Chapter

Mycotoxin Decontamination of Foods Using Nonthermal Plasma and Plasma-Activated Water

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Abstract

Mycotoxins are food safety and public health concerns due to their widespread contamination in agricultural products and adverse health effects on humans. Several decontamination techniques, including physical-, chemical-, and thermal-based treatments, are employed to minimize the levels of mycotoxins in food. However, these treatments present disadvantages, such as negative impacts on the quality and leftover chemical residues on the treated food after physical- and chemical-based treatments. Furthermore, mycotoxins are resistant to heat, thus contributing to the insufficiency of thermal treatments for complete mycotoxin degradation. The use of alternative nonthermal-based treatments, such as nonthermal plasma (NTP) and plasma-activated water (PAW) for mycotoxin degradation in food, have been recently explored to overcome these limitations. NTP and PAW treatments are known to minimize the unfavorable changes in food quality while ensuring safety from food contaminants. The basics of NTP and PAW technologies, their mycotoxin decontamination efficiencies, their underlying mechanisms of action, effects on food quality, and the safety of mycotoxin degradation byproducts and treated food are hereby discussed in this chapter.

Keywords: mycotoxin, nonthermal plasma, plasma-activated water, mechanism of action, food quality, toxicity

1. Introduction

Mycotoxins are naturally occurring toxins or secondary metabolites produced by a wide range of fungal species (molds), including *Aspergillus*, *Claviceps*, *Fusarium*, *Penicillium*, and *Alternaria* [1]. These microorganisms usually colonize in crops and plants; thus, they can release the mycotoxin compounds and further contaminate the agricultural products during pre-harvest, harvest, and post-harvest [2]. Enyiukwu et al. [3] reported that approximately 25% of the global food and feed output is contaminated by mycotoxins. Furthermore, researchers have identified around 300 types of mycotoxins and revealed that 10 of these toxic compounds, such as aflatoxins, ochratoxins, zearalenone (ZEN), ergotamine, deoxynivalenol (DON),

fumonisins, nivalenol, enniatin, citrinin, and trichothecenes, commonly contaminate agriculture-based foods worldwide [4]. These molecules can induce mycotoxicosis (acute and chronic toxic diseases) in humans, raising concerns toward food safety and public health [1]. Additionally, mycotoxin contaminations have been reported to be responsible for significant economic losses [4]. For instance, the costs for the agricultural industry or food supply chain induced by mycotoxin contamination are USD 1.5 billion/year in the United States [5].

Multiple methods, ranging from conventional-, physical-, to chemical-based treatments, have been employed throughout the years to detoxify and decontaminate mycotoxin from agricultural products. The conventional approaches, including cooking and pasteurization, are simple and low-cost treatments; however, several mycotoxins can resist such thermal-based treatments [6]. Meanwhile, physical and chemical approaches, such as microwave [7], ozone [8], essential oils [9], and pulsed light irradiation [10], have been widely applied. However, these typical treatments are still problematic because they may result in undesirable changes in the physical, chemical, and sensory properties of the treated foods.

Nonthermal-based treatments, such as nonthermal plasma (NTP) and plasma-activated water (PAW), have recently gained considerable attention in food safety because they possess significant antimicrobial capacity against a wide range of food-borne pathogens without negative effects on food quality [11, 12]. Gaseous NTP and PAW richly contain multiple charged particles, reactive oxygen species (ROS), and reactive nitrogen species (RNS); thus, these methods have been proposed to prevent the risk of mycotoxin contaminations in various foods [4]. Ultimately, the effectiveness of both systems has rapid growth for decontaminating multiple foods from various microorganisms, such as *Saccharomyces cerevisiae*, *Escherichia coli*, *Staphylococcus aureus*, *Bacillus cereus*, *Klebsiella pneumonia*, and *Listeria monocytogenes*, as widely reviewed by Herianto et al. [11], Perinban et al. [13], Thirumdas et al. [14], and Zhou et al. [15]. Nevertheless, a review focusing on their effects on mycotoxin deactivations is unavailable. Thus, this chapter briefly discusses the applications of NTP and PAW for mycotoxin decontamination in various agricultural foods and their respective effects on food quality according to the most up-to-date studies. In addition, the decontamination mechanism of reactive species by both systems over mycotoxin is elaborated. Finally, constructive suggestions are also provided to stimulate satisfactory research of this field in the future.

2. Fundamentals of NTP and PAW

NTP represents a physical agent compromising a mixture of charged particles, neutral particles, radicals, ultraviolet (UV) radiation, and reactive species (RNS and ROS), which can induce oxidative stress and death of cells or organisms upon interactions [16]. Electrical energy is normally used to introduce feeding gases, such as ambient air, argon (Ar), helium (He), and oxygen (O_2), into the plasma phase to form NTP, which further generates a combination of the above-mentioned species [17]. Plasma can be effectively generated through the following four main systems of devices—electric arc discharges, corona discharges, plasma jet, and dielectric barrier discharges (DBD) [13]. Among these configuration systems, plasma jet and DBD are preferred due to their simplicity and efficient capability of producing richly reactive species [11]. Particularly, plasma jet utilizes discharged plasma electrodes that can extend beyond the area of plasma generation into the surrounding ambiance [18],

further facilitating an effective interaction with the treated foods. Meanwhile, DBD uses discharges produced between two electrodes, which are separated by dielectric barrier materials, such as glass and ceramic [19]. Foods of interest can be placed between two electrodes for plasma exposure and treatment, further allowing for interaction and decontaminations.

Meanwhile, PAW is a liquid product of chemical reactions of NTP with water, containing a rich variety of high ROS and RNS [20]. ROS includes several chemically reactive molecules and free radicals containing molecular oxygen, such as hydrogen peroxide (H_2O_2), hydroxyl radical (•OH), ozone (O_3), superoxides (O_2^-,), singlet oxygen ($^1O_2$), and alpha-oxygen [21]. By contrast, RNS is a group of nitric oxide-derived compounds, including NO_2^-, NO_3^-, nitroxyl anion, peroxynitrite ($OONO^-$), nitrosonium cation, and S-nitrosothiols [22]. In particular, Herianto et al. [11] reviewed the detailed reaction mechanism of the formation of these reactive species. Several key parameters for performing these reactions and successful PAW generations include water sources (sterile distilled water, deionized water, reverse osmosis water, and tap water), working gas (air, Ar, He, and O_2), power, activation time, gas flow rate, and position of the plasma electrode toward water [11, 12].

Unlike NTP, as a liquid solution, PAW enables a maximal exposure of reactive species to the entire surface of the treated foods, suggesting large-scale applications over various agricultural products in large volumes [11, 20]. Overall, both systems have been successfully applied for decontaminating various foods and agricultural products, such as vegetables (baby spinach leaves, mushroom, and mung bean sprout), fruits (grape tomato, grape, Chinese bayberry, and strawberry), fresh-cut fruits and vegetables (fresh-cut apple, pear, kiwifruit, endive lettuce, celery, and radicchio), meats (beef, chicken breast), shrimps, eggs, and rice cake [11, 12, 14, 23–27]. The application of these decontamination systems for mycotoxins is discussed in Section 3.

3. Mycotoxin degradation in food using NTP and PAW

Several researchers have utilized NTP and PAW treatments for the degradation of different mycotoxins in recent years to minimize the mycotoxin levels in food [28, 29]. Two possible pathways are generally available to achieve mycotoxin degradation—(1) inactivation of the fungi that produce the mycotoxins, herein referred to as mycotoxin-producing fungi (MPF), and (2) direct degradation of the mycotoxins. The most recent findings of the studies that target the two pathways using NTP and PAW treatments are respectively presented in Sections 3.1 and 3.2.

3.1 Inactivation of MPF

The application of NTP for the inactivation of MPF in food has been comprehensively reviewed in the past [28, 30], whereas a review on the effects of PAW on MPF inactivation is still lacking. Therefore, this chapter emphasizes the key findings from the most recent NTP studies, particularly in the past 3 years, and all PAW studies, to provide updated information on the current progress of these technologies for MPF inactivation. The application of NTP and PAW is generally commonly prevalent in nuts, seeds, and spices, and the commonly challenged MPF includes species that are mainly from the *Aspergillus (A.)*, *Alternaria (Alt.),* and *Fusarium (F.)* fungal genera due to their capability to produce mycotoxins. These findings are summarized in **Table 1**.

Plasma device and treatment parameters	Food matrix	MPF of concern	Key findings	Source
a. NTP treatment				
Device: DBD Gas: ambient air Power supply: 130 W, 20 kHz, 15 kV Distance from electrode to sample: 3 mm Treatment time: 0.25, 0.50, 1, 1.50, 2, 2.50, 3 min	Pistachio nuts	*A. flavus*	• Population of viable *A. flavus* spores significantly decreased with respect to time compared to control (no treatment) • Complete inactivation of *A. flavus* after 3 min of treatment	Makari et al. [31]
Device: large-scale RF plasma system Gas: O_2 gas Gas flow rate: 202 standard mL/min Power supply: 1500 W, 27.12 mHz Treatment time: 0.25, 0.50, 0.75, 1, 1.50, 2 min	Common and Tartary buckwheat seeds	*Alternaria*, *Fusarium*	• Frequency and diversity of both fungal communities significantly reduced after 1.50 and 2 min of plasma treatment of common and Tartary buckwheat seeds, respectively	Mravlje et al. [30]
Device: planar-type DBD Gas: pure Ar, Ar/O_2 mixture at 80%/20% Gas flow rate: 1 L/min Power supply: 60 Hz, 120 V Treatment time: 10 min, once a day for 3 days	Ginseng seeds	*Fusarium*	• Survival rates of *Fusarium* were about 80 and 55% after Ar/O_2 and Ar NTP treatments, respectively	Lee et al. [32]
Devices: AP-CCP, DC-DP, ICP Gas: Ar Power supply: 50, 75, 100, 150 W (AP-CCP), 250 W (ICP), 50–300 W (DC-DP) Treatment time: 2, 6, 10 min (AP-CCP), 20 min (ICP), 5–20 min (DC-DP)	Pistachio nuts	*A. flavus*	• AP-CCP completely reduced *A. flavus* (6 log reduction) at 150 W and 10 min but produced minor alteration on pistachio shells • ICP achieved 2 log reductions at 250 W and 20 min • DC-DP achieved 5 log reductions at 300 W, 20 min, and 2 Torr pressure • Overall, AP-CCP was the optimum device when fungi inactivation and cost feasibility for large scale application were considered	Ghorashi et al. [33]

Plasma device and treatment parameters	Food matrix	MPF of concern	Key findings	Source
Device: microwave-combined cold plasma (MCP) in low- and high-density modes Gas: He:O_2 mixture at 99.80:0.20 Power supply: 2.45 GHz, 900 W Treatment time: 20 min	Red pepper flakes	*A. flavus*	• *A. flavus* was reduced by 1.50 and 1.60 log spores/cm^2 after low- and high-density MCP treatments, respectively, from 4.20 log spores/cm^2 and remained constant for 150 days storage at 25°C	Kim et al. [34]
Device: RDBD Gas: commercial He Gas flow rate: 1.50 L/min Power supply: 30 W, 850 V Treatment time: 0, 1, 2, 4, 5, 6, 8, 10, 12, 14, 16, 18 min	Roasted ground coffee	*A. westerdijikiae, A. steynii, A. versicolor*	• Complete inhibition of all fungal spores (4 log reductions) after 6 min of treatment	Casas-Junco et al. [35]
Device: AP and LP plasma systems Gas: N_2, air (AP); O_2, N_2, air (LP) Gas flow rate: 3000 L/h (AP) Power supply: 655 W, 25 kHz (AP); 100 W, 13.56 MHz (LP) Distance from electrode/jet to sample: 7 cm (AP); 10 cm (LP) Treatment time: 5 cycles or 1.7 min (AP); 30 min (LP)	Hazelnuts	*A. flavus, A. parasiticus*	• LP plasma treatment resulted in 4.40 (N_2), 4.70 (O_2), and 5.60 (air) log CFU/g reductions in *A. parasiticus*, and 4.50 (O_2), 4.60 (N_2), and 4.70 (air) log CFU/g reduction in *A. flavus* • AP plasma treatment resulted in 5 (N_2) and 5.50 (air) log CFU/g reductions in *A. parasiticus*, and 5 (N_2) and 5.40 (air) log CFU/g reductions in *A. flavus*	Sen et al. [36]
b. PAW treatment				
Device: single-phase GAD Gas: air Gas flow rate: 7.33 dm^3/min Water source: distilled water (20 mL) Power supply: 40 VA apparent power, 50 Hz, 680 V PAW activation time: 5, 10, 20 min Treatment time: 5, 10, 20 min	Beetroot and carrot seeds	Beetroot seeds: *Alt. alternata, A. niger, F. solani, P. expansum, P. nigricans* Carrot seeds: *Alt. alternata, Alt. radicina, A. niger, F. avenaceum, P. expansum*	• PAW characteristics (20 min activation): H_2O_2 = 12 μM NO_2^- = 2.90 mM pH = 3.30 • PAW treatments resulted in either a decrease or increase in fungal colonies depending on treatment duration • PAW generally resulted in a weaker fungal decontamination effect compared to chemical treatment using sodium hypochlorite	Terebun et al. [37]

Plasma device and treatment parameters	Food matrix	MPF of concern	Key findings	Source
Device: ESDP Gas: Ar/air mixture Gas flow rate: 2 L/min Water source: DI water (50 mL) Power supply: 1.50 W/cm^2, 1 kHz PAW activation time: 20 min Treatment time: 0, 20, 40, 60 min	Chinese kale seeds	*Alt. brassicicola*	• PAW characteristics: pH = 3.50 EC[a] = 130 μS/cm ORP[b] = 500 mV • ESDP treatment reduced *Alt. brassicicola* by ~70% after 60 min	Suwannarat et al. [38]

[a]*Electrical conductivity.*
[b]*Oxidation-reduction potential.*

Table 1.
Recent findings on the effects of gaseous NTP and PAW treatments on the inactivation of MPF in food.

These studies revealed that NTP can achieve 100% inactivation of MPF in food, particularly of the *Aspergillus* species, which can produce the most toxic mycotoxins, that is, the aflatoxins. For example, *A. flavus* populations in pistachio nuts were completely inactivated in only 3 min of NTP treatment operated in DBD using ambient air [31]. Similarly, an atmospheric pressure capacitive coupled plasma (AP-CCP) also demonstrated complete inactivation of *A. flavus* in pistachio nuts but only after a long treatment period of 10 min using Ar gas [33]. The said study compared three different kinds of NTP treatment, which includes AP-CCP, and found that AP-CCP was the optimum device due to its most effective MPF inactivation capability and lesser cost requirements compared with direct-current diode plasma (DC-DP) and inductively coupled plasma (ICP) systems [33]. Furthermore, some food crops can be a host to multiple MPF, thus resulting in the co-occurrence of MPF in food. A study also revealed that NTP treatment using a DBD reactor with radiofrequency (RF) generator (RDBD) and He as the feed gas completely inactivated the co-occurring *Aspergillus* species, including *A. westerdijikiae, A. steynii,* and *A. versicolor*, in ground coffee after 6 min [35]. Meanwhile, other studies only achieved partial inactivation of MPF but still reduced their populations significantly. For instance, Mravlje et al. [30] used a large-scale RF plasma system operating in O_2 gas and reported significant reductions in *Alternaria* and *Fusarium* fungal communities in common and Tartary buckwheat seeds in only 1.50 and 2 min of treatment, respectively. Similarly, treatment of ginseng seeds for 3 days at 10 min each day using a planar-type DBD plasma reactor also reduced *Fusarium* populations and found that using Ar as feed gas showed higher reduction compared to that when Ar/O_2 gas mixture was used [32]. Overall, the choice of plasma device, feed gas, treatment duration, type of MPF, and food matrix can affect the efficiency of NTP treatment for MPF inactivation. As an example, Sen et al. [36] reported that the use of AP plasma resulted in higher reductions of *A. flavus* and *A. parasiticus* in hazelnuts compared with low-pressure (LP) plasma using N_2 gas in both treatments. However, AP and LP plasmas achieved an almost similar inactivation of *A. parasiticus* when the air was used.

Meanwhile, the use of PAW treatment for MPF inactivation in food did not produce the best results compared with NTP treatment. PAW generated from Ar/air mixture and distilled water using an electrohydraulic streamer discharge plasma (ESDP) system inhibited *A. brassicicola* spores in Chinese kale seeds by approximately 70% but only after a long treatment period of 60 min [38]. Terebun et al. [37] also showed that PAW operated using a single-phase gliding arc reactor (GAD) at atmospheric pressure produced inconsistent levels of inactivation of several MPF in beetroot and carrot seeds, including *Alt. alternata, A. niger, F. solani, Penicillium (P.) expansum, P. nigricans, Alt. radicina,* and *F. avenaceum*, depending on the treatment duration and fungal species.

Overall, NTP and PAW showed effectiveness in the inactivation of MPF in food. However, the plasma operation and treatment parameters must be carefully considered to achieve the maximum efficiency offered by NTP and PAW considering MPF inactivation in food.

3.2 Direct degradation of mycotoxin

Comprehensive literature reviews on the application of NTP for the degradation of several mycotoxins in food over the past years have been discussed in previous publications, while that of PAW is still lacking [4, 28, 29, 39, 40]. This chapter highlighted the key findings from the past 3 years on the effects of NTP and PAW on the degradation of mycotoxins in food. A summary of these findings is shown in **Table 2**.

Plasma device and treatment parameters	Food matrix	Mycotoxin of concern	Key findings	Source
a. NTP treatment				
Device: DBD Gas: air Power supply: 300 W, 3500 Hz Treatment time: 0, 5, 10 min	Raw wheat grains	T-2, HT-2	• Plasma characteristics: Nitrous fumes (NO_x, NO, NO_2) = 289.50 ppm H_2O_2 = 168 ppm O_3 = 689 ppm • T-2 and HT-2 concentrations significantly decreased up to 79.80 and 70.40%, respectively, after 10 min of air-NTP treatment	Iqdiam et al. [41]
Device: LP-DBD plasma reactor Gas: O_2, N_2 5.0, Ar 5.0, synthetic air Power supply: 6 W, 25 kHz, 2.50 kV Treatment time: 10, 20, 30 min	Oat flour	T-2, HT-2	• Maximum T-2 reduction was 44.42% after 30 min of treatment using N_2 gas • Maximum HT-2 reduction was 40.87% after 30 min of treatment using N_2 gas	Kiš et al. [42]
Device: SBD Gas: ambient air Gas flow rate: 1 L/min Power supply: 0.18 (low) and 0.31 (high) W/cm discharge power Treatment time: 0.50, 1, 2, 4, 8 min	Corn kernels	AFB1	• 100% decontamination of AFB1 was achieved after 4 min of treatment with high discharge power operation of SBD plasma	Hojnik et al. [43]
Device: DBD-ACP Gas: humid air Power supply: 300 W Distance from electrode to sample: 2 mm Treatment time: 0, 2, 4, 6, 8, 10 min	Raw barley grains	DON	• Plasma characteristics: O_3 = 675 ppm H_2O_2 = 200 ppm NO_x = 480 ppm • Maximum DON degradation of 54.4% was achieved after 10 min of ACP treatment • Changing the moisture content of barley did not produce significant differences in DON degradation levels • DON degradation significantly increased when barley grains were steeped without subsequent drying prior to ACP treatment	Feizollahi et al. [44]

Plasma device and treatment parameters	Food matrix	Mycotoxin of concern	Key findings	Source
Device: AP plasma jet generated from a pulsed DBD jet Gas: He Gas flow rate: 2 standard L/min Distance from plasma jet outlet to sample: 12 mm Power supply: 20 kHz, 6 kV Treatment time: 10 min	Maize	AFB1, FB1	• AFB1 and FB1 on maize samples were reduced by 65 and 64%, respectively, after 10 min of plasma exposure • Degradation byproducts were only detected in AFB1 for maize samples, with AFB1-dihydrodiol as the most prominent degraded product	Wielogorska et al. [45]
Device: plasma jet Gas: compressed air Gas flow rate: 107 L/min Power supply: 650 W, 70–90 kHz, 4.40 kV Distance from the nozzle to sample: 5 cm Treatment time: 0.50, 1, 1.50, 2 min (constant treatment), and 3, 4, 5 min (agitated treatment)	Unroasted raw peanuts	AFB1, AFB2	• 2 min of constant APPJ treatment reduced total aflatoxin (AFB1 + AFB2) by 23%, while 5 min of agitated APPJ treatment reduced total aflatoxin by 38%	Iqdiam et al. [46]
Device: RDBD Gas: commercial He Gas flow rate: 1.50 L/min Power supply: 30 W, 850 V Treatment time: 0, 1, 4, 8, 10, 12, 16, 20, 24, 30 min	Roasted ground coffee	OTA	• 30 min of NTP exposure reduced OTA by approximately 50%	Casas-Junco et al. [35]

Plasma device and treatment parameters	Food matrix	Mycotoxin of concern	Key findings	Source
b. PAW treatment				
Device: nonthermal AP plasma jet Gas: air Gas flow rate: 8 L/min Power supply: 4.40 kV Water source: distilled water (100 mL) PAW activation time: 20 min Duration: 0, 5, 10, 15, 20 min	Raw and germinating barley	DON	• PAW characteristics: pH = 2.80 EC[a] = 451.50 μS/cm ORP[b] = 463.80 mV • 20 min of PAW treatment resulted in a maximum reduction of DON by 25.80 and 38.30% in raw and germinating barley, respectively	Chen et al. [47]

[a]*Electrical conductivity.*
[b]*Oxidation-reduction potential.*

Table 2.
Recent findings on the effects of gaseous NTP and PAW treatments on mycotoxin degradation in food.

Among the mycotoxins, the aflatoxins are regarded as one of the most widely distributed and toxic mycotoxins, and the International Agency for Research on Cancer has categorized AFB1, AFB2, AFG1, and AFG2 as Group 1 carcinogens [48, 49]. Thus, most of the research on mycotoxin degradation using NTP has focused on aflatoxins, especially on AFB1. A recent study has shown that AFB1 was completely degraded in corn kernels after treatment for only 4 min with a high discharge power operation of a surface barrier discharge (SBD) system in ambient air [43]. By contrast, a similar study reported a low reduction (65%) of AFB1 in maize after treatment with an AP plasma jet using He as the feed gas for 10 min [45]. The same author also reported a comparable reduction of 64% of fumonisin B1 (FB1) using the same treatment conditions [45]. Meanwhile, short treatment periods of 2–5 min corresponding to constant (peanuts placed directly under the plasma jet flame) and agitated (peanuts placed in a moving conveyor belt) air plasma jet surface treatments reduced the total aflatoxin levels (AFB1 + AFB2) by only 23 and 38%, respectively [46]. T-2 and HT-2, which are trichothecene mycotoxins of the *Fusarium* species, are also commonly studied in recent years. Iqdiam et al. [41] reported that T-2 and HT-2 concentrations in wheat grains significantly decreased up to 79.80 and 70.40%, respectively, after 10 min of air-NTP treatment using a DBD system. Kiš et al. [42] also used an LP-DBD plasma reactor for T-2 and HT-2 degradation in oat flour and achieved relatively low maximum reductions of T-2 (44.42%) and HT-2 (40.87%) after 30 min of treatment using N_2 gas. Additionally, DON in raw barley grains was degraded by 54.40% after 10 min of DBD atmospheric cold plasma (ACP) treatment with air as feed gas [44], which is lower compared with T-2 and HT-2 reductions using similar treatment conditions [41]. Meanwhile, the degradation of 50% of ochratoxin A (OTA) in roasted ground coffee took 30 min of NTP exposure with an RDBD using He gas [35]. Overall, NTP treatment demonstrated the effectiveness of up to 100% of mycotoxin degradation in food but with a large variation. Furthermore, the results from these studies imply that the type of plasma device, feed gas, treatment duration, type of mycotoxin, and food matrix may affect the efficiency of NTP treatment for mycotoxin degradation in food.

Meanwhile, the effect of PAW on the degradation of mycotoxins in food is less studied compared with NTP treatment. In recent years, only one research has shown the applicability of PAW for mycotoxin degradation in the food matrix. Chen et al. [47] demonstrated that 20 min of treatment with PAW generated using a nonthermal AP plasma jet from the air and distilled water resulted in maximum reductions of DON by 25.80 and 38.30% in raw and germinating barley, respectively. This phenomenon may have resulted in less interest in PAW compared to NTP due to the low mycotoxin degradation capability of PAW. Therefore, further research on the use of PAW for mycotoxin degradation is necessary to be optimized for decontamination of food from harmful mycotoxins.

4. Mechanisms of action of NTP and PAW in mycotoxin decontamination of food

4.1 Proposed mechanism of MPF inactivation

The mechanisms involved in the plasma-induced inactivation of MPF have been thoroughly discussed in past literature [30, 50]. The reactive species produced during NTP and PAW generation are generally believed to contribute substantially to the action of these technologies against different microorganisms, including bacteria

and fungi [38, 50, 51]. Particularly, the action of ROS in MPF inactivation has been elucidated in many studies, while that of RNS remains unknown [52].

The harsh oxidative environment of NTP and/or PAW can result in fungal spore inactivation through denaturation of the proteins that comprise the coating of spores, thus leading to the loss of spore coat integrity, which then exposes the center of the spore to plasma ROS [28, 31]. The destruction of spore coat integrity results in the reduction of cell viability [31]. For instance, the disintegration of the cell walls of *A. flavus* and *A. parasiticus* spores led to the release of cytoplasmic structures as clusters following atmospheric NTP treatment [36]. Similarly, the walls of *A. brassicicola* spores had morphological changes, such as breakage or leakage of the outer membranes, following PAW treatment [38]. The authors concluded that the spores of *A. brassicicola* lost their integrity, and the contents of the cells dispersed into clusters as observed in scanning electron microscopy images [38]. In addition, the acidic environment of PAW could affect the cell walls of spores [36]. For instance, a recent study concluded that the inactivation of *A. flavus* spore was due to the synergistic effects of acidified PAW environment and long-lived reactive species [53]. In addition to the denaturation of the spore coat proteins, MPF inactivation may also occur by damaging the lipid bilayers, which results in a ruptured fungal cell wall [28, 31]. The core of the spore becomes vulnerable again to attacks by the plasma reactive species once the cell wall is ruptured, leading to fungal inactivation [28, 31]. Other mechanisms involved in the damage of fungal spores are the accumulation of charged particles and continuous bombardment of reactive species on the external surface of spores, which both lead to cell wall rupture [31]. Reports indicate that the accumulated charged particles resulted in the formation of enlarged pores on the spore surface of *A. flavus* and *A. parasiticus* after NTP treatment due to electroporation, which promotes spore death [54].

Thus far, the mechanisms of MPF inactivation using plasma treatments involve changes in fungi morphology. However, the morphology of *F. oxysporum* spore was not altered after its inactivation using NTP treatment [50]. The authors reported that the increase in lipid accumulation inside the cells induced apoptosis, which is a form of programmed cell death [50]. Considering the direct action of select ROS on MPF inactivation, previous literature suggested that the action of •OH radicals on unsaturated fatty acids and the oxidation of amino acids can respectively lead to lipid peroxidation and protein oxidation, which can result in fungi death [30]. Furthermore, the interaction of oxygen radicals with DNA can lead to the formation of base adducts, resulting in DNA oxidation, which can also cause fungi death [30].

Summarizing the results of the above-mentioned studies, the MPF inactivation of plasma mainly occurs due to changes in the morphology caused by the damage in the protective coating of the fungal spores, membrane peroxidation and leakage, protein oxidation, DNA damage, and apoptosis [4, 30]. Notably, the observed and proposed mechanisms of MPF inactivation by the aforementioned studies may have varied due to the different plasma devices and processing parameters employed in the individual studies, which can lead to different actions of NTP and/or PAW against MPF inactivation.

4.2 Proposed mechanism of mycotoxin degradation

The mechanisms of mycotoxin degradation induced by NTP treatments have been comprehensively reported elsewhere [28, 40, 51]. AFB1 is the major mycotoxin that is studied in plasma investigations; thus, the reports on the mechanism of

mycotoxin degradation induced by plasma mainly revolved around AFB1 [55]. The toxicity of AFB1, and aflatoxins in general, is related to the C8 = C9 double bond on the furan ring, which is considered to be the toxicity site [55]. Generally, the degradation of AFB1 is proposed to have resulted from the action of long-lived ROS with chemical structures of AFB1, particularly at the toxicity site [52, 56]. For example, reports indicated that O_3 and •OH radical were among the primary contributors to the degradation of AFB1 into six major degradation byproducts using DBD-based plasma treatment, and the authors provided an illustration of the proposed degradation mechanism in their work [52]. The authors proposed the following two mechanisms of degradation—(1) an addition reaction involving H_2O, H, or CHO radicals and (2) an epoxidation reaction involving HO_2• and oxidation reactions, including O_3, H_2O_2, and •OH radical [52]. An earlier study also proposed that the O•, H•, and •OH radicals produced from a low-temperature RF plasma were the major reactive species that degraded AFB1 into five major degradation byproducts, and two mechanisms of degradation were introduced [57]. Overall, the two studies revealed that the degradation of AFB1 begins with the breakage of the C8 = C9 double bonds on the furan ring, followed by an attack by the ROS, thus resulting in the formation of AFB1 degradation byproducts [52, 57]. This conclusion was further confirmed in a recent study, which investigated the degradation byproducts of AFB1 using an atmospheric pressure plasma jet generated from a pulsed DBD jet, stating that AFB1 degradation byproducts are produced from the modifications at the furan ring [45].

The degradation of other major mycotoxins, such as OTA, could also be mainly due to ROS molecules and radicals, such as O_3, H_2O_2, and •OH radical, as well as UV irradiation and etching [35]. The ROS could promote the degradation of OTA into slightly toxic compounds, such as L-phenylalanine [35]. Furthermore, the degradation byproducts of ZEN following a plasma jet-based NTP treatment were reported, which identified two degradation byproducts [45].

Studies on the mechanism of action for mycotoxin degradation using PAW treatment and determination of mycotoxin degradation byproducts post-treatment are currently unavailable. However, similar to the gaseous NTP, the different ROS dominates the degradation of mycotoxins during PAW treatment. For example, the H_2O_2, O_3, and nitrate ion (NO_3^-) reactive species were believed to be the major reason for DON degradation in barley during PAW treatment [47].

Overall, the reactive species are the major contributors to the degradation of mycotoxins during NTP treatment of food. Further work on the elucidation of degradation mechanism and byproducts of other major mycotoxins, such as OTA, DON, or ZEN, following NTP treatment, is also needed. Moreover, extensive research on the degradation byproducts of these mycotoxins and proposed mechanisms using PAW treatment is warranted.

5. Effects of NTP and PAW treatments on food quality

In addition to the effective and significant decontamination of food from mycotoxins using NTP and PAW treatments, another known promising characteristic of these technologies is the retainment or negligible impact on the nutritional and other key properties of food. This chapter emphasizes the effects of NTP and PAW treatments on food quality following mycotoxin decontamination from the most recent studies.

Results revealed that the overall likeability was positively correlated with the overall texture (r = 0.77) and flavor (r = 0.87) of peanuts [46]. Generally, NTP treatment did not produce a negative effect on the sensory properties of food [34, 46]. For example, the treatment of red pepper flakes for *A. flavus* inactivation did not significantly affect its color and flavor properties compared with the control [34]. Similarly, the overall appearance of peanuts after NTP treatment using a plasma jet device did not significantly change, while the overall likeability, flavor, and texture of the NTP-treated peanuts significantly increased; this finding indicates that NTP treatment can also enhance the sensory characteristics of peanuts [46].

By contrast, plasma treatments had varying effects on the physicochemical properties of food. NTP treatment of pistachio nuts for *A. flavus* inactivation revealed a slight increase in the antioxidant activity and a significant increase in malondialdehyde values, while the total phenolic content remained unchanged; however, a decrease in chlorophyll, total carotenoid, and color parameters was observed [31]. NTP treatment was also found to significantly lower the capsaicin and ascorbic acid levels of red pepper flakes, but its antioxidant activity and color were unaffected by the treatment [34]. Similarly, the color of wheat grains did not also show changes after NTP treatment, along with the nitrogen, protein, starch, and moisture contents [41]. Another study also reported the absence of significant differences in the moisture, protein, and β-glucan contents of barley after NTP treatment compared with control [44]. The peanut oil extracted from NTP-treated peanuts also had no significant difference in its peroxide value, free fatty acid, acidity value, and oxidative stability index compared with control after the treatment [46]. Meanwhile, the NTP treatment of corn kernels and peanuts produced slight oxidation and bitterness in taste [43, 46]. By contrast, PAW treatment did not affect the overall quality of Chinese kale seeds [38].

Overall, the effects of NTP and PAW treatments on food quality may differ depending on the processing parameters employed and the type of food matrix tested [11].

6. Safety of mycotoxin degradation byproducts in treated food after NTP and PAW treatments

Examining the safety or toxicity of the food post-treatment and the byproducts produced during the process is important for any emerging technology, especially in the field of food processing. However, investigations regarding these concerns in the field of plasma research for mycotoxin decontamination are still limited in the current state of literature. The AFB1 byproducts are hypothesized to have reduced toxicity due to the loss of the C8 = C9 double bond, which is related to its toxicity [57]. This finding was confirmed in a recent study, which reported that the degradation byproducts of AFB1 after AP plasma jet treatment showed no increased cytotoxicity in human hepatocarcinoma (HepG2) cells [45]. Additionally, another study revealed through a brine shrimp (*Artemia salina*) lethality bioassay that the OTA extract from untreated coffee was "toxic," which corresponds to a 50–88.30% mortality in brine shrimp larvae [35]. However, the mortality rate was reduced to "slightly toxic" levels (10–33.33% mortality) when OTA extract from NTP-treated coffee was exposed to brine shrimp larvae [35]. Meanwhile, the safety or toxicity of the original food that has undergone NTP or PAW treatment for mycotoxin decontamination has not been currently assessed.

Overall, the current investigations demonstrate that NTP treatment can degrade mycotoxins and produce degradation byproducts that are nontoxic or with lower degrees of toxicity compared with the toxic parent compound. However, the safety of the food treated with NTP or PAW remains unknown. Hence, future research should address this issue to guarantee the safety of plasma-treated food for human consumption.

7. Conclusions

The nonthermal-based treatments such as NTP and PAW have shown promising results in the field of food decontamination against biological and chemical contaminants. Particularly, their effects on decontaminating foods from mycotoxins have been exceptional, and the capability of NTP and PAW to inactivate fungi and degrade mycotoxins is due to the oxidizing capacities of the existing reactive species in the plasma. The existing literature reveals that NTP and PAW inactivated the fungi that produce the mycotoxins as well as degraded the mycotoxins in foods, such as nuts, seeds, and spices, without producing harmful byproducts and having mild impacts on food quality. However, the result is still inconsistent in all studies. For instance, the current literature indicates NTP as the better treatment option for MPF inactivation and mycotoxin degradation compared with PAW. This finding is due to the desirable inactivation or degradation efficiencies of NTP treatment of up to 100% in no longer than 30 min, whereas low efficiencies of PAW treatment were observed and can only be achieved at long treatments. However, NTP treatment is more prone to induce undesirable effects on food quality compared with PAW.

Overall, the decontamination of foods from mycotoxins using NTP and PAW treatments and their effects on food quality is dependent on many factors, including the plasma device, the treatment parameters (such as power supply, type of feed gas, and treatment duration), the fungi species, the type of mycotoxin, and the food matrix. Thus, comparison of the results from various studies is difficult due to this diversity in plasma operation techniques. Therefore, deciding which NTP or PAW treatment is the best for mycotoxin decontamination of food remains unclear. Hence, consideration and optimization of the results from the current studies are crucial to ensure maximum utilization of NTP and PAW technologies for mycotoxin decontamination of food.

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