whereas a negative value suggests a more greenish appearance. The b* color index represents the degree of blueness (with negative values) to yellowness (with positive values) in the color of the seeds. To clarify further, a positive value in the b* color index indicates more yellowness in the color, while a negative value implies more blueness. The ΔE signifies the total color difference between the treated samples and the control sample. The values L^*_1, a^*_1, and b^*_1 correspond to the color indices of the control sample, while L^*_2, a^*_2, and b^*_2 represent the color indices of the cumin seeds after undergoing the treatment [30].

2.6. Essential oil analysis

The essential oil of cumin seeds was extracted using a Clevenger-type apparatus, following the method described in the European Pharmacopeia [31]. For this purpose, 30 g of the seeds were mixed with 400 mL of distilled water. The extraction process took 4 h, after which the water and essential oil mixture was treated with anhydrous sodium sulphate (Na_2SO_4) to remove the water content. The essential oil obtained was subsequently preserved in a freezer until it was prepared for analysis through gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS) systems. The quantity of essential oil was determined using the formula outlined in Equation (3) [32,33].

$$\text{Essential oil amount} = \frac{weight\ of\ extracted\ essential\ oil}{weight\ of\ cumin\ powder} * 100 \tag{3}$$

The essential oil analysis was performed using a GC instrument model 7890 B from Agilent Technologies (USA). The GC was equipped with a flame ionization detector (FID) and an HP-5 column with dimensions of 30 m in length, 0.32 mm in inner diameter, and a film thickness of 0.25 μm. Helium gas was used as the carrier gas, flowing at a linear velocity of 1.1 mL/min. The oven temperature was programmed to initiate at 60°C and maintained for 5 min, following which it was raised at a rate of 5°C per minute until it reached a temperature of 250°C.

The essential oil components were analyzed using a gas chromatography-mass spectrometry (GC-MS) device model Trace GC/MS from Thermoquest Finnigan (USA). The sample injection volume was set at 0.2 mL, and the injector temperature was maintained at 250°C. The GC column featured dimensions of 30 m in length, an internal diameter of 0.25 mm, and a film thickness of 0.25 μm. The ionization voltage was established at 70 eV, and the mass scan range spanned from 40 to 460 atomic mass units (amu). Helium, as the Carrier gas with a flow rate of 1.1 mL/min and a split ratio of 1/100 was used. The oven temperature ranged from 60 to 250°C, with specific time intervals at 0, 38, and 40 min. The identification of all essential oil components was performed by comparing their retention indices and mass spectra with those stored in the NIST[1] database. Moreover, the peak retention indices were cross-referenced with a series of n-alkanes (ranging from C8 to C24) subjected to the same operating conditions to corroborate the identification of essential oil components [34,35].

[1] National Institute of Standards and Technology.

2.7. Scanning electron microscopy (SEM)

In this study, scanning electron microscopy (XL 30 SEM, Philips, Netherlands) was used to examine the effect of non-contact induction heating treatment on the surface morphology of cumin seeds. Seed samples were affixed to aluminum specimen stubs using carbon glue. These samples were subsequently coated with a thin layer of gold and subjected to analysis at a voltage of 25 kV, a current intensity of 75 μA, and within a vacuum pressure of 10e-5 mbar.

2.8. Energy consumption

A power analyzer (DW-6090, Lutron, Taiwan) was used to calculate the amount of energy consumed throughout the treatment. The probes of the power analyzer were strategically positioned along the route of the input electrical supply to the induction heating system. This configuration enabled the measurement of the energy consumption for each treatment.

2.10. Statistical analysis

The experiment adhered to a completely randomized design and utilized a factorial approach. The independent variables in this study were the decontamination temperature (115, 135, and 155 °C) and decontamination duration time (45, 60, and 75 s), while the dependent variables included microbial load (aerobic plate count, mold and yeast, and coliform), color indices, essential oil content, and energy consumption. The experiments were conducted in triplicate and mean ± SD[2] are presented. Analysis of variance was performed using the GLM procedure of SAS 9. The Tukey test was employed to compare the means of the various treatments. The level of significance of differences between treatments was determined at 95 % confidence intervals.

3. Results and discussion

3.1. Microbial load analysis

Table 1 displays the ANOVA results for microbial load. Temperature and decontamination time duration, as well as their interactions had a substantial influence on aerobic plate count, mold, yeast, and coliforms (99% confidence intervals). Microbial load of different treatments and control samples are shown in Fig. 2. Aerobic plate count values ranged from 2.97 to 6.21 CFU/g. The aerobic plate count in all treated samples was significantly reduced compared to the control sample (95% confidence intervals). The treatment combination of 155 °C for 60 s (g) yielded the most substantial reduction in aerobic plate count (2.97 CFU/g), which decreased by 3.24 CFU/g in comparison to the control sample (6.21 CFU/g). However, no significant difference was found between the treatment combination of 155°C for 60 and 155°C for 45 s in terms of aerobic plate count.

In addition, the amount of mold and coliform for different treatments ranged from 3.01 to 6.27 CFU/g and 2.16–5.76 CFU/g, respectively. In all the treated samples, there were significantly lower levels of mold, yeast, and coliform in comparison to the control sample (95% confidence intervals). Notably, among the treatments, the combination of 155°C for 45 s demonstrated the most substantial reduction in mold and yeast (3.17 CFU/g) as well as coliform (3.6 CFU/g) compared to the control sample (6.27 CFU/g). The results showed that increasing the temperature and decontamination time duration led to a decrease in microbial load compared to the control sample.

However, it is worth noting that there was a notable observation concerning the microbial load of the samples, specifically an increase in aerobic plate count as well as mold and yeast, as the decontamination time duration was extended at higher temperatures (155°C) (95% confidence intervals), could potentially be attributed to the slow rotational speed of the screw conveyor. In other words, poor product mixing during the decontamination process caused this phenomenon. Previous research has discovered connections between temperature distribution uniformity of induction heating system and material pasteurization.

Non-contact Induction heating for surface decontamination exhibits a notable correlation between temperature and decontamination time duration, as higher values of these parameters lead to a rapid increase in the surface temperature of the sample. The thermal effect generated by non-contact induction heating plays a pivotal role in accomplishing the decontamination process. This heat generation mechanism bears similarity to infrared radiation and is capable of causing damage to the DNA, RNA, and proteins within microbial cells. Consequently, this process effectively inactivates microorganisms present on the surface of the treated product [36,37].

These findings are in accordance with the results obtained in prior studies. For example, Pijls et al., 2017 have reported that exposure to temperatures of 60°C and higher for 3.5 min resulted in a 6-log reduction or more in microorganisms (S. epidermidis, *S. aureus*, *P. aeruginosa*, C. albicans, and B. cereus). At this temperature, the shortest effective induction heating time was 1.5 min, leading to a 6-log reduction or higher in the targeted microorganisms [38]. Furthermore, in a similar study, Pijls et al., 2020 found that induction heating with the 24-h biofilm model at temperatures of 50°C, 55°C, 60°C, 65°C, 70°C, 80°C, and 90°C led to a reduction of 1.0 log, 3.2 log, 4.4 log, 5.0 log, 5.8 log, 6.4 log, and 6.9 log in CFUs/cm^2, respectively. Under the conditions of no antibiotic treatment within the seven-day biofilm model, at a temperature of 60°C, reductions of 6.7 log and 5.2 log in CFUs/cm^2 were achieved within 3.5

[2] Standard deviation.

Table 1
The effect of temperature and time of process on microbial load of cumin seed samples during decontamination.

Sources	df	Mean of square		
		Aerobic plate count (CFU/g)	Mold and yeast (CFU/g)	Coliform (CFU/g)
Decontamination temperature (°C)	2	2.96[a]	2.46[a]	6.88[a]
Decontamination time duration (s)	2	0.3[a]	0.43[a]	0.054[b]
Temperature × time	4	0.28[a]	0.38[a]	0.12[a]
Error	18	0.003	0.003	0.016
CV (%)	–	1.48	1.6	4.007

[a] Significance at the 1% level.
[b] Significance at the 5% level.

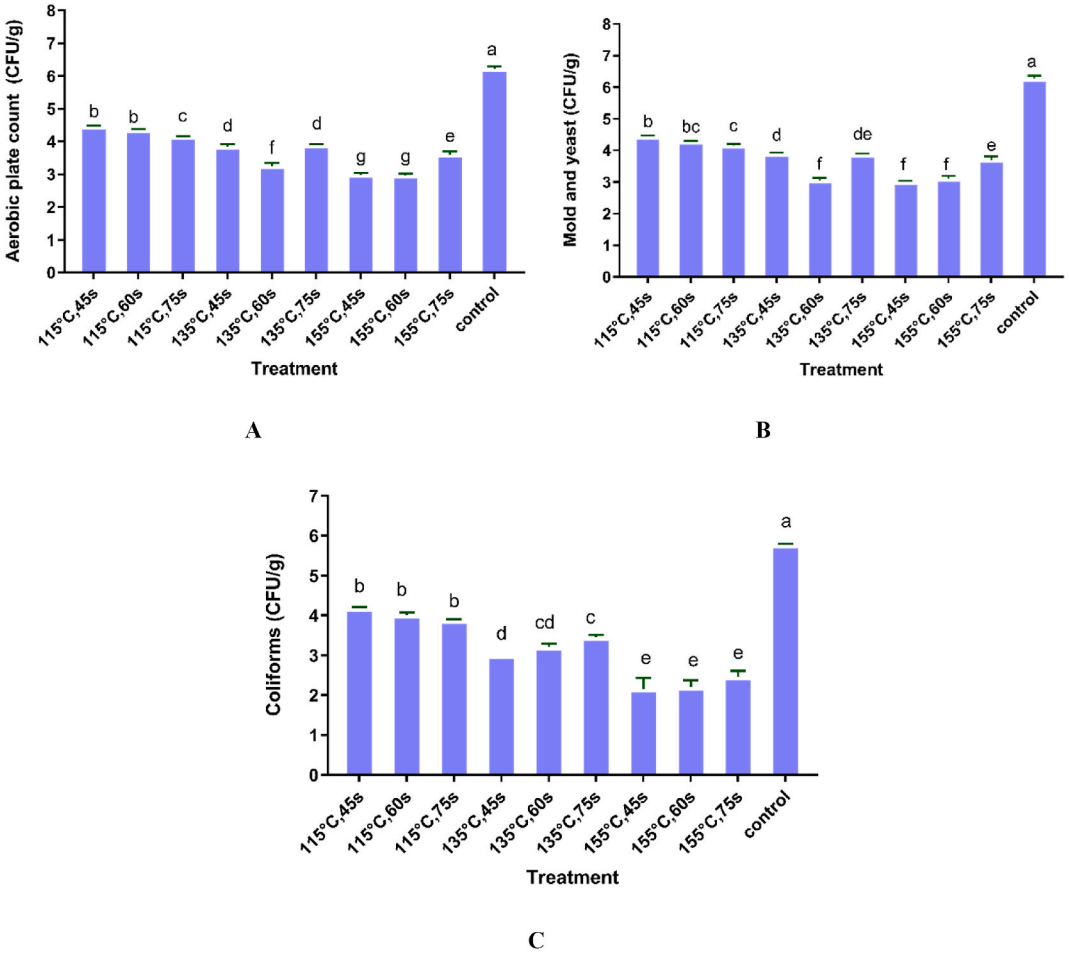

Fig. 2. Log reduction of microbial load on cumin seeds processed using a lab scale non-contact induction heating chamber at different treatment; (a) Aerobic plate count, (b) Mold and yeast, and (c) Coliforms (Error bars represent standard deviation from three replicates. Different lowercase letters above the error bars indicate a significant difference between mean treatment groups at 95 % confidence intervals.

min and 1 min, respectively [39]. In addition, Tsai et al. (2022) found that the optimal heating conditions (microwave-assisted induction heating) for pasteurization of barramundi meat, taking into account appearance, microbial count and texture, were reported to be 90°C for 110 s and 70°C for 130 s [40].

The application of induction heating treatment resulted in a significant reduction in aerobic plate count, mold and yeast, and coliform by 3.24, 3.26 and 3.6 log units, respectively. This reduction in microbial counts (measured in log units) can be attributed to several factors, including the unique mechanism of induction heating, the initial contamination level of the samples, the botanical species, the conditions under which the spices were stored, the quantity of sterilized samples used, and the duration of the treatment process. It is important to highlight that the aerobic plate count and mold and yeast in the cumin seeds ultimately met the microbial contamination standards for spices, as established by the World Health Organization (WHO) [41] which are typically set at 10^4 CFU/g

for aerobic plate count and 10^3 CFU/g for mold and yeast.

The conveyor speed in this study allows for adjustment of the decontamination time. In other words, increasing the decontamination time resulted in a lower rotational speed of conveyor. The interaction effect between temperature and time on the microbial load (aerobic plate count, mold and yeast, and coliforms) was significant (99% confidence intervals), as can be seen in Table 1. This suggests that the microbial load variable is influenced by both independent variables. It can be inferred that at a temperature of 135°C and a time of 60 s, temperature is the predominant factor in the decontamination process. However, at a time of 75 s (especially with the low rotational speed of the conveyor), time becomes the dominant variable, leading to less uniform decontamination and, consequently, a higher microbial load.

3.2. Color parameter analysis

The results of the ANOVA for the color indices and total color differences of the treated samples and the control sample are shown in Table 2. The main effect of the temperature variable had a significant effect on the a*, b* color indices, and total color differences (99 % confidence intervals). Additionally, the interaction effects of the decontamination temperature and time duration (temperature-time) had a significant effect on the L* parameter. Increasing the decontamination temperature and time duration resulted in partial changes in the L* color index in different treatments (95 % confidence intervals). Increasing the temperature and decontamination time effectively led to an increase in the a* and b* color indices in different treatments compared to the control sample (95 % confidence intervals). The values of the a* index varied between 3.34 and 6.16, and the values of the b* parameter ranged from 10.46 to 14.15 in the various treatment conditions. The lowest values for both the a* and b* color indices were noted in the treatment involving a temperature of 115°C and a time duration of 60 s (Fig. 3). The comparative findings of the mean ΔE values at different treatment conditions are depicted in Fig. 3. The ΔE values spanned from 2.7 to 4.87, with the smallest value recorded in the treatment involving 115°C for 45 s. Additionally, the most significant color changes were observed at the highest decontamination time duration and temperature. Generally, the redness and yellowness of the samples increased with increasing decontamination temperature and decontamination time duration in the current study. However, the effect of temperature on color change was more pronounced compared to the effect of time duration. Indeed, the observed color changes in the current study are consistent with previous research on thermal treatments. Heat treatments can lead to the degradation and alteration of chlorophyll pigments, leading to the formation of pheophytin and subsequent discoloration of the sample [42]. Consequently, longer treatment durations result in more significant pigment degradation and, consequently, more noticeable color changes. These findings are in line with prior studies investigating the effects of heat on color changes in various food products [43,44].

3.3. Scanning electron microscope analysis

Presently, electron microscopy has garnered substantial attention in the food and pharmaceutical industries for investigating how various technologies, including drying, pulsed electric field, and ultrasound, influence the microstructure and surface attributes of a wide range of food products [45]. Thermal and non-thermal food decontamination may result in changes in natural structure (pore size and number) and sample composition [46]. Electron microscope images of non-contact induction heating treatments and control samples are shown in Fig. 4 (A-D). Elevated decontamination temperatures induced alterations in the surface structure of cumin seeds in contrast to the control sample. It's important to note that cumin seeds typically possess a hard and relatively impermeable outer layer, which can impede the extraction of essential oils. The non-contact induction heating treatment caused pores and cracks in the seed surface. This may be due to an instantaneous heat shock to the product during induction process. Previous research has reported analogous results regarding the impact of infrared treatment on peanut oil extraction. Examination via electron microscopy unveiled that the infrared treatment led to damage in the microstructure of cells and the membranes of oil bodies, ultimately resulting in enhanced oil extraction. As a result, there was a significant increase in oil yields compared to the control group (8.74%) [47]. In another study, the effectiveness of induction heating method was compared with conventional heating methods for the extraction of pectin from citrange fruit (at temperature of 80°C and extraction time of 90 min). Electron microscopy analysis revealed that the heating treatment induced significant changes in the surface morphology of the extracted product. Furthermore, it was noted that higher treatment temperatures resulted in the disruption of the cellular structure of parenchymal cells and an expansion of the intercellular space within the plant samples [48].

Table 2
The effect of temperature and time duration on color indices and total color differences of cumin seed samples during decontamination.

Sources	Df	Mean of square			
		L*	a*	b*	ΔE
Decontamination time duration (s)	2	0.29	0.877[a]	0.306	0.29 [ns]
Decontamination temperature (°C)	2	0.96	11.29[a]	10.55[a]	12.63[a]
Temperature × time	4	1.52[a]	0.03	0.074	0.07 [ns]
Error	18	0.35	0.058	0.126	0.24
CV (%)	–	1.45	5.18	2.72	14.54

[a] Significance at the 1% level.
[ns] not significant.

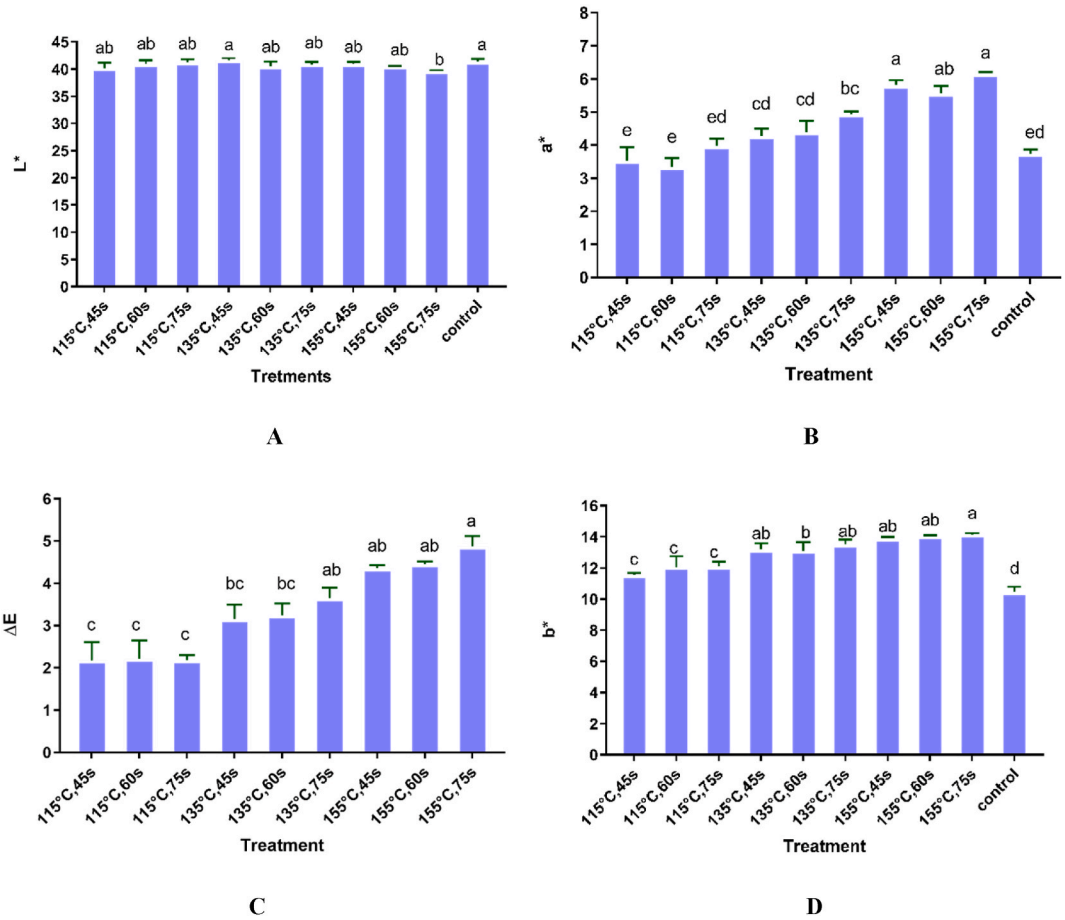

Fig. 3. Average values of color indices and total color differences of cumin seeds processed using a lab scale non-contact induction heating chamber at different treatment; (a) L*, (b), a*, (c) Δ*E*, and (d) b* (Error bars represent standard deviation from three replicates. Different lowercase letters above the error bars indicate a significant difference between mean treatment groups at 95 % confidence intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.4. Surface temperature analysis

Thermal imaging results provide information on the sample's surface temperature distribution, dimensions, and structural analysis [49–52]. Fig. 5 (A-C) depicts images related to the temperature treatment of 155°C. In the samples subjected to decontamination processes lasting 45, 60, and 75 s, the product temperature ranged from 73.9°C to 103.2°C, 68°C–93.6°C, and 68.2°C–87.9°C, respectively. The average temperature of these samples (Sp1-Sp4) was approximately 86.47°C, 79.97°C, and 77.5°C, respectively. The initial surface temperature of cumin seeds was 25°C, which increased during the decontamination process. The increase in temperature was driven by heat transfer between the screw conveyor and the product's contact surface. The temperature difference between the surface temperature of the conveyor (decontamination temperature) and the temperature of the product can be attributed to the duration of the decontamination process. As a consequence of the limited time available for decontamination, the product may not have adequate time to attain the same temperature as the decontamination temperature of the conveyor. The temperature of the processed sample plays a crucial role in determining the physico-chemical properties of the product. To minimize heat shock and preserve the product's quality, it is important to implement a rapid cooling process immediately after the decontamination process [53]. In high-temperature heating processes, it is generally advisable to keep the decontamination times as brief as possible to mitigate the loss of volatile compounds and uphold the quality parameters of the product [54].

In this study, product surface average temperatures of 86.47, 79.97, and 77.5°C (Fig. 5- Sp1-Sp4) were used to calculate thermal doses. These values refer to the treatment combination of 155°C-45 s, 155°C-60 s, and 155°C-75 s. After the final calculations, the log-transformation was performed. According to the images related to the temperature treatment of 155°C, the value of CEM43°C (log CEM43 °C) for treatment combinations 155°C-45 s, 155°C-60 s and 155°C-70 s was 12.96, 11.13 and 10.48 min, respectively.

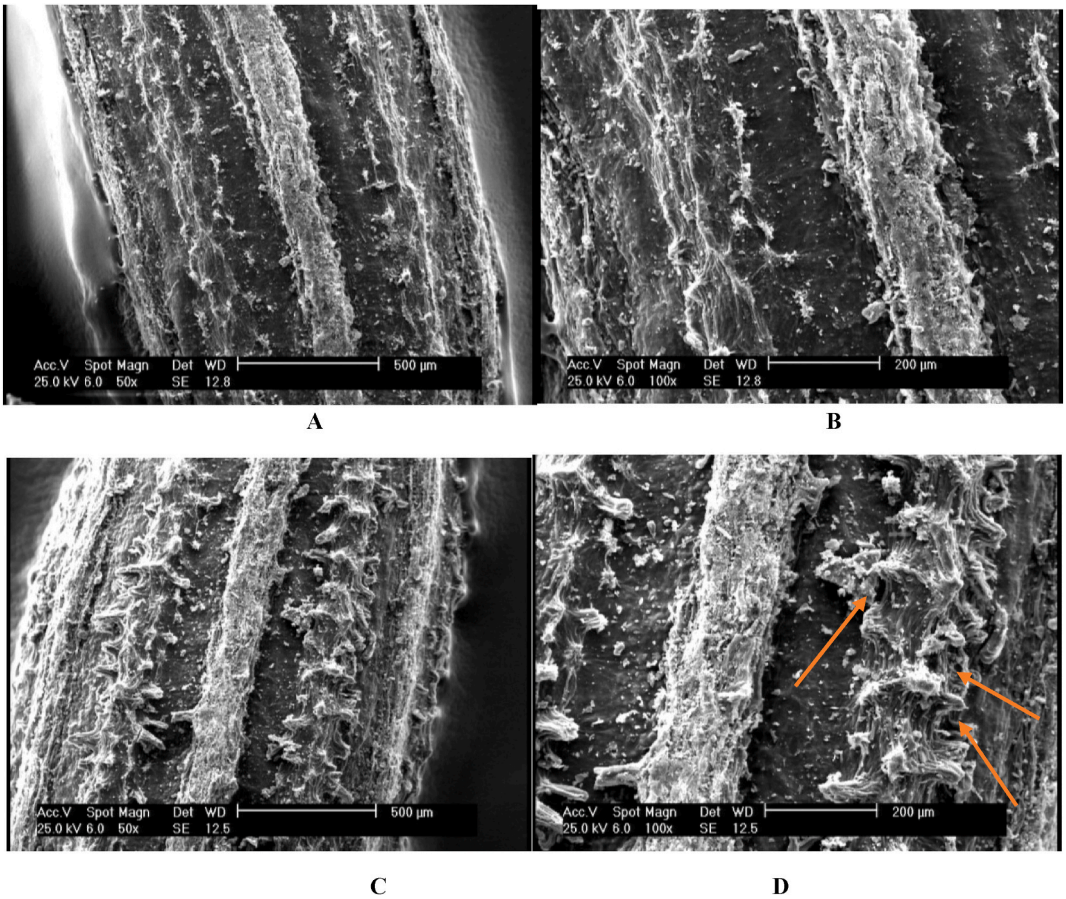

Fig. 4. Scanning electron micrographs of cumin seed samples; (a) control sample (Magnification: 50 ×), (b) control sample (Magnification: 100 ×), (c) non-contact Induction heating sample (155-45s) (Magnification: 50 ×), (d) non-contact Induction heating sample (155-45s) (Magnification: 100 ×).

3.5. Evaluation of the essential oil content and its compounds

The essential oil amount and related compounds were analyzed to determine the effect of different decontamination treatments on the phytochemical compounds of cumin seeds. Table 3 shows the ANOVA results of essential oil in different treatments. The interactions of temperature and decontamination time duration had a very significant effect on the essential oil content (99% confidence intervals). Fig. 6 illustrates the fluctuation in essential oil content across various non-contact induction heating treatments and the control sample. The essential oil content of different treatments ranged from 1.69 to 2.74%. There was no discernible distinction in the essential oil content among the various treatment combinations when compared to the control sample. The treatment combination involving 155°C for 45 s yielded the highest quantity of essential oil, whereas the treatment combination of 115°C for 45 s had the lowest amount. However, compared to the control sample, the non-contact induction heating treatment led to a slight increase in the essential oil content, particularly in the treatment combination of 155°C for 45 s. The hard and impermeable outer layer of the control sample may result in reduced essential oil production. Plant cell walls predominantly consist of cellulose and pectin. As cell walls are further broken down or disrupted, more plant chemicals are released [32]. According to the electron microscope images, the increment of essential oil extraction was caused by the physical change of the seed surface and the shattering of the surface texture of cumin seeds at high temperatures [53]. In a study that analyzed the volatile organic compounds of eight indigenous populations of cumin seeds for their chemical constituents and antimicrobial characteristics, the data revealed that the essential oil content varied within the range of 2.9%–3.7% [4]. However, the amount of essential oil differs depending on environmental circumstances, genetic factors, plant age, and the type of treatment.

The flavor and aroma of spices are primarily attributed to their volatile compounds. Consequently, it is of paramount importance to safeguard these volatile compounds throughout specialized processes to guarantee the acceptability of the end product [29]. Fig. 7 depicts the heat map of volatile components of cumin seed essential oil. Log transformation was employed on the data to better illustrate the substantial variation between the maximum and minimum values. This transformation aids in normalizing the data and enhancing the efficacy of statistical analysis. According to the results, 23 compounds have been found in cumin seeds. Terpinen-7-al <γ> (38.96%), Cuminaldehyde (20.75%), γ-Terpinene (18.81%), β-Pinene (13.66%), and p-Cymene (6.2%) were the major

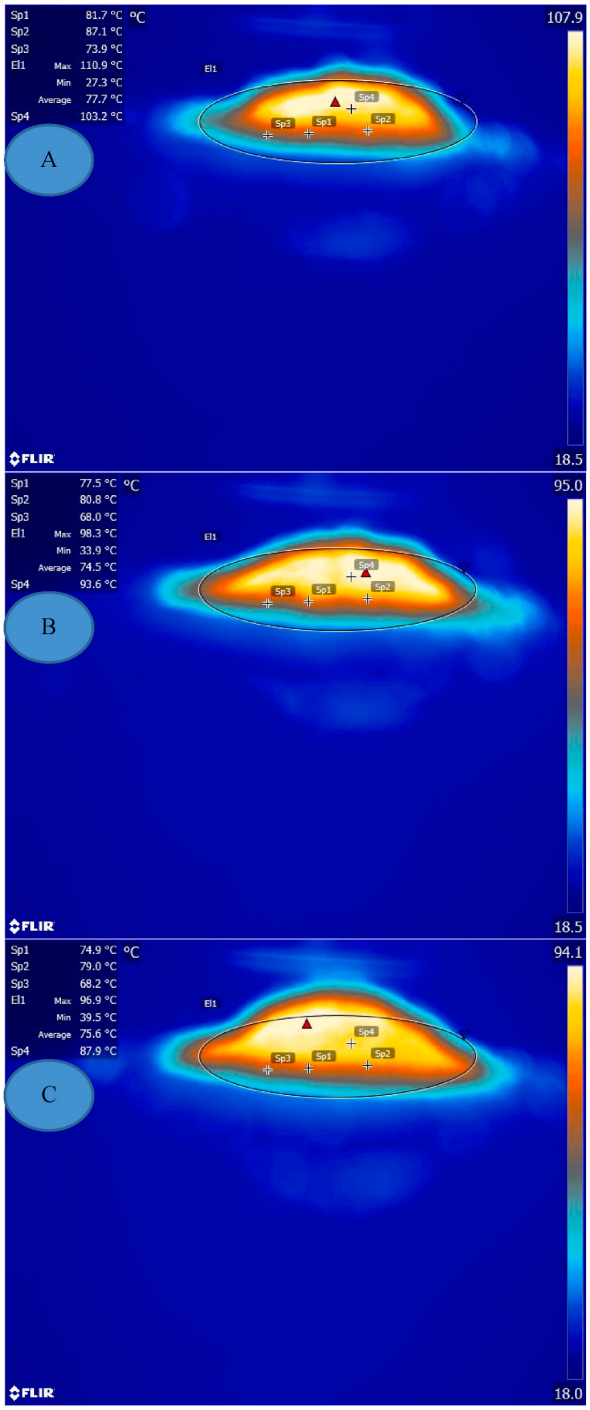

Fig. 5. Thermal images related to temperature treatment of cumin seeds at 155 °C and different times of (A) 45, (B) 60 and (C) 75 s.

components of cumin seed essential oil. These five components accounted for 98.38% of the essential oil volatile compounds. In the current study, the percentage of some volatile compounds increased after treatment. The highest amounts of Cumin aldehyde, γ-Terpinene, and β-Pinene were found in the 135°C-60s, 115°C-45s, and 115°C-45s treatments, with values of 20.75%, 18.81%, and 513.66%, respectively, representing an increase of 8.28%, 8.95%, and 12.09%, in that order, compared to the control sample. However, the Terpinen-7-al <γ-> composition remained unchanged compared to the control sample. A parallel trend was noted in various compounds when cumin seeds were treated with a radiofrequency heating system, as reported in a study conducted by Ref. [53]. In this study, the major volatile compounds (>7% area) of cumin seeds were β-pinene, p-cymene, γ-terpinene, 3-carene and

Table 3
The effect of temperature and time of process on essential oil content of cumin seed samples during decontamination.

Sources	df	Mean of square
		Essential oil content (%)
Decontamination temperature (°C)	2	0.1787 [ns]
Decontamination time duration (s)	2	0.0046 [ns]
Temperature × time	4	0.5399[a]
Error	18	0.098
CV (%)	–	14.56

[a] Significance at the 1% level.
[ns] not significant.

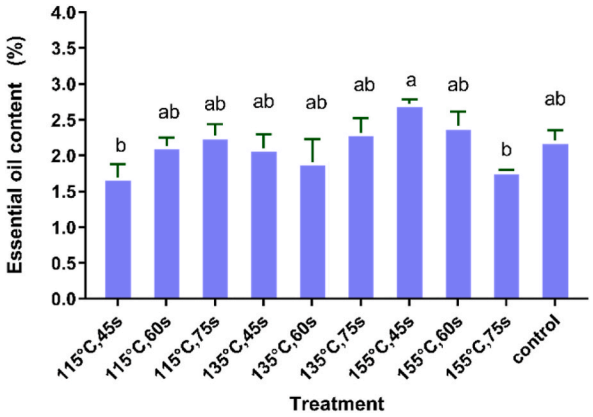

Fig. 6. Average values of essential oil content of cumin seeds processed using a lab scale non-contact induction heating chamber at different treatment (Error bars represent standard deviation from three replicates. Different lowercase letters above the error bars indicate a significant difference between mean treatment groups at 95 % confidence intervals.

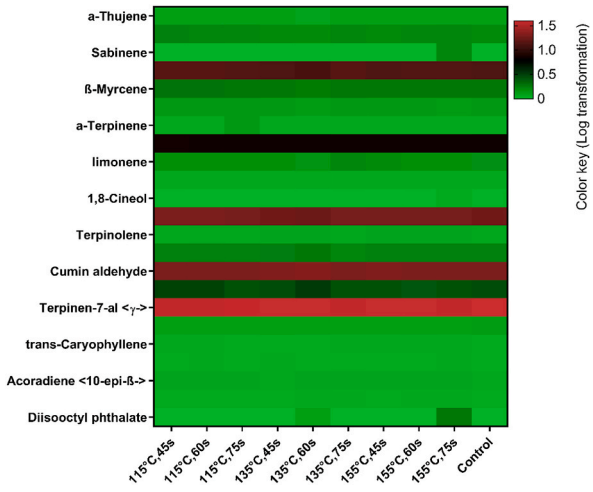

Fig. 7. The heat map of volatile compounds of cumin seed essential oil in control samples and non-contact induction heating treatments.

cumin aldehyde which made up ~82% of the total volatile constituents. The chemical composition of the cumin seed essential oil in this study was consistent with previous research findings [4,53,55]. Environmental factors, plant species, harvest stage, storage conditions, and essential oil extraction procedures synergistically contribute to changes in chemical compounds [56–58].

3.6. Energy consumption analysis

To a significant extent, comprehending the energy consumption in diverse decontamination technologies can be invaluable for the design of equipment, the selection of materials for equipment construction, process optimization, and the successful transition of technology from laboratory-scale applications to commercial-scale operations. One of the key design parameters to consider while building a new system is energy consumption [59]. Table 4 shows the ANOVA of energy consumption of the induction system in different treatments. Temperature and decontamination time duration, as well as their interactions, had a substantial effect on energy consumption (99 % confidence intervals).

The total energy consumption of the system in this study fell within the range of 20.55–53.29 kJ. The highest and lowest energy usage during the decontamination process were observed at 155°C for 75 s and 115°C for 45 s, respectively. Fig. 8 depicts the energy consumption with respect to several decontamination procedures. There was a considerable difference between high temperature treatments and other treatments, thus the system's energy consumption increased with the temperature increment. The non-contact induction heating decontamination technology is a rapid heating procedure in which the heat generated in the conveyor swiftly transferred to the product's surface, resulting in a rapid increase in product temperature. Rapid increase in product surface temperature leads to reduced decontamination time duration and thus reduced energy consumption. According to the results, the treatment combinations of 135°C-60 s, 115°C-45 s, and 155°C-60 s had the lowest energy consumption in order to reduce 1 CFU/g of aerobic plate count, with the values of 11.54, 11.81, and 13.76 kJ, respectively. The amount of energy for the treatment combination of 155°C-60 s increased by 14 and 16 %, respectively, as compared to combinations of 115°C-45 s and 135 °C −60 s. Furthermore, the treatment combinations of 135 °C for 60 s (ed), 115 °C for 45 s (g) and 155 °C for 45 s (c) exhibited the lowest energy consumption required for a 1 CFU/g reduction in mold and yeast, with values of 10.61 kJ, 11.29 kJ, and 12.018 kJ, respectively. In comparison to the treatment combinations of 135°C for 60 s and 115°C for 45 s, the value of this parameter for the treatment combination of 155°C for 45 s increased by 11.7% and 6%, respectively. However, the energy consumption for reducing 1 CFU/g of coliform was found to be 10.82, 11.87, and 12.92 kJ in the treatment combinations of 155°C-45 s, 135°C-45 s, and 115°C-45 s, respectively. This value has declined by 9.07 and 19.4 for the two treatments 135°C-45 s and 115°C-45 s, accordingly, as compared to 155°C-45 s treatment. The lowest energy consumption for reducing coliform by 1 CFU/g was observed at the highest temperature. Thus, it is quite compelling to recognize that lower temperatures may not effectively inhibit or halt the growth and proliferation of microorganisms.

4. Conclusions

In this study, a continuous decontamination system (lab-scale) was developed to decontaminate cumin seeds. The results revealed that the system's efficiency for microbial load inactivation was augmented by increasing temperature and temperature distribution uniformity. Maximum microbial load decline was recorded for aerobic plate count (3.24 CFU/g) at 155°C for 60 s, and for mold and yeast (3.17 CFU/g) and coliform (3.6 CFU/g) at 155°C for 45 s. Alterations in the color indices of cumin seeds were observed with the increase in temperature and decontamination time duration, as well as due to the elevation of the sample surface temperature, when compared to the control sample. According to the findings from electron microscopy, the rise in the percentage of essential oil was correlated with alterations in the surface morphology of the seeds. Based on the findings, the treatment combination of 155°C for 45 s was identified as the most effective treatment, as it led to the highest reduction in microbial load and the greatest content of essential oil. This is the first research study that determines the feasibility and effectiveness of non-contact induction heating of spices in reducing bacterial load. However, the high temperature of the product surface during the decontamination process resulted in color changes in the sample. These color alterations could be mitigated to some extent by implementing a rapid cooling process after decontamination. The uniformity of the temperature distribution and mixing effect are crucial for decontamination process. So, the optimal design of the screw conveyor is essential. In addition, the effect of non-contact induction heating on storage period of cumin seed will be subjected to future studies.

Data availability statement

Data will be made available on request.

Additional Information

No additional information is available for this paper.

CRediT authorship contribution statement

Edris Rahmati: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Hadi Khoshtaghaza:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Ahmad Banakar:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mohammad-Taghi Ebadi:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Zohreh Hamidi-Esfahani:** Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Table 4
The effect of temperature and time of process on energy consumption of the induction system during decontamination of the cumin seed samples.

Source	df	Mean of square
		Energy consumption (kJ)
Decontamination temperature (°C)	2	764.33[a]
Decontamination time duration (s)	2	298[a]
Temperature × time	4	21.21[a]
Error	18	1.85
CV (%)	–	3.77

[a] Significance at the 1% level.

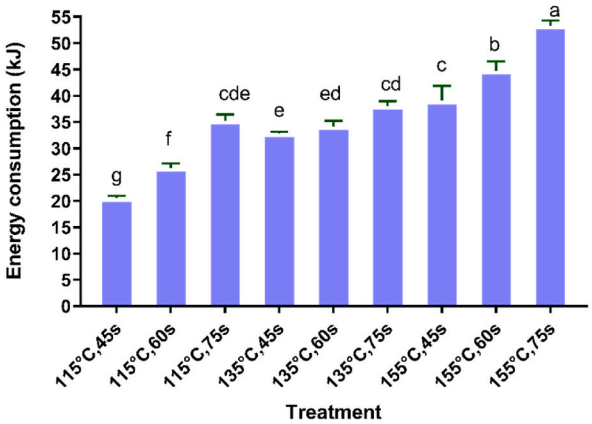

Fig. 8. Average values of energy consumption of cumin seeds processed using a lab scale non-contact induction heating chamber at different treatment (Error bars represent standard deviation from three replicates. Different lowercase letters above the error bars indicate a significant difference between mean treatment groups at 95 % confidence intervals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Iran National Science Foundation (INSF: No. 98023013) for funding this work and Tarbiat Modares University for supporting the experimental equipment of this project.

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