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Decontamination kinetics, quality attributes, and shelf life extension of stuffed pasta (mantı) processed by combined microwave drying and low-pressure argon cold plasma treatment

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Abstract

In this study, a novel combined process utilizing microwave drying and vacuum microwave-plasma techniques was investigated as an alternative to traditional drying methods to ensure the quality preservation and shelf-life extension of stuffed pasta (Turkish mantı). A custom-designed microwave plasma system was developed for this purpose. The Turkish mantı samples were first dried in a microwave oven operating at a calibrated actual output power of 460 W and a frequency of 2.45 GHz until reaching a final moisture content of 12%, and were subsequently subjected to a microwave-induced low-pressure argon cold plasma treatment sustained at an effective discharge power of 300 W. Physicochemical (pH, color), sensory, and microbiological (total mesophilic aerobic bacteria, total aerobic psychrophilic bacteria, mold, and yeast) properties of the samples were determined and compared to those of their conventionally dried counterparts. The study revealed that the application of low-pressure cold plasma following microwave drying significantly ($\mathbf{p < 0.05}$) preserved the sensory quality and color values of the samples over one month of storage. In addition, mineral analysis results indicated that plasma treatments selectively influenced mineral retention depending on the specific element and the applied plasma parameters. Traditional drying tended to preserve minerals originating from plant ingredients and meat (Cu, K), whereas specific plasma conditions enhanced the retention of protein-bound or matrix-encapsulated minerals (Ca, Mg, Na). Overall, this combined microwave–plasma approach maintained the core quality attributes of the product within the studied 30-d storage period. While these results indicate a highly promising preservation potential, further comprehensive studies are required to fully evaluate long-term nutritional changes and lipid–protein oxidation kinetics under commercial retail conditions.

Keywords Stuffed pasta · Plasma · Microwave · Quality features · Shelf life

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Introduction

Plasma technologies, encompassing both thermal and microwave-induced low-pressure plasma systems, have established themselves as pivotal tools across various high-tech industrial sectors, including polymer processing, environmental engineering, and green synthesis[1]. Recently, this versatile technological framework has paved the way for non-thermal (cold) plasma innovations in agricultural biotechnology and food processing[2]. Cold plasma, operated under low-pressure or atmospheric conditions, is characterized by its thermodynamic non-equilibrium state, where highly energetic free electrons drive chemical reactions while the bulk gas temperature remains close to ambient levels[3]. This unique property permits the processing of heat-sensitive biological materials, inducing effective surface microbial decontamination without causing thermal degradation, while simultaneously modifying structural components and extending shelf life[4].

Traditional foods, such as stuffed pasta (Turkish mantı), represent high-demand convenience products. Standard Turkish mantı consists of small dough parcels filled with seasoned minced beef or soy protein, which are subsequently dried and boiled prior to consumption. However, formulations containing ground beef are highly perishable and categorized as high-risk foods regarding foodborne illnesses due to their elevated water activity and high nutrient content[5]. To achieve ambient stability in commercial retail channels, industrial processors rely on dehydration to reduce moisture levels below 12%. Traditional hot-air drying often requires prolonged exposure to high temperatures, which can adversely affect lipid stability, color, and rehydration quality. While microwave processing offers rapid dielectric heating by directly coupling electromagnetic energy with water molecules to drive moisture outward[6,7], thermal processing alone may be insufficient to achieve surface sterilization without overcooking or degrading heat-sensitive food components[8,9].

To address these limitations, non-thermal preservation technologies have gained substantial interest[10–12]. Cold plasma applications have successfully decontaminated various single-component food matrices, including fruits, cheese, and eggs, while reducing cooking times and preserving essential nutrients[13–15]. Recent advancements in non-thermal plasma applications within related starch- and protein-based matrices are summarized in Table 1.

Despite these advancements in single-component matrices, a distinct research gap remains regarding the sequential combination of thermal microwave drying and non-thermal low-pressure cold plasma treatment in complex, multi-component stuffed pasta systems containing raw meat fillings[11,12,16,17]. The structural complexity of a starch-rich dough crust encapsulating a high-moisture, protein-rich beef filling presents unique microbiological risks and mass transfer barriers that single-technology interventions cannot adequately resolve.

To address this challenge, the main objective and novelty of this study is to systematically validate a customized, sequential microwave-assisted drying and low-pressure argon cold plasma protocol for Turkish mantı. We hypothesized that initial microwave drying rapidly fixes the product structure and reduces bulk moisture, while subsequent low-pressure argon cold plasma treatment induces rapid surface microbial decontamination without

Table 1 Summary of cold plasma and hybrid processing in food matrices.

Authors	Food matrix	Processing / plasma parameters	Key findings & research gaps addressed
Karimi et al. (2026)	Parboiled rice	Low-pressure plasma, Ar/Air gas	Shortened cooking time, increased water absorption, and modified starch structure; however, it did not address filled or multi-component food matrices
Wan et al. (2025)	Mussel meat	Cold plasma combined with heat pump drying	Enhanced drying kinetics and reduced microbial load, but induced minor lipid oxidation. The study was limited to evaluating a single-matrix protein source
da Cruz et al. (2025)	Sliced cheese	Atmospheric dielectric barrier discharge	Achieved effective surface decontamination without significant changes in pH or color; however, the application was limited to dairy matrices
This study	Stuffed pasta (Turkish mantı)	Hybrid Microwave drying + Low-pressure Argon Plasma (1.5–3.0 L/min, 15–30 s)	Addressed the critical knowledge gap of treating a complex, combined starch–protein matrix containing a raw beef filling under rapid non-thermal conditions

imposing additional thermal stress on the meat filling. Specifically, this research aims to: (i) evaluate the decontamination kinetics and sterilization efficacy of the hybrid process against natural microflora (yeasts, molds, and total aerobic bacteria), (ii) assess the physical, chemical, color, and sensory quality attributes of the treated product, and (iii) determine the impact of plasma treatment on mineral retention and surface mass transfer behavior.

A full list of abbreviations used in this study is provided in Table 2.

Materials and methods

Materials

The Turkish mantı samples were custom-manufactured by a commercial producer in Konya, Turkey, immediately blast-frozen at -35 °C upon shaping and transported to our laboratory within 2 h under strict cold-chain conditions (at -18 °C). Drying and plasma experiments were initiated within 24 h of production to ensure consistency and maximum freshness. According to the product label, the dough contained wheat flour, potable water, salt, and sunflower oil, while the internal filling consisted of ground beef, soy protein, onion, animal fat, salt, black pepper, and cumin.

Methods

Experimental design and treatment groups

Approximately 5 kg of Turkish mantı was used per experimental batch, divided into 250 g portions. The blast-frozen samples were systematically divided into 250 g portions prior to processing.

The 250 g sample size was chosen based on specific physical, operational, and commercial criteria: (i) *Commercial Relevance:* 250 g represents a standard retail single-consumer packaging size in the commercial stuffed pasta industry; and (ii) *Chamber Aerodynamics and Uniformity:* Preliminary tests indicated that a 250 g portion allows the Turkish mantı pieces (yielding approximately 60–80 individual units per batch) to be distributed in a single, non-overlapping layer across the custom food-grade aluminum tray (diameter: 24 cm) inside the Pyrex vacuum chamber. This single-layer distribution is essential to guarantee uniform dielectric coupling of the microwave field and homogeneous surface exposure to the ionized gas species, preventing cold-spot formation or localized over-processing. Two main drying methods were applied:

Table 2 List of abbreviations used in this study.

Abbreviation	Full term
APB	Aerobic psychrophilic bacteria
Ar	Argon
Days	d
Hours	h
ICP-OES	Inductively coupled plasma optical emission spectroscopy
MW	Microwave
M	Molar
Minutes	Min
PDA	Potato dextrose agar
RONS	Reactive oxygen and nitrogen species
Seconds	s
TBA	Thiobarbituric acid
TMAB	Total mesophilic aerobic bacteria
TVMM	Total viable mesophilic microorganisms

Traditional drying method Prior to processing, 250 g frozen samples were tempered at 4 °C for 2 h until reaching an initial core temperature of 4 ± 0.5 °C. The traditional drying process was conducted using a laboratory forced-air oven (Yücebaş Makine, Turkey). The process parameters for traditional hot-air pre-baking were set at 250 °C with an air velocity of 0.2 m/s inside the drying chamber and an ambient relative humidity maintained at 45 ± 5%. This temperature was designated to emulate commercial and small-scale artisanal practices standard in Turkey, where short-duration, high-temperature thermal exposure is traditionally utilized to rapidly induce starch gelatinization on the outer dough layer, thereby setting the initial crust rigidity and fixing the product shape. This thermal treatment was maintained until the moisture content of the Turkish *mantı* samples decreased to 12%[18].

Microwave drying method Prior to microwave processing, 250 g frozen samples were tempered under identical conditions (at 4 °C for 2 h) to reach an initial core temperature of 4 ± 0.5 °C. In the microwave drying process, the 250 g tempered Turkish *mantı* samples were placed in a microwave oven (VESTEL MD-20 MB model; 17 L volume, 2.45 GHz frequency). In accordance with the IEC 60,705 international standard, the actual absorbed microwave power was calibrated via the temperature rise of a water load, confirming **an** effective output power of 460 W. Drying was continued until the samples reached a final moisture content of 12%, identical to the traditional method. At the end of the microwave drying process, the core sample temperature reached 88 ± 2 °C. Unlike the severe surface overheating and potential case-hardening associated with 250 °C convective hot air, this moderate internal core temperature effectively set the starch-protein matrix without thermal damage or surface scorching. The operative power level of 460 W was established through preliminary optimization trials to enhance internal moisture evaporation and mass transfer kinetics while strictly preventing macro-structural defects such as dough cracking, blistering, structural puffing, or localized thermal scorching.

Plasma treatment after microwave drying Following the microwave drying process, the samples were subjected to microwave-induced cold plasma (MICP) treatments under various operational conditions to evaluate their effect on product quality. The details of the treatment groups are given in Table 3.

Plasma experimental setup

The microwave plasma assembly/system used in the study was constructed in Eratek innovation Co., Konya, TR, and all the materials and system used were shown in Figs. 1 and 2.

The setup included:

- A microwave oven with inverter-type power supply (maximum output: 1000 W) to precisely control energy output.
- Microwave frequency: 2.45 GHz; wavelength: 12.25 cm; internal volume: 17 L (26.2 × 45.2 × 32.5 cm).
- Vacuum chamber: Constructed from heat-resistant Pyrex glass; sample tray made of food-grade aluminum.
- Vacuum pump: Vacuum pump oil and the seals were also a from food-compatible material. Operated continuously during plasma generation to ensure low-pressure conditions.

Table 3 Experimental setup and plasma conditions*.

Group code	Argon gas flow rate (L/min)	Exposure time (s)	Description
Microwave + Plasma I	1.5	15	Microwave-dried samples Treated with cold plasma (low argon flow, short time)
Microwave + Plasma II	3.0	15	Microwave-dried samples Treated with cold plasma (high argon flow, short time)
Microwave + Plasma III	1.5	30	Microwave-dried samples Treated with cold plasma (low argon flow, long time)
Microwave + Plasma IV	3.0	30	Microwave-dried samples Treated with cold plasma (high argon flow, long time)
Traditional V (Control-No plasma treatment)	-	-	Dried by traditional oven, (Hot-air at 250 °C until moisture content reached 12%)[18]

* All experiments were performed on three replicates. Each sample group was analyzed in triplicate (n = 3) for all physico-chemical, sensory, microbiological, mineral/heavy metal parameters during each storage interval.

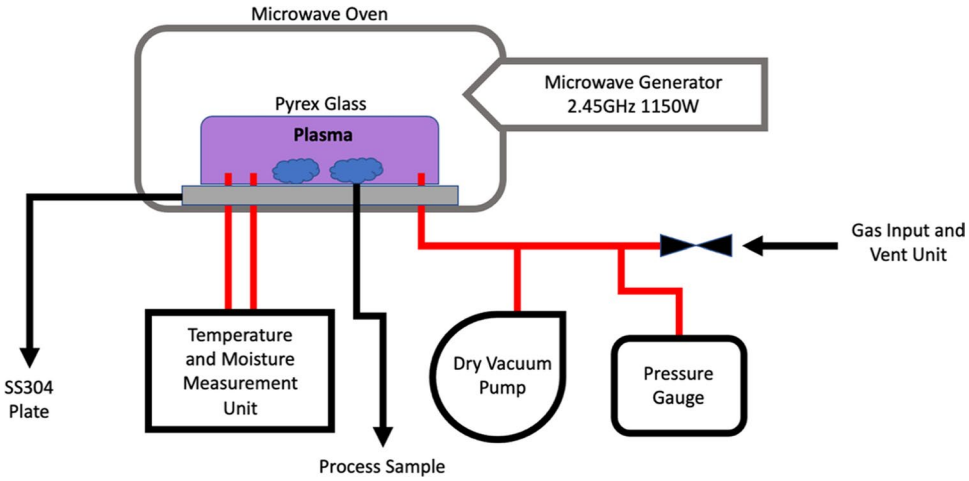


Fig. 1 Visual appearance and physical geometry of stuffed pasta (Turkish mantı) samples at different production and treatment stages: (**a**) fresh/raw meat-filled formulation, (**b**) after microwave drying (460 W, 2.45 GHz to 12% moisture content), and (**c**) following low-pressure argon microwave-plasma decontamination (300 W).



Fig. 2 Microwave plasma heat resistant chamber assembly/system.

- Gas source: Pure argon gas supplied at controlled flow rates (1.5 and 3.0 L/min), regulated using mass flow controllers.
- Plasma formation: Cold plasma in a non-thermal equilibrium state was produced by ionizing argon using microwave irradiation under vacuum conditions. Because cold plasma does not harm the food materials with minimal nutritional loss.
- Temperature monitoring: The internal temperature of the samples during traditional drying was recorded with a digital conductivity/pH pen (Ohaus ST20 M-B).
- Power calibration and operational metrics: To resolve discrepancies between nominal electrical power consumption and actual processing energy (as exemplified by the gross 1150 W nominal rating indicated on the equipment chassis versus the actual operational settings), the microwave oven's effective thermal output power utilized for the drying phase was calibrated in accordance with the international standard IEC 60,705. The power level reported for the microwave drying stage throughout this study strictly represents this calculated actual absorbed thermal power (460 W) at 2.45 GHz. Concurrently, the power reported for the vacuum cold plasma treatment represents the net effective discharge power (300 W) sustained by the custom microwave-plasma generator. All relevant figures and textual references have been systematically updated to ensure full consistency across these calibrated values.

Table 4 Microwave plasma application parameters.

Parameters	Microwave application	Plasma application
Microwave power	Med (460) W	300 W
Microwave frequency	2.45 GHz	2.45 GHz
Time	Moisture up to 12%	15 and 30 s
Gas-flow (Ar) (Lt/min)	-	(1.5 and 3)



Fig. 3 .



Fig. 4 .

Application procedure

Following the microwave drying step to a target moisture content of 12%, selected sample groups were subjected to microwave-induced cold plasma (MICP) treatment within the same integrated chamber. Plasma discharge was generated at an operating power of 300 W using high-purity argon gas. Exposure times were set at 15 or 30 s under argon flow rates of 1.5 or 3.0 L/min. A continuous vacuum pump system was employed to maintain the required negative working pressure during treatment, with gas flow precisely controlled via a mass flow controller. The operational parameters and experimental design matrix for the combined microwave and plasma treatments are summarized in Table 4.

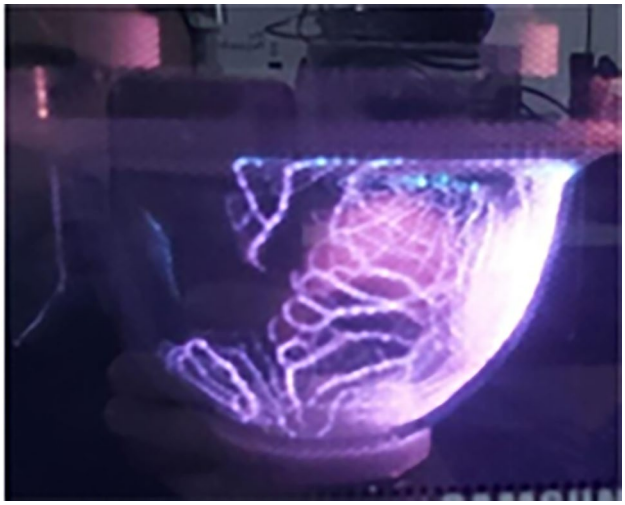
Preliminary observations indicated that higher argon flow rates (3.0 L/min) or prolonged exposure times (30 s) induced a severe caustic effect on the surface of the Turkish *mantı* samples (Fig. 3). Representative visual records of the microwave drying setup and the cold plasma discharge state are shown in Figs. 4 and 5, respectively.

In this study, following physicochemical [ph and color determination thiobarbituric acid (TBA)], microbiological (total aerobic mesophilic bacteria, total aerobic psychrophilic, total yeast and mold), sensory analyses and mineral contents were performed on the processed Turkish mantı samples.

Physicochemical analysis

pH To determine the pH values of the dried Turkish *mantı* samples, 10 g of whole Turkish *mantı* (including both dough and filling) was homogenized with 90 mL of distilled water, and the pH was measured using a digital pH

Fig. 5 .



meter (Ohaus ST 20 M-B pH and Conductivity Pen Type Multiparameter)[19]. Prior to each measurement session, the pH meter was calibrated using standard commercial buffer solutions at pH 4.01, 7.00, and 10.01 at 25 °C.

Color analysis Color parameters (L^*, a^*, and b^*) of the whole Turkish *mantı* samples were measured using a colorimeter (Konica Minolta Chroma Meter CR-400, Japan) equipped with a standard illuminant C. Prior to testing, the instrument was calibrated against a standard white calibration plate ($Y = 93.5$, $x = 0.3114$, $y = 0.3190$). The samples were placed in clean sample containers, and surface color measurements were recorded at multiple random points[5,20]. To assess perceptible changes in color during storage, the total color difference (ΔE) between storage intervals was calculated using the following formula[17,21]:

$$\Delta E = \sqrt{((L_2 * - L_1 *)^2 + (a_2 * - a_1 *)^2 + (b_2 * - b_1 *)^2)}$$

where L*, a∗, and b∗represent the color values at two different storage times. The ΔE values were interpreted according to the following standard scale:

The ΔE values were interpreted based on the following standard scale[21,22]:

ΔE < 1: Not perceptible by human eyes
1 < ΔE < 2: Perceptible through close observation
2 < ΔE < 3.5: Perceptible at a glance
ΔE > 3.5: Large color difference

Thiobarbituric acid (TBA) analysis TBA analysis was carried out according to the method suggested by Gökmen & Kocabaş (2017) [23]. Briefly, 10 g of ground sample was homogenized with 50 mL of 7.5% trichloroacetic acid (TCA) solution. After filtration, 5 mL of filtrate was reacted with 5 mL of 0.02 M 2-thiobarbituric acid in a boiling water bath for 35 min. The absorbance of the cooled solution was measured at 532 nm, and results were expressed as mg malondialdehyde (MDA) per kg of sample.

Microbiological analyses

Total viable mesophilic microorganisms (TVMM) To determine the total aerobic mesophilic bacterial count, samples were homogenized in an isotonic solution at a 1:10 dilution ratio. Serial dilutions were plated on Plate Count Agar (PCA) using the pour plate method and incubated at 35 ± 1 °C for 48 h. Although some colonies may develop within the agar matrix, the method is widely accepted in literature for estimating total viable aerobic

mesophilic bacteria, including facultative aerobes growing in microaerophilic zones[24,25]. All visible colonies, including surface and subsurface, were counted, and results were expressed as log CFU/g.

Aerobic psychrophilic bacteria (APB) To determine the total psychrotrophic bacterial counts, samples were homogenized in an isotonic solution at a 1:10 dilution ratio. Serial dilutions were prepared and plated onto Plate Count Agar (PCA) using the pour plate method. The plates were incubated at 4 ± 1 °C for 7 d (168 h). After incubation, both surface and subsurface colonies were counted, and results were expressed as colony-forming units per gram (CFU/g)[24].

Total yeast and mold count To enumerate yeast and mold populations, samples were plated onto Potato Dextrose Agar (PDA) using the pour plate method. The plates were incubated under aerobic conditions at 25 ± 1 °C for 5 d, in accordance with internationally accepted microbiological guidelines[24,26]. After incubation, colonies were counted, and results were expressed as colony-forming units per gram (CFU/g).

Sensory analysis

Sensory analyses in Turkish mantı samples were carried out according to the methods described by Sitti (2011)[18]. After a brief preliminary briefing was given to the panel group of 7 experienced member in the sensory analysis, they were asked to evaluate the cooked Turkish mantı samples presented on white plastic plates with a 5-scale hedonic scale in terms of appearance, odor, taste, mouthfeel (texture), and overall acceptability. In the scale, 5 is defined as very good and 1 as very bad[3,22].

Ethical considerations and sensory analysis All methods involving human participants were carried out in accordance with the relevant institutional and national guidelines and regulations. The sensory evaluation phase of this study was conducted during the initial stage of the project framework, prior to the 2022 national regulatory updates (TR Dizin/ULAKBİM) that strictly mandate prospective institutional ethics committee approval for non-invasive food tastings. Under the national regulations and institutional frameworks applicable at the time of data collection, formal ethical committee approval was not required for routine, non-invasive food tastings that did not involve sensitive personal data collection. Furthermore, under the updated framework, retrospective ethical clearance cannot be issued for historical datasets. Informed consent was formally obtained from all participants prior to their inclusion in the study. The sensory evaluation was strictly limited to adult volunteers and conducted with seven experienced panelists.

Mineral and heavy metal analysis

Macro-minerals (Ca, Na, K, Mg) and micro-minerals, including heavy metals (Fe, Cu, Zn, Mn, Ni, Se), were quantified by inductively coupled plasma optical emission spectroscopy (ICP-OES, Agilent 720 Series, axial view, Agilent Technologies, USA) following Peng et al.[27] with minor modifications. Samples were dry-ashed at 600 °C for 8 h, treated with 1 mL of 25% HNO_3, diluted to 100 mL with ultrapure water, and filtered before analysis. Measurements were carried out at the Central Laboratory of Karamanoğlu Mehmetbey University (Karaman, Türkiye). Instrument parameters and quality control results, including recoveries and deviations, are summarized in Fig. 6 and 7.

Statistical analysis

All experimental treatments were performed in triplicate ($n = 3$), and data are presented as mean ± standard deviation (SD). Statistical analyses were carried out using SPSS software (Version 13.0, SPSS Inc., Chicago, IL, USA) at a 95% confidence level ($\alpha = 0.05$). Significant differences between treatment groups were evaluated using Student's t-test for pairwise comparisons and one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test for multiple comparisons[28].

Fig. 6 Operating conditions of the inductively coupled plasma optical emission spectrometer (ICP-OES) for mineral analysis.

Analyte	Recovery (%)	Deviations (%)
100%	98–102	(−2) to (+2)
100%	98–102	(−2) to (+2)
100%	97–103	(−3) to (+3)
100%	95–105	(−5) to (+5)
100 ppm	90–107	(−10) to (+7)
10 ppm	80–110	(−20) to (+10)
1 ppm	80–110	(−20) to (+10)
100 ppb	80–110	(−20) to (+10)
10 ppb	60–115	(−40) to (+15)
1 ppb	40–120	(−60) to (+20)

Fig. 7 Recovery rates and analytical performance parameters for mineral and heavy metal analysis by ICP-OES.

Analyte	Recovery (%)	Deviations (%)
100%	98–102	(−2) to (+2)
100%	98–102	(−2) to (+2)
100%	97–103	(−3) to (+3)
100%	95–105	(−5) to (+5)
100 ppm	90–107	(−10) to (+7)
10 ppm	80–110	(−20) to (+10)
1 ppm	80–110	(−20) to (+10)
100 ppb	80–110	(−20) to (+10)
10 ppb	60–115	(−40) to (+15)
1 ppb	40–120	(−60) to (+20)

Results

In this study, a drying method was developed by using microwave and/or vacuum microwave with cold plasma techniques as an alternative to the traditional drying method, and a traditional product (Turkish mantı) was dried with this method and compared with other options. Then some physicochemical (pH, color), microbiological and sensory properties of the dried Turkish mantı samples were determined.

pH stability and color parameters of Turkish manti samples

In the results, following changes were observed; for example, in the pH values of Turkish mantı samples, showed not much changes during the beginning and at the end of storage time (Table 5) applied in this study.

As seen in Table 5, the pH values of the Turkish mantı samples dried with different methods showed no statistically significant differences ($p > 0.05$) but the values numerically lower at the beginning compared to 30 d of storage. Changes in pH levels in foods have been associated with biochemical reactions that may occur during storage of the foods[5]. For example, it was reported that pH value may decrease in the bakery products during the storage as the carbon dioxide dissolves in it [20, 21, 64]. Contrary to the research stated above, in this study,

Table 5 pH values of the stuffed pasta (Turkish mantı) samples dried by different methods.

Storage*	Plasma I	Plasma II	Plasma III	Plasma IV	Traditional
0. day	6.59 ± 0.21	6.35 ± 0.25	6.53 ± 0.12	6.45 ± 0.15	6.63 ± 0.13
30. day	6.85 ± 0.18	6.78 ± 0.08	6.70 ± 0.06	6.73 ± 0.13	6.75 ± 0.08

*: In this table, the differences between the variables were not statistically significant.

Table 6 Changes in color parameters (L, a*, b*) of stuffed pasta (Turkish mantı) samples treated with different drying methods during 30 D of storage.

Storage (d)	Parameter	Plasma I	Plasma II	Plasma III	Plasma IV	Traditional
0	L*	61.47 ± 8.45^{Aa}	67.06 ± 12.10^{Aa}	68.26 ± 5.53^{Aa}	70.57 ± 10.11^{Aa}	63.85 ± 2.20^{Aa}
	a*	0.24 ± 0.20^{Aa}	0.13 ± 0.15^{Aa}	0.17 ± 0.14^{Aa}	0.17 ± 0.14^{Aa}	0.32 ± 0.22^{Aa}
	b*	13.26 ± 1.33^{Aa}	14.46 ± 0.98^{Aa}	13.97 ± 1.17^{Aa}	14.64 ± 1.31^{Aa}	14.69 ± 2.28^{Aa}
30	L*	42.38 ± 5.71^{Ba}	40.25 ± 3.04^{Ba}	41.52 ± 6.71^{Ba}	39.69 ± 6.62^{Ba}	40.55 ± 10.93^{Ba}
	a*	0.42 ± 0.17^{Bb}	0.39 ± 0.13^{Bb}	0.55 ± 0.24^{Bb}	0.36 ± 0.17^{Bb}	0.91 ± 0.45^{Ba}
	b*	10.10 ± 1.60^{Bb}	9.54 ± 0.58^{Bb}	10.94 ± 1.01^{Bab}	10.00 ± 1.19^{Bb}	11.98 ± 2.40^{Aa}
ΔE (0–30)		19.62	26.87	26.74	31.02	23.82

Different capital letters show statistical difference between the storage periods in the same column ($p < 0.05$). Different lowercase letters in the same row indicate significant difference between applications ($p < 0.05$). ΔE values represent total color difference between Day 0 and Day 30. values above 3.5 indicate a perceptible change to the human eye.

statistically no significant changes were observed in the pH values of the Turkish mantı samples, both at the beginning and during storage. The reason for this result might be the biochemical events did not occur due to the drying process of Turkish mantı samples at the high temperatures. In addition, the pH values of Turkish mantı samples showed no statistically significant changes throughout storage in any treatment group. This stability may be attributed to the inactivation of microbial and enzymatic activity due to thermal and plasma processing. In previous studies, decreases in pH were associated with microbial load or dissolution of CO_2 in bakery products during storage[5,20]. However, in this study, the rapid reduction in microbial load especially in the plasma-treated groups may have suppressed such biochemical changes, leading to consistent pH values. Similar findings were reported by Gürol et al.[13], who observed no significant pH alterations in plasma-treated milk samples.

Changes in the color during the process may lead a significant concern since it is one of the important attributes of the food products quality that affects the consumer perception. So, the color changes in the Turkish mantı samples dried with different drying methods were given in Table 6.

The effect of storage period on color parameters of the Turkish mantı samples were given in Table 6. According to the L* value of the samples, a statistically significant ($p < 0.05$) decrease in brightness (lightness) value was observed with the storage period. The b* value represents the measurement of yellowness properties of the foodstuff. Although there were relatively small changes in a* and b* values of microwave drying + plasma and traditional dried Turkish mantı samples during storage, this change was not statistically significant ($p > 0.05$).

In Hunter color measurements, the L* value indicates its brightness (lightness) status of the foods. While the L*value decreases, the color gets darker, and if the L* value increases as the color of the food gets lighter[20]. In this study, statistically significant differences were detected between the color values of Turkish mantı samples with the effects of drying method. A general decrease in L* values was detected during the 30 d of storage (Tables 6). The study revealed the Turkish mantı samples, which were initially applied Plasma IV and Plasma III methods had the highest L values, but the Plasma I and traditional methods had the lowest L values. The main reason for the low L value of the traditionally dried Turkish mantı is the problems in reaching the Turkish mantı mortar of the dry hot air at high temperatures. As the internal temperature of the Turkish mantı is low, the temperature of the outer surface is high. For this reason, the amount of darkening on the surface of Turkish mantı was so high[20]. In general, the obtained results were in consistent with the previous literature.

The ΔE scale value indicates the magnitude of the difference between two colors; as the value increases, the color difference becomes more noticeable to the human eye[29]. According to the standard ΔE interpretation scale,

all treatments exhibited ΔE values far exceeding the threshold of 3.5, indicating color differences that are highly perceptible to the human eye. Among the treatments, the smallest color change during storage was observed in the Plasma I group (ΔE = 19.35), whereas the Plasma IV group showed the largest change (ΔE = 31.23). Plasma II (ΔE = 27.26) and Plasma III (ΔE = 26.91) exhibited similarly high levels of color change, while the traditional method resulted in a ΔE of 23.46. These findings suggest that Plasma I treatment may have a relatively better potential for maintaining the initial color of Turkish mantı during storage compared to the other treatments. However, the overall magnitude of ΔE values indicates that substantial color deterioration occurred in all samples over the 30-d storage period.

Since the literature on the effect of plasma application on the physicochemical properties of Turkish mantı and Turkish mantı-like products could not be reached, so the results obtained in this research were compared with similar literature. In a study, it was reported that plasma treatment did not cause a significant change in pH and color values of raw milk samples[13]. Likewise, in this study, no significant difference was found between the pH and color values of the Turkish mantı samples with and without plasma treatment, both at the beginning and during storage.

Color is a crucial quality attribute for consumer acceptance. The significant reduction in L* values observed in traditionally dried Turkish mantı samples suggests excessive surface darkening, likely due to Maillard reactions induced by prolonged high-temperature exposure. In contrast, plasma-treated samples, particularly Plasma III and IV, maintained higher L* values, which may be attributed to shorter processing time and reduced thermal stress. Cold plasma has been reported to cause minimal color changes in food matrices, preserving natural pigments due to its non-thermal nature[8,12,14,30,31]. In terms of physicochemical stability, the relatively stable pH and minimal color changes in plasma-treated Turkish mantı samples mirror those observed in milk and cheese studies[29,32] further supporting the gentle nature of plasma on product quality. So, in this study, the obtained results were compatible with the literature published on the subject.

Oxidative stability [Thiobarbituric acid (TBA) values]

The changes in Thiobarbituric acid (TBA) values of the Turkish mantı samples studied were given in Table 7.

The changes in Thiobarbituric Acid (TBA) values of the Turkish mantı samples during storage are presented in Table 7. Among the Turkish mantı samples processed with different drying and plasma application methods, the highest initial TBA value (D 0) occurred in the Plasma III group (Table 7). Following 30 d of storage, the highest TBA value was observed in the Plasma IV group. Conversely, the lowest initial TBA value on D 0 was recorded in the Turkish mantı samples produced by the traditional method (Table 7), whereas the lowest TBA value at the end of the 30 d storage period was determined in the Plasma II group. As expected, a statistically significant ($p < 0.05$) increase in TBA values was observed across all Turkish mantı groups over the course of storage (Table 7).

In general, Turkish mantı prepared with minced beef filling is a lipid-dense matrix sensitive to oxidative degradation; hence, monitoring TBA values is essential for evaluating primary/secondary lipid peroxidation products. Lipid oxidation remained within acceptable quality limits across all treatment groups throughout storage. Interestingly, the lowest TBA values at the end of storage were recorded in Plasma II samples. This outcome might be attributed to the shorter plasma exposure duration and moderate gas flow rate employed, which minimized oxidative stress on unsaturated fatty acids while preserving antimicrobial efficacy. Cold plasma processing has

Table 7 Thiobarbituric acid (TBA) values (mg MDA/kg) of stuffed pasta (Turkish mantı) samples subjected to different drying methods during 30-day storage.

Storage	Plasma I	Plasma II	Plasma III	Plasma IV	Traditional method
0. day	0.54 ± 0.016^{Aa}	0.42 ± 0.129^{Aa}	0.92 ± 0.292^{Aa}	0.44 ± 0.175^{Ab}	0.34 ± 0.03^{Ab}
30. day	0.72 ± 0.033^{Aa}	0.55 ± 0.031^{Aa}	2.75 ± 1.78^{Bb}	4.73 ± 0.91^{Bb}	2.15 ± 0.048^{Bb}

Different capital letters show statistical difference between storage periods in the same column ($p < 0.05$). Different lowercase letters in the same row indicate difference between applications ($p < 0.05$).

previously been reported to exert variable effects on lipid oxidation depending on exposure duration, gas composition, and food matrix characteristics[11,33]. The slight elevation in TBA values observed in certain groups can be linked to reactive species generated during plasma discharge, which are known to initiate lipid peroxidation pathways if processing parameters are not strictly optimized. Therefore, optimizing processing time and controlling argon gas flow are critical operational factors for controlling lipid oxidation during storage.

The interaction between low-pressure argon plasma and the lipid components of the beef filling serves as a key determinant of final product quality. Argon is utilized as an inert carrier gas to initiate a stable plasma discharge under vacuum conditions. However, during plasma generation, reactive oxygen and nitrogen species (RONS) are inevitably formed due to the ionization of residual air within the vacuum chamber and trace moisture evaporation from the dough-filling matrix[34]. These energetic radical species (such as singlet oxygen, hydroxyl radicals, and ozone) interact with unsaturated fatty acids in the beef filling, initiating autoxidation pathways via hydrogen abstraction[35]. This chemical mechanism explains the statistically significant ($p < 0.05$) increase in TBA values observed in the Plasma III and Plasma IV groups, which were subjected to longer plasma exposure times (30 s). Consequently, restricting the treatment to a shorter duration (15 s) under moderate gas flow conditions (as applied in Plasma I and Plasma II) is critical for keeping lipid oxidation within acceptable limits while simultaneously achieving target microbial safety.

Microbiological quality

Total mesophilic aerobic bacteria counts

Within the scope of this study, total mesophilic aerobic bacteria count (TMAB) and aerobic psychrophilic bacteria(APB) counts were determined on the 0th and 30th d of the research. The obtained results were given in Table 8.

The highest number of TMAB colonies wereobserved in the traditionally dried Turkish mantı samples (Table 8). Again, total mesophilic aerobic bacteria count on30th day werehigher than the number of colonies on the 0th d (Table 6).Psychrophilic aerobic bacteria were not determined because the colony formation was not observed in any of the Turkish mantı samples dried by different methods.

Mold and yeast counts

Mold and yeast counts of Turkish mantı samples were given in Table 9.

Even on the 25th d of storage, countless colonies (Too Numerous To Count) were observed in the dried Turkish mantı samples processed by traditional methods (Table 9).

As can be seen in Table 8, the highest increase in colony during storage was in the TVMM count in the dried Turkish mantı samples processed with traditional method. This might be the reason for shortening of the shelf life of Turkish mantı. It was determined that the Turkish mantı samples analyzed in this study were in accordance with Turkish standard, TS 12,980 in terms of the TVMM. However, the TVMM in the microwave + plasma treated samples were significantly lower than that of the Turkish mantı samples dried by traditional method.

Table 8 Total mesophilic aerobic bacteria (TMAB) counts (cfu/g) of stuffed pasta (Turkish mantı) samples treated with different drying methods during 30 days of storage.

Storage	0. Day	30. Day
Plasma I	9.700 cfu/g	246.850 cfu/g
Plasma II	8.200 cfu/g	191.900 cfu/g
Plasma III	9.200 cfu/g	241.950 cfu/g
Plasma IV	7.500 cfu/g	229.600 cfu/g
Traditional method	37.500 cfu/g	266.650 cfu/g

Table 9 Yeast and mold counts (cfu/g) of stuffed pasta (Turkish mantı) samples treated with different drying methods during 30 days of storage.

Methods	0. day	30. day
Plasma I	2	4
Plasma II	ND	ND
Plasma III	ND	3
Plasma IV	ND	3
Traditional method	64	UC

ND: Not Detected UC: Uncountable, i.e. too many.

Again, as can be seen in the Table 5,excessive amount of yeast and mold growth was observed at the 25th d of storage in the traditional method applied Turkish mantı samples while no yeast and mold growth was observed in the microwave + plasma applied Turkish mantı samples. Therefore, the positive effect of plasma applications on the shelf life of the product was obvious (Table 9).

Microbiological analysis revealed that plasma-treated samples had significantly lower total viable mesophilic microorganisms (TVMM) counts compared to traditional drying, both at the beginning and end of storage. This supports the hypothesis that microwave-induced cold plasma can inactivate a broad range of microbial contaminants via membrane disruption, protein denaturation, and nucleic acid damage caused by reactive oxygen and nitrogen species (RONS)[30,31,36,37]. Notably, psychrophilic bacteria were not detected in any sample, indicating effective elimination of cold-tolerant organisms regardless of treatment. So, it was concluded that in addition to the traditional Turkish mantı drying method, microwave drying, and four different plasma applications could be an alternative to the conventional Turkish mantı drying method in terms of drying time due to the short process time and the microbial count, especially in terms of total bacteria. The fundamental differences in physical and sensory quality between traditionally dried and microwave-plasma dried Turkish mantı are deeply rooted in their distinct heat and mass transfer mechanisms. In traditional oven pre-baking (conducted at 250 °C), heat transfer occurs from the external environment to the product's surface via conduction and convection, creating a steep temperature gradient. This rapid superficial moisture loss induces surface 'case-hardening,' trapping water inside the internal beef filling and accelerating Maillard browning on the starch crust[38]. Conversely, microwave drying operates via volumetric heat generation driven by dielectric heating[39]. Electromagnetic waves couple directly with the high-dielectric water molecules distributed within both the dough crust and the internal raw beef core, generating rapid internal vapor pressure. This internal-to-external pressure gradient drives moisture outward continuously, resulting in highly uniform moisture migration, significantly shorter processing durations, and completely preventing the structural collapse or case-hardening associated with conventional conductive methods[40].

Since no studies have specifically examined the effect of plasma application on the microbiological quality of Turkish mantı or Turkish mantı-like products, our results were compared with similar research on other food matrices. Cold atmospheric plasma treatment for 20 min completely inhibited *Aspergillus flavus* in brown rice flakes[41], which is consistent with the absence of mold growth in our plasma-treated Turkish mantı samples. Plasma application has also been shown to reduce the total microbial load in wheat and beans[40] and to enhance microbial safety in sliced cheese[36], cow milk[42], pork[43], as well as in fruits, vegetables, and spices such as pepper seeds, crushed thyme, and red pepper powder[44,45]. In our study, yeast and mold growth occurred only in the traditional drying group at d 25, indicating insufficient microbial inactivation, whereas all plasma-treated groups remained free of fungal contamination throughout storage. These results demonstrate the effectiveness of microwave-assisted cold plasma treatment in inhibiting fungal development during storage.

Sensory quality

Sensory analyses in Turkish mantı samples were carried out on the samples that subjected to different drying methods, and the changes in taste values was given in Table 8. In the first stage of this study, Turkish mantı

samples dried using the Plasma I method received the highest scores at the beginning of storage, and the differences were statistically significant ($p<0.05$) (Table 10). These samples also maintained superior sensory quality in terms of taste and flavor throughout the 30-d storage period (Table 10).

In contrast, samples dried using the traditional method consistently received lower sensory scores, particularly for taste and odor attributes. This may be attributed to the longer exposure to heat (250 °C), which can lead to Maillard reactions and loss of volatile aroma compounds, affecting palatability. Although no direct comparison was made with industrially produced samples, the sensory properties of traditionally dried Turkish mantı were generally considered less acceptable by panelists compared to the plasma-dried samples.

The changes in the odor values of the samples were given in Table 10. The highest odor scores were with the samples dried by the Plasma I method for both at the 0 and 30th d while the lowest scores were again with the Plasma III method (Table 10) and the results were statistically significant ($p<0.05$).

It was observed that the highest appearance value was with the samples dried with the Plasma I method for both on the d of 0 and 30 d of storage. Plasma III method had the lowest appearance value at the 30 d of storage (Table 10). These values were statistically significant ($p<0.05$).

The lowest mouthfeel (texture) values for the Turkish mantı samples determined was with the Plasma III application for all d studied, and the values were statistically significant ($p<0.05$) too (Table 10).

Finally, the changes in the overall acceptance values of the Turkish mantı samples were given in Table 10. It was observed that the Turkish mantı samples dried with the Plasma I method had the highest values of mouth feel and overall acceptance for both at the d 0 and d 30 of the study (Table 10). Plasma IV method had also scored high in terms of mouth-feel parameter. The results for these values were also statistically significant ($p<0.05$).

Sensory scores for taste, odor, and mouthfeel (texture) were generally higher in Plasma I and Plasma IV groups, while Plasma III and the traditionally dried Turkish mantı samples received significantly lower scores ($p<0.05$). These results suggest that high argon flow and longer exposure in Plasma III might negatively impact sensory properties, while shorter plasma treatments preserved sensory quality more effectively.

In general, plasma application did not adversely affect the sensory quality of the Turkish mantı samples. Taste and smell of Turkish mantı were not changed after cooking. In terms of the color and appearance parameters, the Turkish mantı must maintain its unique color and appearance values. Structurally, Turkish mantı should not split or stick to each other too[5,18,46]. Since the literature on the effect of plasma application on the sensory quality of Turkish mantı and/or Turkish mantı-like products could not be reached in the literature, the results with some foods treated with plasma were compared, and it was determined that the sensory properties of the product are not generally adversely affected by the plasma technology[47]. Our results were also compatible with the literature. For example, low pressure cold plasma application on rice had shortened the cooking time, increased the water

Table 10 Sensory evaluation scores of stuffed pasta (Turkish manti) samples subjected to different drying methods over 30 days of storage.

Storage (d)	Parameter	Plasma I	Plasma II	Plasma III	Plasma IV	Traditional
0	Taste	3.82 ± 0.64^{Aa}	3.07 ± 0.56^{Ab}	2.00 ± 0.93^{Ad}	3.72 ± 0.45^{Aa}	2.51 ± 0.70^{Ac}
	Odor	3.61 ± 0.65^{Aa}	3.06 ± 0.25^{Ab}	2.56 ± 0.76^{Ac}	3.64 ± 0.75^{Aa}	2.33 ± 0.91^{Ac}
	Appearance	4.29 ± 0.64^{Aa}	3.94 ± 0.90^{Aa}	2.54 ± 0.88^{Ab}	4.00 ± 0.80^{Aa}	2.83 ± 0.64^{Ab}
	Mouth feel (Texture)	3.91 ± 0.27^{Aa}	3.06 ± 0.63^{Ab}	1.75 ± 0.73^{Ad}	3.70 ± 0.62^{Aa}	2.18 ± 1.00^{Ac}
	Overall acceptability	3.97 ± 0.43^{Aa}	3.13 ± 0.73^{Ac}	2.04 ± 0.65^{Ad}	3.52 ± 0.50^{Ab}	2.25 ± 0.85^{Ad}
30	Taste	3.80 ± 0.63^{Ba}	3.10 ± 0.56^{Bb}	2.00 ± 0.94^{Bc}	3.70 ± 0.48^{Bab}	2.40 ± 0.84^{Bc}
	Odor	3.60 ± 0.69^{Ba}	3.10 ± 0.31^{Bab}	2.50 ± 0.84^{Bbc}	3.60 ± 0.84^{Ba}	2.30 ± 0.94^{Bc}
	Appearance	4.30 ± 0.67^{Ba}	3.80 ± 0.91^{Ba}	2.50 ± 0.97^{Bb}	4.00 ± 0.81^{Ba}	2.80 ± 0.78^{Bb}
	Mouth feel (Texture)	3.90 ± 0.31^{Ba}	3.00 ± 0.66^{Bb}	1.80 ± 0.78^{Bc}	3.70 ± 0.67^{Ba}	2.20 ± 0.32^{Bc}
	Overall acceptability	4.00 ± 0.47^{Ba}	3.10 ± 0.73^{Bb}	2.00 ± 0.66^{Bc}	3.50 ± 0.52^{Bab}	$2.20\pm0.0.91^{Bc}$

Same capital letters show no statistical difference between the storage periods in a same column ($p<0.05$). Different lowercase letters in a same line indicate the difference between the applications ($p>0.05$). Sensory attributes were evaluated on a 5-point hedonic scale (1 = Dislike very much, 5 = Like very much).

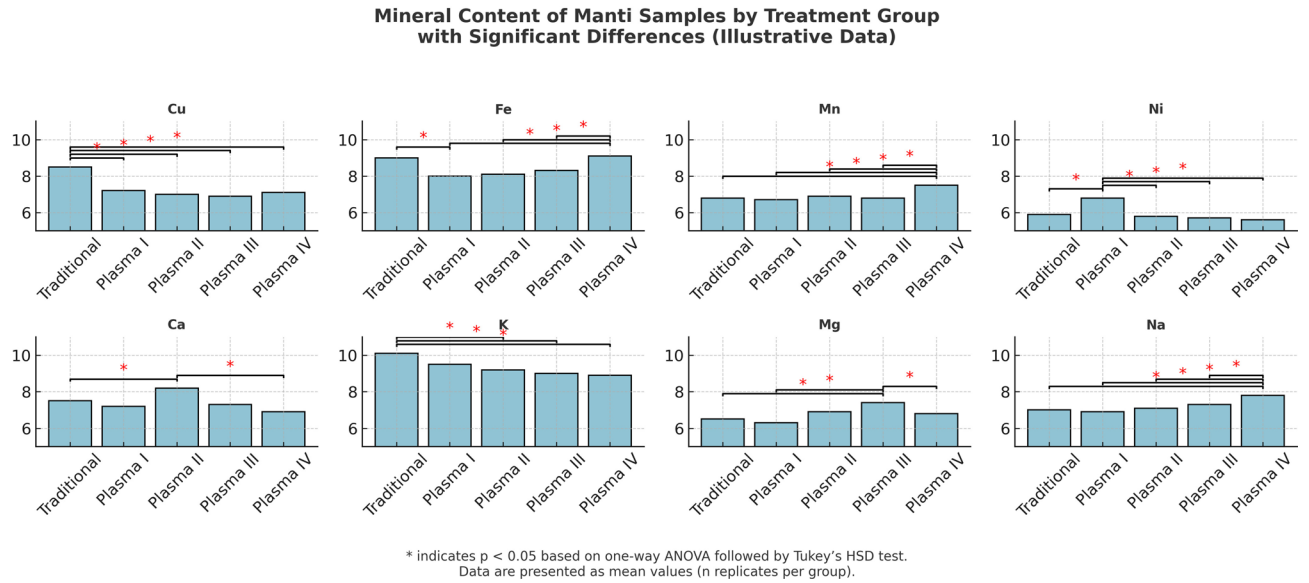


Fig. 8 (Initially, macro- and microelement composition of stuffed pasta (Turkish mantı) samples).

absorption rate and decreased the hardness and stickiness properties of the samples[10]. According to in another study, it was reported that the cooking time of brown rice was shorter and its sensory qualities higher[48]. In our study, plasma application had also a positive effect on the sensory quality of Turkish mantı samples. Sruthi (2022)[17] found that plasma-treated cheese maintained acceptable taste and odor. Similarly, in our study, Plasma I and IV preserved sensory characteristics better than traditional or extended plasma (Plasma III) methods.

As a result, sensory evaluations confirmed that plasma treatment did not negatively affect consumer-perceived quality. Sensory evaluations confirmed that plasma treatment did not negatively impact consumer-perceivable quality. The taste, odor, and texture of Turkish mantı remained acceptable in all plasma-treated groups.

Mineral and heavy metal profiles

Initially, minerals and heavy metal results of the Turkish mantı samples were given in Fig. 8.

Copper (Cu)

Cu concentration was significantly higher in the traditionally dried samples compared to all plasma-treated counterparts ($p<0.05$) (Fig. 8). This is likely due to the retention of Cu from vegetable-based ingredients (e.g., onion) and flour during traditional drying, where no plasma-induced surface modifications occur. In contrast, plasma treatment generates reactive oxygen and nitrogen species (RONS) that may induce subtle surface oxidation, reducing the binding affinity of Cu ions to proteins and carbohydrates, and potentially facilitating their leaching during subsequent cooking. Similar trends have been reported by Ncube (2022) [49], who observed higher Cu levels in conventionally dried foods compared to those processed using modern techniques.

Iron (Fe)

Fe content was highest in Plasma IV and Traditional groups ($p<0.05$) (Fig. 8). Given that Fe is primarily derived from the meat filling, the elevated values in Plasma IV could be explained by this treatment's longer exposure time and possibly higher energy density, which may have promoted protein unfolding, exposing heme and

non-heme Fe to stronger binding sites within the matrix. Yang et al. (2026) [50] reported that structural modification of muscle proteins can influence Fe retention by altering the accessibility of myoglobin-bound Fe.

Manganese (Mn)

Mn levels were relatively higher in the Plasma IV group compared to most other treatments (Fig. 8). Since Mn primarily originates from wheat flour, the higher retention may be linked to the possible surface sealing effect of plasma, which could reduce mineral loss during application [51]. Prolonged plasma treatment may form a cross-linked protein-starch matrix that encapsulates Mn, reducing its mobility. This observation aligns with Klimczak (2024) [52], who found that plasma treatment could redistribute and stabilize certain minerals in cereal-based products.

Nickel (Ni)

Ni concentration peaked in the Plasma I group, being significantly higher than all other groups ($p < 0.05$) (Fig. 8). This anomaly might be linked to the short plasma treatment in Plasma I, which was insufficient to modify the surface in a way that prevents Ni migration from stainless steel processing equipment. Longer plasma exposures in later treatments may have formed a thin oxidative layer acting as a barrier. Hernández-Montoya et al. (2026) [53] emphasized the role of equipment–food contact surfaces in trace metal transfer, particularly Ni.

Calcium (Ca)

The highest Ca content was recorded in Plasma II, significantly exceeding Plasma IV and Traditional ($p < 0.05$) (Fig. 8). This may be related to moderate plasma exposure promoting the unmasking of calcium-binding sites on proteins (especially casein residues in dairy ingredients) without causing excessive leaching during application. Overexposure (Plasma IV) might have damaged these binding sites, reducing retention. Similar enhancement of Ca-binding capacity following plasma treatment was reported by Li et al. (2025) [43] in milk protein systems.

Potassium (K)

K was most abundant in the Traditional group ($p < 0.05$) (Fig. 8). Potassium is highly water-soluble and prone to leaching during cooking. Plasma-treated samples may have undergone surface oxidation or microstructural changes that increased water permeability, facilitating K loss during boiling. The lack of significant K retention improvement under plasma treatment supports Farooq et al. (2023) [54], who found that non-thermal processing methods did not protect against K loss in high-moisture foods.

Mg content was highest in Plasma III and lowest in Plasma I ($p < 0.05$) (Fig. 8). This suggests that intermediate plasma conditions (Plasma III) may favor Mg retention by strengthening Mg–phytate or Mg–protein complexes in the dough. Conversely, Plasma I's low energy input might have failed to induce beneficial structural changes, while still allowing Mg loss during drying. Farooq et al. (2023) [54] , noted that plasma can alter mineral-binding capacity, particularly for divalent cations like Mg.

Sodium (Na)

Na concentration peaked in Plasma IV ($p < 0.05$) (Fig. 8). Since Na primarily originates from added salt, this increase may result from enhanced surface solubility of NaCl crystals due to prolonged plasma exposure, combined with possible concentration effects from minor surface dehydration during treatment. This agrees with Rao et al. (2023) [49], who observed plasma-induced modifications in salt solubility and surface distribution in treated foods. No significant differences ($p > 0.05$) were observed in the contents of other minerals among the treatments.

The mineral analysis results indicate that plasma treatments can selectively influence mineral retention in Turkish mantı depending on the specific element and the plasma parameters applied[51,55]. Traditional drying tends to preserve minerals from plant ingredients and meat (Cu, K), whereas certain plasma conditions enhance the retention of protein-bound or matrix-encapsulated minerals (Ca, Mg, Na). This suggests that cold plasma technology could be strategically applied to optimize the nutritional profile of Turkish mantı, potentially enhancing specific mineral contents while maintaining product quality.

Overall, the combined use of microwave drying and cold plasma appears to be a promising alternative to conventional drying, offering improved microbial safety, minimal quality degradation, and potential for shelf-life extension. These findings contribute to the expanding body of research advocating non-thermal plasma applications for safe, high-quality, ready-to-cook traditional foods.

Energy and economic feasibility analysis

To evaluate the industrial viability of the proposed technology against conventional methods, a comparative energy consumption analysis was performed. The cumulative electrical energy consumption (E, in kWh) for each system was calculated based on the standard power-time relationship:

$$E = \sum (P_i \times t_i)$$

where P_i represents the operational electrical power draw (in kW) of each component , and t_i is the corresponding processing duration (in h).

Traditional oven pre-baking requires the continuous thermal operation of an industrial convective oven drawing approximately 3.50 kW for a 35-min duration (0.58 h) to reduce the product moisture content down to 12%. This translates to a total energy expenditure of roughly 2.03 kWh per batch.

In contrast, the hybrid microwave-plasma system drastically compresses the operational runtime. Factoring in system efficiencies, the microwave drying stage exhibits a total electrical power draw of approximately 0.75 kW (delivering 0.46 kW of electromagnetic output) for 8 min (0.13 h), consuming 0.098 kWh. The subsequent low-pressure plasma generation draws 0.30 kW for an ultra-short exposure of 15 s (0.004 h), consuming 0.001 kWh. Including the continuous operation of the mechanical vacuum pump (0.75 kW for the entire 10-min vacuum/process cycle, or 0.16 h) which consumes 0.120 kWh, the cumulative energy expenditure for the hybrid process totals approximately 0.22 kWh per batch.

While the baseline capital investment cost for specialized microwave-vacuum plasma infrastructure is higher than standard thermal convective ovens, the resulting ~ 89% reduction in electrical energy consumption combined with the virtual elimination of ambient thermal dissipation demonstrates that the proposed hybrid technology is highly energy-efficient and economically sustainable for modern industrial food processing operations.

Conclusion

This study successfully demonstrated that the integration of microwave drying and low-pressure argon cold plasma treatment presents a highly viable, energy-efficient alternative to traditional thermal processing for traditional stuffed pasta (Turkish mantı). The core findings of this investigation indicate that:

- The hybrid process dramatically reduces processing time while avoiding thermal degradation, resulting in superior retention of visual and sensory attributes.
- Low-pressure argon plasma acts as a potent non-thermal antimicrobial intervention, achieving effective control over yeasts and molds while significantly reducing total viable mesophilic microorganism (TVMM) loads throughout a 30-d storage period.

- The optimal processing window was identified as the Plasma I group (15 s exposure, 1.5 L/min Argon flow rate), which successfully maximizes microbial inactivation while keeping lipid autoxidation (TBA values) well within acceptable safety thresholds.
- Mineral profiling revealed that plasma treatments selectively interact with the food surface matrix, altering element binding and retention profiles without causing overall nutritional degradation.

Limitations and future outlook

Despite these promising outcomes, certain limitations must be addressed to guide future industrial translation. This study focused on a 30-d storage period under controlled conditions; therefore, longer-term shelf-life trials under varying commercial retail humidities are necessary. Additionally, the complex chemical interaction between plasma-induced reactive oxygen and nitrogen species (RONS) and different lipid fractions in the beef filling demands further deep lipidomic analysis. Finally, future research should aim to scale up this vacuum batch-chamber design into a continuous-conveyor plasma system to facilitate its structural implementation in large-scale commercial food processing lines.

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Author contributions SG: investigation, formal analyses, methodology HK: writing, editing, formal analyses MOE: investigation, methodology HY: Writing – original draft, Writing – review & editing. FB: Writing – original draft, Writing – review & editing.

Data availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable. This study does not utilize any custom or bespoke computational tools, algorithms, or private software pipelines. All data analyses were performed using standard commercial statistical tools.

Declarations

Competing interests The authors declare no competing financial or non-financial interests.

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