Journal of Food Processing and Preservation

WILEY

RESEARCH ARTICLE OPEN ACCESS

Optimization of Cold Plasma Treatment for *Aspergillus niger* Decontamination in Dried Apricots (*Prunus armeniaca*)

Maryam Davarpanah[1] | Seyed Alireza Banihashemi[2] | Saber Amiri[2] | Mohammad Reza Vardast[3] | Nima Shaykh-Baygloo[1] | Mohammad Yousefi[4]

[1]Department of Biology, Faculty of Science, Urmia University, Urmia, Iran | [2]Department of Food Science and Technology, Faculty of Agriculture, Urmia University, Urmia, Iran | [3]Department of Medicinal Chemistry, School of Pharmacy, Urmia University of Medical Sciences, Urmia, West Azerbaijan, Iran | [4]Food and Beverages Safety Research Center, Urmia University of Medical Sciences, Urmia, Iran

Correspondence: Nima Shaykh-Baygloo (n.baygloo@urmia.ac.ir) | Mohammad Yousefi (yousefi.sbu@gmail.com)

Received: 11 May 2025 | **Revised:** 14 February 2026 | **Accepted:** 18 February 2026

Academic Editor: Poulami Jha

Keywords: cold plasma | DPPH | fungal decontamination | TPC

ABSTRACT

Dried apricots are highly susceptible to fungal contamination, particularly by *Aspergillus niger*, posing serious concerns for food safety and shelf life. This study is the first to systematically evaluate and optimize cold plasma treatment (CPT) parameters for the decontamination of *A. niger* in dried apricot samples (DASs). A central composite design (CCD) was used to assess the effects of exposure time and the distance between the plasma source and the sample. The optimized conditions (15 min exposure at 2 cm distance) resulted in a maximum fungal reduction of 4.3 log colony-forming unit (CFU)/g (the mean value of the center-point replicates was 4.63 ± 0.13). Scanning electron microscopy (SEM) revealed significant surface damage, confirming the etching effect of CPT. Moreover, the treatment enhanced total phenolic content (TPC) (from 104 to 204.3 mg GAE/100 g, the mean value of the center-point replicates was 198.3 ± 0.9 mg GAE/100 g [$n = 5$]) and improved antioxidant activity, indicated by decreased 2,2-diphenyl-1-picrylhydrazyl (DPPH) absorbance (from 0.052 to 0.033 at 517 nm, the mean value of the center-point replicates was 0.036 ± 0.005 [$n = 5$]), without significantly affecting pH or titratable acidity. These findings demonstrate that CPT not only effectively reduces fungal contamination but also improves functional quality, indicating its strong potential for industrial-scale application in the dried fruit sector.

1 | Introduction

Dried apricots (*Prunus armeniaca*), as a key agricultural product in Iran, hold a significant place in both domestic consumption and international trade due to their rich nutritional profile and long shelf life. These dried fruits are a valuable source of essential vitamins, such as A, C, and E, as well as minerals like potassium and iron, making them a popular healthy food [1]. However, despite their benefits, dried apricots are highly susceptible to microbial contamination, particularly by fungal species. Among these, *Aspergillus niger* (*A. niger*) stands out as a major concern. *A. niger* is a common filamentous fungus that can be found in soil, decaying plant matter, and various food items. While it is important for industrial uses, such as producing citric acid and enzymes, its presence in dried foods like apricots raises concerns about spoilage and the risk of mycotoxin production. A study that examined 50 samples of dried fruits, including apricots, cranberries, papaya, pineapple, and raisins, revealed that live fungi contaminated 25% of the apricot samples. Researchers identified *A. niger* as the most frequent mold, followed by species of

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Copyright © 2026 Maryam Davarpanah et al. *Journal of Food Processing and Preservation* published by John Wiley & Sons Ltd.

Penicillium. This research underscores the common occurrence of *A. niger* in dried apricots and other dried fruits [2].

One major concern regarding *A. niger* contamination in dried foods is its capacity to produce mycotoxins, especially ochratoxin A (OTA). Researchers have linked OTA, a nephrotoxic compound, to kidney damage and believe it may have carcinogenic effects. The presence of *A. niger* strains that produce OTA in dried fruits poses serious health risks for consumers [3]. Additionally, people with weakened immune systems or respiratory issues may face heightened risks when exposed to *A. niger*. Breathing in fungal spores can trigger allergic reactions or lead to invasive infections, highlighting the need for careful monitoring and control of fungal contamination in food products. The presence of OTA in dried fruits can lead to several economic challenges in international trade, such as rejection of shipments, increased testing and certification costs, market access limitations, and price depressions. For instance, 17.1% of dried fruits from Morocco were found to be contaminated with OTA. These contamination rates suggest potential economic risks, especially concerning export quality standards.

Current global food safety regulations impose strict limits on OTA in food products to protect consumer health and ensure the safety of the global food supply. For instance, the European Union has set strict maximum levels for OTA in various food commodities under Commission Regulation (EC) No 1881/2006, ranging from 2.0 μg/kg in wine to 15.0 μg/kg in certain spices. Noncompliance with these standards can result in the rejection of contaminated products in international markets, leading to significant economic losses for producers and exporters. As a result, there is an urgent need for effective decontamination methods that reduce fungal contamination while maintaining the quality of food products. Implementing such methods not only helps ensure compliance with food safety regulations but also minimizes the risk of market rejection and economic damage.

Traditional decontamination methods, such as thermal treatments and chemical fumigation, have been widely used to control microbial contamination in food products. While these methods can be effective in reducing fungal loads, they often come with significant drawbacks [4]. Thermal treatments can cause undesirable changes in the sensory and nutritional properties of dried fruits, such as alterations in texture, flavor, and color [5, 6]. Similarly, chemical fumigants, while efficient in killing fungi, pose environmental and health risks due to the residues they leave behind [4, 7]. Moreover, growing consumer demand for natural and chemical-free food products has increased the pressure on the food industry to adopt safer and more sustainable alternatives to conventional decontamination techniques.

In response to these challenges, nonthermal technologies such as cold plasma, pulsed electric fields (PEFs), high-pressure processing (HPP), ultraviolet-C (UV-C) irradiation, and ultrasound have gained increasing attention due to their ability to reduce microbial load while preserving nutritional and sensory attributes [5, 8]. Cold plasma is a partially ionized gas containing reactive species, such as reactive oxygen species (ROS) and reactive nitrogen species (RNS), which can effectively inactivate a wide range of microorganisms, including bacteria, fungi, and viruses [9]. The advantage of cold plasma lies in its ability to deactivate pathogens without the use of chemicals or excessive heat, thus minimizing any negative impact on the quality of the treated food. This technology has been shown to disrupt the cell walls of microorganisms, cause oxidative damage to DNA and proteins, and ultimately lead to microbial inactivation [10].

Cold plasma is a particularly attractive option for the treatment of dried fruits, as it offers a noninvasive approach to reduce fungal contamination without compromising the sensory and nutritional attributes of the fruit. Furthermore, cold plasma is considered an environmentally friendly technology due to its low energy consumption and lack of chemical residues [11]. Although several studies have demonstrated the effectiveness of cold plasma in decontaminating various food products, such as grains and fresh produce, its specific application in dried apricots remains underexplored. Prior research has largely focused on other dried fruits, leaving a gap in understanding the optimal parameters and effects of this technology in apricot matrices [12, 13, 14]. Moreover, existing studies have often lacked a detailed statistical optimization approach, limiting their ability to propose practical guidelines for industrial application.

The present study seeks to address this research gap by investigating the efficacy of cold plasma for decontamination of dried apricots contaminated with *A. niger*. Using a central composite design (CCD), the key variables, exposure time and distance between the plasma source and the sample, were optimized through response surface methodology (RSM) to achieve maximum fungal reduction. This study not only evaluates the antifungal performance of cold plasma but also its impact on the physicochemical and functional properties of dried apricots. By providing a statistically optimized treatment protocol, this research contributes a scalable and sustainable solution for improving food safety in dried fruit production.

2 | Materials and Methods

2.1 | Sample Preparation

Dried apricots (*P. armeniaca*) were obtained from a local market in Urmia, Iran. The fruits were processed using traditional drying methods with sulfur dioxide and stored in a dry environment at room temperature until further analysis. Prior to cold plasma treatment (CPT), the dried apricots were confirmed to be free of fungal contamination and subsequently inoculated with *A. niger* under controlled laboratory conditions to evaluate the decontamination efficacy of cold plasma. To ensure that the apricots were free of natural fungal contamination prior to inoculation, all samples were subjected to microbiological screening. Approximately 10 g of each sample was aseptically homogenized in 90 mL of sterile peptone water and serially diluted. A 100 μL aliquot from each dilution was plated onto potato dextrose agar (PDA) supplemented with chloramphenicol (100 mg/L) to inhibit bacterial growth. Plates were incubated at 28°C for 3–5 days. Samples showing no visible fungal colonies were considered fungal-free and used for subsequent inoculation with *A. niger*. Fungal inoculation was performed using a standardized *A. niger* spore suspension. The inoculum was prepared by flooding a 7-day-old culture of *A. niger* grown on PDA plates with 10 mL of sterile 0.1% Tween-80 solution and gently scraping the surface to release the spores. The resulting suspension was filtered through sterile gauze to remove mycelial fragments. Spore concentration

was adjusted to 1×10^6 spores/mL using a hemocytometer and confirmed spectrophotometrically (OD_{550}). Each dried apricot sample (DAS) (~10 g) was inoculated with 100 μL of the standardized spore suspension (1×10^6 spores/mL), resulting in an estimated initial load of 1×10^4 colony-forming units (CFUs)/g. The inoculum was spread evenly over the surface and allowed to attach for 30 min under a biosafety cabinet before CPT.

2.2 | CPT

Prepared samples were placed in sterile, empty Petri dishes, and CPT was applied using a custom-built cold atmospheric pressure plasma jet (CAPPJ) system developed at Urmia University (pulsed high-voltage direct current [DC] [12 kHz]). The device consists of a single-electrode configuration with a quartz dielectric barrier and cylindrical nozzle. The plasma is generated using high-voltage DC at a frequency of 12 kHz. Ambient air served as the working gas. Specific parameters such as gas flow rate, nozzle diameter, and power density were not recorded for this custom device and are therefore acknowledged as limitations for reproducibility. The device's configuration and operational settings are described above to provide as much detail as possible for replication. The plasma jet was directed vertically onto the sample surface at varying exposure times and distances. A total of 13 experimental runs were performed by combining these two variables. During treatment, the emission of a purple glow visually confirmed plasma exposure. Detailed treatment parameters are provided in Table 1. The extraction procedure was conducted in four replicates. In each run, 160 g of finely chopped dried apricots were mixed with 800 mL of solvent (comprising 640 mL of methanol and 160 mL of distilled water) and stirred at room temperature for 6 h. The resulting mixture underwent initial filtration through sterile gauze, followed by vacuum filtration using filter paper. The final extract was concentrated using a rotary evaporator to isolate the pure extract.

2.3 | Morphological Analysis by Scanning Electron Microscopy (SEM)

For morphological analysis, both a control sample and a sample exposed to cold plasma at optimal conditions (15 min exposure and 2 cm distance) were prepared. The samples were coated with a thin layer of gold to enhance conductivity and improve imaging resolution. SEM was then used to observe the surface morphology, allowing for detailed examination of surface changes caused by the CPT. All SEM images were captured at a magnification of 100 × with an accelerating voltage of 5.00 kV. The scale bar shown in each image represents 500 μm, providing a reference for structural comparison. This method provides high-resolution images of the sample's microstructure, offering insights into surface modifications at the micrometer-scale level.

2.4 | Chemical and Antioxidant Analysis

For the determination of total phenolic content (TPC), 1 mL of apricot extract was mixed with 5 mL of Folin–Ciocalteu reagent and 4 mL of sodium bicarbonate. The mixture was incubated in darkness for 2 h, after which the absorbance was measured using a spectrophotometer. The phenolic content was quantified by constructing a calibration curve using various concentrations of gallic acid. The absorbance values of solutions containing gallic acid instead of extract were plotted, and the equation $y = ax + b$ was obtained, where a and b are constants derived from the gallic acid calibration. The phenolic content (x) was then calculated and multiplied by 10 to express the result as milligrams of phenol per liter.

For the antioxidant activity assessment using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, 0.004 g of DPPH powder was dissolved in 100 mL of methanol in a flask wrapped with aluminum foil. A 5 mL portion of this solution was combined with 1 mL of apricot extract and left in darkness for 30 min. A control was prepared by mixing 5 mL of the DPPH solution with 1 mL of distilled water. The reduction in absorbance at 517 nm was used as an indicator of antioxidant capacity; therefore, lower absorbance values correspond to higher DPPH radical scavenging activity, reflecting stronger antioxidant potential.

The pH of the apricot extract was measured using a calibrated pH meter. Acidity was quantified via titration with 0.1N sodium hydroxide, using phenol red as an indicator. A 2 mL sample was diluted, and titration proceeded until the pH reached 8.1.

2.5 | Microbial Response to CPT

PDA medium was prepared by dissolving 39 g of PDA in 1 L of distilled water, followed by autoclaving at 121°C for 15 min. After cooling, the medium was poured into sterile Petri dishes. Peptone water was also prepared by dissolving 1.1 g of peptone in 110 mL of distilled water for use as a dilution medium. A suspension of *A. niger* was prepared by adding sterile distilled water to a Petri dish containing mold mycelium, creating a 0.5 McFarland standard suspension, verified using a spectrophotometer at 550 nm. The suspension was diluted in a 1:10 ratio with the extract and peptone water. For colony counting, 100 μL of the diluted samples were spread onto PDA plates. After incubation at 28°C for 48 h, the colonies were counted. The antifungal effect of each treatment was quantified by calculating the log reduction using the following formula:

$$\text{Log reduction} = \log_{10}\left(\frac{N_0}{N}\right),$$

where N_0 is the mean colony count of the untreated control sample, and N is the mean colony count after CPT. The optimal treatment condition was identified as the one achieving the highest log reduction in CFUs.

TABLE 1 | Cold plasma treatment conditions.

Type of the cold plasma	Power source	Sample	Working gas	Distance between sample and the nozzle tip	Exposure time
CAPPJ	Voltage: 15 KV high voltage DC Frequency: 12 kHz	Dried apricots	Air	2, 5, 8 cm	5, 10, 15 min

Note: Distance = distance between sample and nozzle tip, exposure time = duration of plasma treatment, working gas = ambient air.
Abbreviations: CAPPJ, cold atmospheric pressure plasma jet; DC, direct current.

2.6 | Statistical Analysis

Statistical analysis was performed using version 8 of Design-Expert software, based on RSM and the CCD model. In this design, plasma exposure time and the distance between the device and the sample were considered as independent variables. The software generated a statistically significant model, and experiments were conducted in 13 runs according to the design matrix. This approach enabled the evaluation of the individual and interactive effects of the variables and the optimization of CPT conditions. Model performance for microbial analysis was assessed using standard diagnostic criteria: $R^2 = (0.88)$, adjusted $R^2 = (0.80)$, predicted $R^2 = (0.64)$, and lack-of-fit p-value = (0.71), confirming the model's adequacy and predictive reliability. The experimental design included five center point replicates to allow estimation of pure error and model adequacy. However, factorial and axial points were not replicated. All measurements were performed in triplicate, and results are presented as mean ± standard deviation (SD). Statistical significance among treatments was determined using ANOVA followed by Tukey's post hoc test at a confidence level of $p < 0.05$.

TABLE 2 | Central composite design matrix showing standard order, run number, and factor levels (time and distance) for cold plasma treatment of dried apricots.

Standard order	Run	Time (min)	Distance (cm)
6	1	15	5
11	2	10	5
2	3	15	2
8	4	10	8
1	5	5	2
9	6	10	5
10	7	10	5
7	8	10	2
5	9	5	5
3	10	5	8
13	11	10	5
12	12	10	5
4	13	15	8

Note: Time = exposure time in min; distance = distance from plasma nozzle tip in centimeters.

3 | Results and Discussion

3.1 | Optimization of CPT Processing Conditions Using Response Surface Methodology

The experimental design matrix generated by RSM is presented in Table 2, outlining CPT conditions (treatment time and distance). The corresponding results are reported separately in Table 3 (physicochemical properties) and Table 4 (fungal load) for clarity and detailed analysis.

The optimization aimed to evaluate the strong inactivation potential of cold plasma on microbial load while maintaining product quality. The optimal CPT condition, 15 min exposure at 2 cm distance, resulted in a maximum fungal reduction of 4.3 log CFU/g, highlighting strong inactivation while preserving the quality of samples. The RSM model revealed a statistically

TABLE 3 | Physicochemical properties of dried apricots after cold plasma treatment.

Std	Run	A: Time (min)	B: Distance (cm)	pH	Acidity (mg malic acid equivalents/100 g)	TPC (mg GAE/100 g)	DPPH (absorbance at 517 nm [unitless])
6	1	15	5	4.24	73.5	191.1	0.05
11	2	10	5	4.27	59.9	198.6	0.036
2	3	15	2	4.24	62.1	204.3	0.052
8	4	10	8	4.36	76.3	193	0.038
1	5	5	2	4.33	76	203.8	0.032
9	6	10	5	4.38	60.9	197.2	0.035
10	7	10	5	4.34	60.7	198.9	0.036
7	8	10	2	4.28	58.5	202.5	0.036
5	9	5	5	4.29	65	201.7	0.035
3	10	5	8	4.28	67	195.5	0.035
13	11	10	5	4.42	60.4	199.3	0.033
12	12	10	5	4.26	59.7	197.7	0.044
4	13	15	8	4.25	87.6	186.2	0.049

Note: A = exposure time (min); B = distance from nozzle (cm). Factorial and axial design points represent single experimental observations. The center point condition (10 min exposure time, 5 cm distance) was replicated five times as part of the CCD to estimate experimental variability. For the center point, the mean ± standard deviation (SD) values were as follows: pH = 4.33 ± 0.07, titratable acidity = 60.32 ± 0.5 mg malic acid equivalents/100 g, total phenolic content = 198.3 ± 0.9 mg GAE/100 g, and DPPH absorbance = 0.037 ± 0.004 ($n = 5$).
Abbreviations: DPPH, 2,2-diphenyl-1-picrylhydrazyl; GAE, gallic acid equivalents; TPC, total phenolic content.

TABLE 4 | Fungal load (microbial response).

Standard order	6	11	2	8	1	9	10	7	5	3	13	12	4
Time (min)	15	10	15	10	5	10	10	10	5	5	10	10	15
Distance (cm)	5	5	2	8	2	5	5	2	5	8	5	5	8
A. niger (log CFU/g)	4.72	4.5	4.3	4.98	4.9	4.53	4.6	4.42	5.05	5.1	4.72	4.8	4.93

Note: For the center point, the mean ± standard deviation (SD) values were 4.63 ± 0.13.

significant interaction between exposure time and distance. Specifically, fungal inactivation and enhancement of TPC/DPPH increased with longer exposure times and shorter distances, but a threshold effect was observed. For instance, while increasing exposure from 5 to 10 min at 2 cm significantly improved outcomes, further extension to 15 min showed only marginal gains, indicating diminishing returns. Similarly, reducing the distance from 8 to 5 cm enhanced plasma efficiency, but the improvement from 5 to 2 cm was less dramatic. These nonlinear effects are evident in the response surface plots (Figures 1–3), where the slope of improvement plateaus beyond certain parameter values. This interaction suggests the presence of optimal windows rather than a linear benefit from increasing intensity, emphasizing the importance of precise calibration for energy efficiency and quality preservation. The second-order regression model and 3D plots generated by Design-Expert confirmed the significant interaction term (time × distance) and supported the selection of 15 min and 2 cm as the optimal compromise between microbial inactivation and quality retention. This finding mirrors similar optimization studies in other dried products, such as nuts and seeds, where short-distance, extended exposure treatments also maximized microbial inactivation [14, 15].

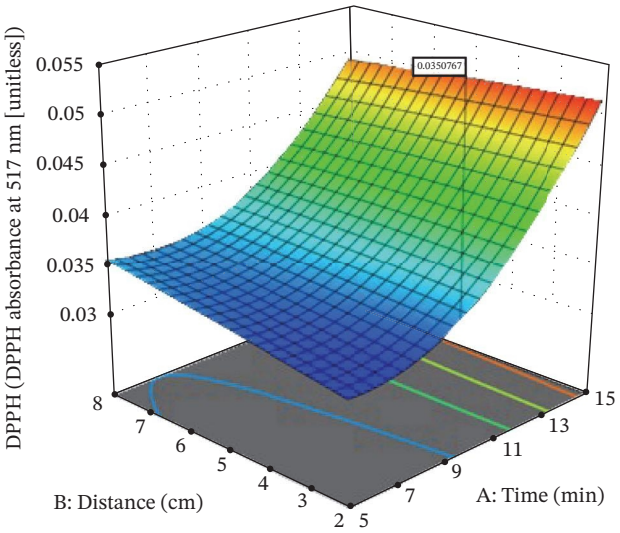


FIGURE 2 | Response surface plot showing the effect of cold plasma exposure time (min) and distance from nozzle (cm) on DPPH absorbance of dried apricots (517 nm, unitless). The predicted optimum condition is indicated as a flag on the surface.

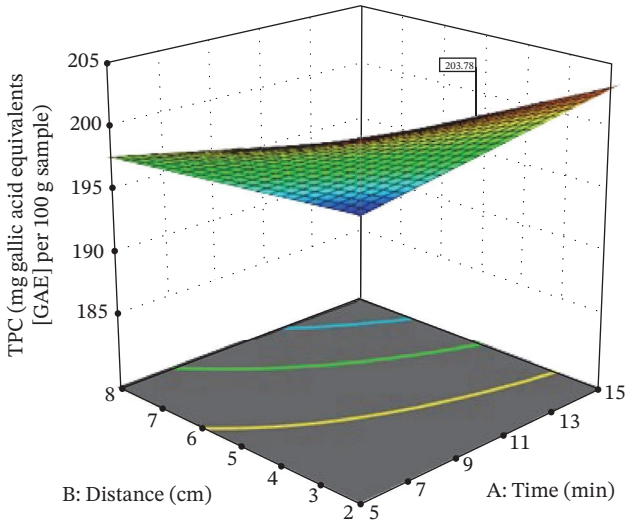


FIGURE 1 | Response surface plot showing the effect of cold plasma exposure time (min) and distance from nozzle (cm) on total phenolic content of dried apricots (mg GAE/100 g). The predicted optimum condition is indicated as a flag on the surface.

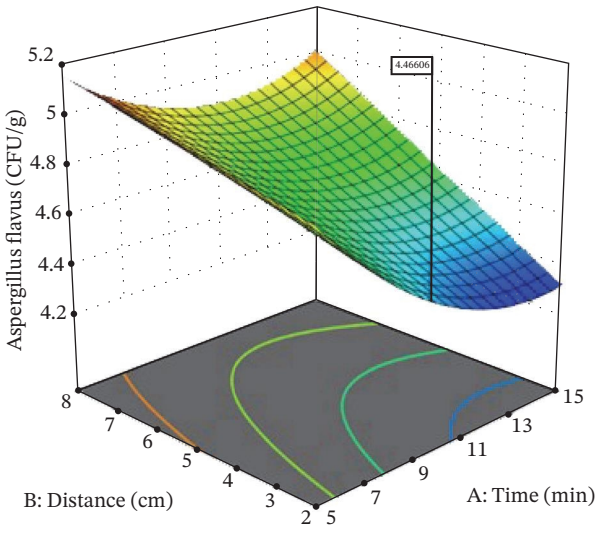


FIGURE 3 | Response surface plot showing the effect of cold plasma exposure time (min) and distance from nozzle (cm) on *Aspergillus niger* population (log CFU/g) in dried apricots. The predicted optimum condition is indicated as a flag on the surface.

3.2 | Microstructural and Morphological Characterization

3.2.1 | Surface Microstructure of Cold Plasma-Treated Apricots

SEM observations showed noticeable microstructural differences between cold plasma–treated dried apricots and the untreated control samples (Figure 4). The treated samples displayed surface etching, increased roughness, and the presence of small pores, whereas the control samples retained a more compact and relatively smooth surface structure.

Cold plasma affects plant tissues through multiple interconnected mechanisms, primarily driven by reactive oxygen and nitrogen species (RONS). These mechanisms, including surface oxidation, cell wall disruption, protein denaturation, activation of secondary metabolism, and hydrophobicity enhancement, collectively modify both the surface and internal structures of the tissues, enhancing the extraction of valuable compounds. Recent studies have shown that cold plasma etches various segments of plant tissues, making it a promising pretreatment for extracting bioactive compounds, as it increases yield and reduces extraction time. This finding highlights the potential of CPT as a pretreatment technique for modifying texture for different purposes, such as extraction [16].

Cold plasma generates a complex mixture of ROS and RNS, such as ozone (O_3), singlet oxygen ($^1O_2$), hydroxyl radicals (·OH), and nitric oxide (NO), which can interact with plant tissue surfaces. These reactive species induce oxidative stress, disrupting cell wall polysaccharides, denaturing membrane proteins, and increasing membrane permeability. This action facilitates water uptake, loosens the matrix structure, and enhances the release of intracellular components, including phenolics and organic acids. Additionally, localized oxidation on the cuticle or surface layers may contribute to microstructural changes such as pore formation. In addition to altering surface appearance, the pore structures generated by cold plasma may influence functional properties of dried apricots. Increased surface porosity can enhance moisture diffusion and reduce water retention, which may in turn reduce the risk of mold regrowth during storage. Conversely, in some cases, excessive pore formation may accelerate moisture loss and affect textural stability. Therefore, these microstructural changes may have implications for shelf-life extension by limiting available moisture for fungal proliferation.

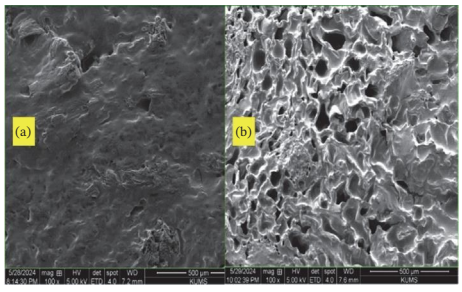


FIGURE 4 | Surface microstructure of dried apricots observed by scanning electron microscopy at 100× magnification. Plasma-treated samples (15 min exposure, 2 cm distance) (b) show increased surface roughness and formation of micro-scale pores compared with untreated control samples (a). Scale bar = 500 μm. Images are representative of three independent biological replicates. Only one magnification was used; this is acknowledged as a limitation.

While SEM analysis confirmed no overt visual damage to the apricot surface, the formation of pores and surface etching indicates notable microstructural alteration. These changes, although potentially beneficial for extraction and bioavailability, may negatively impact the textural integrity and moisture retention of the final product. Such structural modifications could accelerate moisture loss or influence mouthfeel, which may in turn affect consumer acceptance. Additionally, increased porosity might expose the internal matrix to oxidative or microbial recontamination during storage, thus potentially reducing shelf life if not properly packaged. Therefore, optimizing treatment parameters is essential to balance microbial inactivation and bioactive enhancement while minimizing adverse impacts on quality attributes.

3.3 | Antioxidant and Chemical Properties

3.3.1 | Impact of CPT on Phenolics, Antioxidant Activity, and Acidity

One of the study's key objectives was to evaluate whether CPT enhances functional compounds in dried apricots, beyond microbial inactivation. The application of CPT on DAS significantly influenced both the TPC and antioxidant activity (DPPH), showcasing its potential to enhance bioactive compounds while also revealing some limitations when treatment is prolonged. The TPC of DAS was assessed using a gallic acid calibration curve. In control samples, TPC was measured at 104 mg/L, whereas CPT resulted in a significant increase, with values ranging between 187 and 200 mg/L. This rise in phenolic content underscores the ability of cold plasma to enhance the bioactive profile of the apricots. Also, it was observed that extended plasma exposure increased TPC (Figure 1). The antioxidant capacity, as measured by the DPPH assay, improved following CPT. Absorbance values at 517 nm decreased significantly in plasma-treated samples compared to the control (0.045), indicating enhanced radical scavenging activity, particularly at 15-min exposure times and at 2, 5, and 8 cm distances. Prolonged exposure conditions further increased antioxidant activity (Figure 2), while the distance factor did not significantly influence either DPPH or TPC outcomes. CPT significantly increased TPC values ($p < 0.05$), with the highest increase observed at 15 min exposure at 2 cm. Treatments at 5 and 8 cm showed no statistically significant difference ($p > 0.05$). In overall, CPT significantly enhances the TPC and DPPH radical scavenging activity in dried apricots, with longer exposure times further amplifying these effects. These findings highlight CPT's effectiveness in boosting the antioxidant properties of dried apricots.

Researchers attribute the rise in TPC after CPT to the plasma-induced breakdown of cellular structures, which helps release and extract phenolic compounds. Reactive species generated by the plasma, such as RONS, can disrupt cell walls and membranes, making bound phenolics more accessible [17]. Extended CPT likely intensifies this effect by further permeabilizing cellular barriers, resulting in an even greater release of these compounds. The observed increase in TPC is likely a result of multiple converging mechanisms. Primarily, plasma-induced membrane disruption facilitates the release of phenolics that are normally bound to the cell wall matrix. Additionally, RONS may chemically cleave esterified or glycosylated phenolics,

converting them into more soluble and bioactive forms. There is also a possibility that short-term oxidative stress triggers de novo biosynthesis of phenolic compounds via the phenylpropanoid pathway, although this mechanism requires further confirmation. The balance between these effects depends on treatment duration, intensity, and the physiological status of the tissue. The simultaneous increase in DPPH radical scavenging activity suggests that the released phenolic compounds remain bioactive and may even be activated by CPT. Prolonged exposure to plasma could encourage the formation of additional antioxidant molecules or convert existing phenolics into more effective antioxidant forms. Other studies have reported similar observations; for instance, research on fresh-cut pitaya (*Hylocereus undatus*) fruit found that CPT treatment resulted in higher levels of phenolic compounds and improved antioxidant activity. The study noted an increase in TPC and DPPH radical scavenging activity, suggesting that phenolic precursors were transformed into more effective antioxidant substances.

Moreover, the absence of degradation or reduction in TPC and DPPH with extended CPT in this study indicates that the treatment parameters, such as power intensity, frequency, and gas composition, were optimally configured to enhance rather than degrade phenolic compounds. This highlights the necessity of carefully managing CPT conditions to maximize benefits while avoiding oxidative damage to sensitive bioactive compounds. In summary, the increase in TPC and DPPH in dried apricots with prolonged CPT exposure underscores its potential as a valuable processing technique for improving nutritional and functional properties.

Our findings are supported by previous research where CPT enhanced phenolic content in fresh-cut pitaya and strawberries [17], likely due to reactive species disrupting plant tissues and releasing bound phenolics. Similar enhancements in antioxidant activity post-CPT have been reported by [11], highlighting the ability of CPT to simultaneously improve nutritional properties and extend shelf life.

The plasma treatment had no significant impact on the pH, which remained consistently acidic within the range of 4.2–4.4. However, the plasma variables did influence the acidity, although the changes followed no clear or consistent pattern. The acidity levels varied within a range of 58–87, with a quadratic response suggested by the data.

The measured pH, acidity, TPC, and DPPH values for the experimental runs are reported individually for each standard run, with SDs not applicable for single-replicate points (factorial and axial points due to the limited design). For the center points, the average pH was 4.33 with a SD of 0.07, the mean acidity was 60.32 mg FMA with a SD of 0.5 mg FMA, the mean TPC was 198.3 nm with a SD of 0.9 nm, and the average DPPH radical scavenging activity was 0.037 with a SD of 0.004.

3.4 | Microbial Inactivation

3.4.1 | Effects of CPT Parameters on Fungal Inactivation

Achieving effective fungal decontamination, particularly of *A. niger*, was the core goal of this study. The CPT significantly reduced the fungal contamination of *A. niger* in dried apricots (Figures 3 and 5). The mean *A. niger* count for the center points

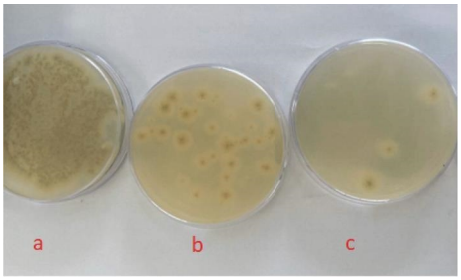


FIGURE 5 | *Aspergillus niger* counts in control sample (a), 8 cm distance and 5 min cold plasma treatment (b), and 2 cm distance and 15 min cold plasma treatment (c).

was 4.68 log CFU/g, with a SD of 0.28 log CFU/g. The effect of time and distance on the reduction of *A. niger* counts was investigated in the experimental runs. The log CFU/g values varied from 4.3 to 5.1, indicating that both factors influenced microbial reduction. Notably, reducing the distance from 8 to 2 cm increased microbial inactivation; for example, at 15 min, the log count decreased from 4.98 log CFU/g at 8 cm (run 8) to 4.3 log CFU/g at 2 cm (run 2), representing approximately a 13.7% reduction in microbial load. Similarly, shorter distances combined with longer exposure times consistently resulted in lower counts, with run 1 (5 min, 2 cm) and run 7 (10 min, 2 cm) showing log CFU/g values of 4.9 and 4.42, respectively, compared to higher values at longer distances. These results highlight the significant interaction between time and distance, demonstrating that microbial reduction improves markedly when the treatment distance is decreased while maintaining sufficient exposure time.

By reducing the distance between the plasma source and the sample, a higher concentration of reactive species can directly target the fungal cells, boosting their antimicrobial effectiveness. When plasma is applied from a closer range, reactive particles like ozone, hydroxyl radicals, and nitrogen oxides interact more efficiently with fungal spores and cells. This interaction disrupts cell membranes, induces oxidative stress, and ultimately leads to the death of microbial cells. Earlier research also supports this finding by showing a direct correlation between plasma intensity and microbial inactivation rates in wheat flour, where closer exposure to plasma results in a more potent antimicrobial effect [15]. Additionally, extending the CPT exposure time further helps reduce fungal contamination by increasing the total dose of reactive species that interact with fungal cells. Longer plasma treatment likely intensifies oxidative stress, causing protein denaturation, lipid peroxidation, and DNA damage, which decreases fungal viability. For instance, a study on buckwheat seeds demonstrated that increasing the treatment duration from 15 to 120 s significantly reduced fungal colonization. The longest exposure of 120 s resulted in a lower average number of fungal morphotypes per plate in both common and Tartary buckwheat species. However, while longer treatment times are advantageous for inactivating fungi, it is important to consider possible negative impacts on product quality, such as alterations in texture, color, or nutritional value, which may require adjustment of the treatment parameters.

The reduction in *A. niger* was significantly higher at 2 cm compared to 5 and 8 cm ($p < 0.05$). Complete elimination of *A. niger* was not achieved in this study. This limited inactivation is likely due to the high resistance of *A. niger* spores, which have thick

melanized walls and low water content, and may also be partially shielded within surface micro-crevices of dried apricots. Stronger plasma conditions—such as longer exposure times, higher discharge voltage, or the use of more reactive gases (e.g., oxygen or argon)—could potentially increase inactivation, although such intensified treatments may affect product quality. These results indicate that both exposure time and proximity to the plasma source are critical factors in achieving effective fungal inactivation. Reducing the distance between the plasma device and the sample, along with longer exposure durations, significantly enhances fungal reduction in dried apricots during CPT.

Comparatively, our findings are in line with Waskow et al. [14], who reported up to 4 log reductions in microbial load on seeds using cold atmospheric plasma, and Janić Hajnal et al. [15], who found that shorter plasma distances and longer exposure significantly decreased *Alternaria* toxins in wheat flour. These studies further emphasize the key role of plasma-sample proximity and treatment duration in maximizing microbial inactivation across dried foods.

3.4.2 | Practical Implications and Scalability

The optimized CPT conditions (15 min exposure at 2 cm distance) demonstrated a significant reduction of *A. niger* without adversely affecting the physicochemical quality of dried apricots. These parameters, although developed under laboratory-scale conditions, offer promising potential for scale-up in industrial applications. In commercial settings, cold plasma systems can be integrated into batch treatment systems for high-value products or adapted into continuous-flow conveyor systems for high-throughput lines. However, applying a 2 cm distance uniformly across large batches presents technical challenges, as plasma intensity diminishes with increased distance or inconsistent orientation. Therefore, industrial-scale designs may require multi-nozzle arrays, plasma tunnels, or adjustable height mechanisms to ensure uniform exposure. The 15-min treatment time, while suitable for lab tests, might need to be optimized (e.g., increased power or dual-side treatment) to reduce processing time and improve efficiency. Moreover, since ambient air was used as the plasma-generating gas, the system remains cost-effective and eco-friendly, with minimal additional inputs required. This increases the feasibility of integration into existing drying or packaging lines in the dried fruit industry. Further pilot-scale trials are needed to validate consistency, energy consumption, and throughput under real-world operating conditions. Similar cold plasma systems have already been scaled for industrial applications, including continuous-flow conveyor-based plasma treatment units for nuts and dried fruits, air-plasma tunnels used for decontaminating packaging materials, and roll-to-roll atmospheric plasma systems for grain surface sterilization. These examples demonstrate that the technology can be adapted for continuous processing and has strong potential for integration into dried fruit production lines.

4 | Conclusion

This study demonstrated that CPT is an effective nonthermal approach for reducing *A. niger* contamination in dried apricots. The optimized condition (15 min exposure at 2 cm distance) achieved a maximum reduction of 4.3 log CFU/g while preserving the physicochemical quality of the product. CPT also enhanced TPC and antioxidant activity without significantly affecting pH or titratable acidity. SEM analysis confirmed surface modifications that support plasma-induced structural changes. Overall, the findings highlight the potential of cold plasma as a promising technology for improving microbial safety and functional quality in dried apricots.

Although the current study quantified TPC and DPPH absorbance, more detailed analyses such as %DPPH inhibition or IC_{50} determination, HPLC-based phenolic profiling, and OTA quantification were not performed. These analyses are recommended for future studies to provide a more comprehensive understanding of the antioxidant capacity and mycotoxin decontamination efficacy of CPT in dried apricots.

Author Contributions

Mohammad Yousefi: conceptualization, data curation, formal analysis, investigation, methodology, supervision, validation, visualization, writing – original draft, writing – review and editing. **Maryam Davarpanah**: data curation, investigation, methodology, writing – review and editing. **Seyed Alireza Banihashemib**, **Saber Amiri, Mohammad Reza Vardast, and Nima Shaykh-Baygloo**: data curation, investigation, methodology, writing – review and editing.

Funding

This study was funded by the Urmia University of Medical Sciences, Urmia, Iran (Grant IR.UMSU.REC.1402.276).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. O. Alajil, V. R. Sagar, C. Kaur, et al., "Nutritional and Phytochemical Traits of Apricots (*Prunus Armeniaca* L.) for Application in Nutraceutical and Health Industry," *Foods* 10, no. 6 (2021): 1344.

2. V. H. Tournas, N. S. Niazi, and J. S. Kohn, "Fungal Presence in Selected Tree Nuts and Dried Fruits," *Microbiology Insights* 8 (2015): MBI. S24308.

3. J. C. M. Banahene, I. W. Ofosu, B. T. Odai, H. E. Lutterodt, P. A. Agyemang, and W. O. Ellis, "Ochratoxin A in Food Commodities: A Review of Occurrence, Toxicity, and Management Strategies," *Heliyon* 10, no. 20 (2024): e39313.

4. H. Zolfaghari, A. Khezerlou, S. A. Banihashemi, M. Tavassoli, and A. Ehsani, "Review on Bio-Detoxification of Aflatoxins Based on Lactic Acid Bacteria: Mechanism and Applications," *Journal of Microbiology, Biotechnology and Food Sciences* 13, no. 1 (2023): e9424–e9424.

5. A. Hazervazifeh, A. Rezazadeh, A. Banihashemi, Z. Ghasempour, and E. M. Kia, "Pulsed Microwave Radiation for Extraction of Betalains From Red Beetroot: Engineering and Technological Aspects," *Process Biochemistry* 134 (2023): 121–130.

6. D. Piotrowski, E. Kostyra, P. Grzegory, and E. Janiszewska-Turak, "Influence of Drying Methods on the Structure, Mechanical and Sensory

Properties of Strawberries," *European Food Research and Technology* 247, no. 8 (2021): 1859–1867.

7. Y. Hua and G. Liu, "Food Pesticide Residues Monitoring and Health Risk Assessment," *Foods* 13, no. 3 (2024): 474.

8. J. Bora, T. Khan, and N. K. Mahnot, "Cold Plasma Treatment concerning Quality and Safety of Food: A Review," *Current Research in Nutrition and Food Science Journal* 10, no. 2 (2022): 427–446.

9. T. Ding, E. Xu, and X. Liao, "Inactivation of Bacteria by Cold Plasma," in *Applications of Cold Plasma in Food Safety*, eds. T. Ding, P. J. Cullen, and W. Yan, (Springer Singapore, 2022): 47–73.

10. N. Ravash, J. Hesari, E. Feizollahi, H. K. Dhaliwal, and M. S. Roopesh, "Valorization of Cold Plasma Technologies for Eliminating Biological and Chemical Food Hazards," *Food Engineering Reviews* 16, no. 1 (2024): 22–58.

11. S. Farooq, A. H. Dar, K. K. Dash, et al., "Cold Plasma Treatment Advancements in Food Processing and Impact on the Physiochemical Characteristics of Food Products," *Food Science and Biotechnology* 32, no. 5 (2023): 621–638.

12. R. Ma and Z. Jiao, "Inactivation of Fungi and Fungal Toxins by Cold Plasma," in *Applications of Cold Plasma in Food Safety*, (Springer Nature, 2022): 113–166.

13. P. Mostashari, S. Amiri, L. Rezazad Bari, M. Hashemi Moosavi, and A. Mousavi Khaneghah, "Physical Decontamination and Degradation of Aflatoxins," in *Aflatoxins in Food: A Recent Perspective*, (Springer, 2022): 207–232.

14. A. Waskow, J. Betschart, D. Butscher, et al., "Characterization of Efficiency and Mechanisms of Cold Atmospheric Pressure Plasma Decontamination of Seeds for Sprout Production," *Frontiers in Microbiology* 9 (2018): 3164.

15. E. Janić Hajnal, M. Vukić, L. Pezo, et al., "Effect of Atmospheric Cold Plasma Treatments on Reduction of Alternaria Toxins Content in Wheat Flour," *Toxins* 11, no. 12 (2019): 704.

16. M. Heydari, K. Carbone, F. Gervasi, et al., "Cold Plasma-Assisted Extraction of Phytochemicals: A Review," *Foods* 12, no. 17 (2023): 3181.

17. M. Mandal, M. Sarkar, A. Khan, et al., "Reactive Oxygen Species (ROS) and Reactive Nitrogen Species (RNS) in Plants–Maintenance of Structural Individuality and Functional Blend," *Advances in Redox Research* 5 (2022): 100039.