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Evaluating Atmospheric Pressure Plasma Treatments for Suppression of White Bread's Mold Growth

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Abstract: Food wastage accounts for up to 44% of global waste, posing a serious economic and environmental concern. A major contribution to this issue is microbial contamination, which leads to food spoiled and poses health risks to humans. White bread, a dietary staple consumed worldwide, is particularly vulnerable to microbial contamination – despite an estimated global production of 100 million tons annually, hundreds of tons are discarded daily due to microbial spoilage, particularly mold. Thus, to address this issue, the use of atmospheric pressure plasma (AAP) as a non-thermal food preservation technology is explored in the present study. Two types of plasma generators: dielectric barrier discharge (DBD) and atmospheric pressure plasma jet (APPJ) were used to treat white bread samples. The progression of mold growth on the samples was observed for seven days after treatment durations ranging from 60 to 120 seconds. On day seven, the percentages of mold growth were 51.23% and 21.39% for samples A1 and A2, respectively, while untreated samples exhibited 68.88% mold growth. Meanwhile, sample D1, which was treated with DBD plasma, demonstrated remarkable resistance, with only 1.70% mold growth progression. The optimal treatment parameters identified were 13.6 kV for 120 seconds for DBD and 16.1 kV for 120 seconds for APPJ. Under these optimal discharge conditions, both plasma generators significantly suppressed the progression of mold growth progression, with DBD treatment showing superior performance. The findings demonstrate the potential of plasma-based treatments to effectively extend the shelf life of white bread and reduce food wastage.

Keywords: Food treatment, white bread, mold decontamination, atmospheric pressure plasma jet, dielectric barrier discharge

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1. INTRODUCTION

Nowadays, food wastage has become a world concern, which directly causes economic loss. Food waste is the food removed from the food supply chain during the pre-consumer and post-consumer phases. The increase in food wastage is against the Sustainable Development Goal (SDG), especially SDG 12.3, which is global food loss and waste. Food waste has increased up to 44% of global waste, according to the report by S. Kaza et al. in 2018 [1]. Food waste is due to the contamination of food by microbes, which causes food to be spoiled and harmful to consumption.

White bread, a dietary staple for millions worldwide, is highly susceptible to microbial contamination risks due to its porous structure, highly nutritious properties with various nutrients, and high moisture content. Thus, white bread waste is inevitable despite the advancement of its storage and packaging methods. Global bread production is estimated to be up to 100 million tons per year, leading to hundreds of tons of daily bread waste [2]. This has negatively impacted the environment and economy, and these issues have become a challenge that the world needs to face while striving to reduce the amount of global bread waste by 2030 [3]. Hence, microorganisms such as bacteria and molds can thrive in this environment, leading to bread waste and potential foodborne illnesses.

Therefore, to prevent the waste, the food treatment is required to ensure the food safety and preservation. There are various technologies in food processing, such as thermal, chemical, and, most recently, non-thermal treatment. However, thermal and chemical technology can negatively impact food quality and nutrition. In some cases, these technologies cannot effectively decontaminate the microbes on food [4], [5], [6]. Hence, non-thermal technology is the most promising in preserving and increasing food safety without negatively impacting its quality and nutrition.

The advancement of non-thermal technology in food processing has been widely applied because of its low temperature, and it can avoid harm caused by thermal treatment technology [7]. It also aims to prolong the shelf life of food by decontaminating the microbes on food surfaces with minimal or no harm to food quality and nutrition. The non-thermal technologies for food processing are classified as pulse electric field (PEF) [8], pulsed light, ultrasound treatment [9], irradiation [10], high-pressure processing [11], and atmospheric pressure plasma (APP) or cold atmospheric plasma (CAP). However, according to Priyadarshini et al. [12], these technologies have pros and cons, especially regarding financial constraints. Among all these non-thermal technologies, APP is the most promising in food treatment applications because of its low operating cost, simple technology construction, and ease of usage.

Plasma is a fourth state of matter which can be described as ionised gas with zero net electrical charges that generate reactive oxygen and nitrogen species (RONS) such as ozone, nitric oxide, hydroxyl radicals etc., ultraviolet (UV), and charged particles [13], [14]. Atmospheric pressure plasma (APP) is generated at atmospheric pressure. The generated RONS play a vital role in the decontamination of microbials. There are various APP sources, such as dielectric barrier discharge (DBD), corona discharge (CD), atmospheric pressure plasma jet (APPJ), radio frequency discharge (RF), and microwave discharge (MW). The most common plasma sources used for food treatment are DBD and APPJ. Several studies have been conducted in food treatment using DBD and APPJ, such as chicken breast [15], [16], wheat flour [17], rice [18], milk [19], [20] etc. However, based on the collective literature review, there are scarcely comprehensive studies that underscore the effectiveness of DBD and APPJ treatment on white bread to improve its preservation and safety. Additionally, given the importance of white bread as a dietary staple and its susceptibility to microbial contamination, which makes it have a relatively short expiry time of bakery products, it is crucial to explore the potential of DBD plasma and plasma jet treatments in improving the extension of white bread shelf-life.

This research aims to compare the optimal parameters between plasma sources, i.e., DBD and APPJ, to ensure microbial decontamination while preserving the quality value of the bread. The white bread was treated using DBD and APPJ. The varied parameters are voltage (13.6 kV to 16.1 kV) and treatment time (60s to 120s), while the frequency was fixed for both plasma sources. The RONS produced during the process were observed using optical emission spectroscopy (OES). Then, the bread was stored in an open space to observe mold growth within seven days. The optimal parameters were determined based on the minimal mold growth observed in the white bread samples. By investigating the specific effects of DBD plasma and plasma jet treatments on white bread, this study can contribute to developing innovative food preservation strategies that meet the growing demand for minimally processed and naturally preserved food products. Additionally, this research can shape future advancements in food preservation technology, contributing to the broader goal of ensuring food security and safety.

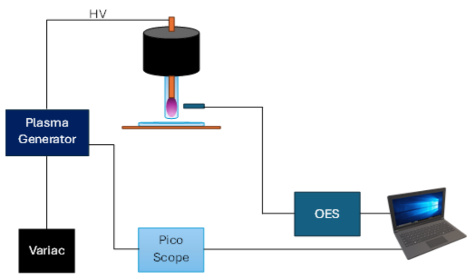
2. METHODOLOGY

2.1 Materials

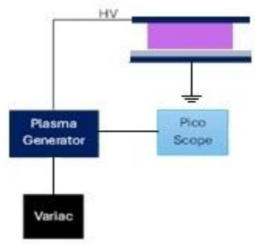
The white bread was placed in ambient air at room temperature. A slice of white bread was cut into 14 pieces in a round shape. Hand gloves were used during this process, and a knife was sterilised before cutting the bread to ensure the bread was not contaminated with other bacteria. Then, the pieces of bread were stored in zip-tight plastic before treatment to ensure the pieces of bread were not exposed to the air. For APPJ treatment, 9 out of 14 bread samples were exposed to varying applied voltages and treatment times, while 3 samples underwent DBD treatment with different treatment times. Two untreated samples served as controls. The entire treatment process was repeated three times. After the treatment, the mold growth of the bread was monitored over seven days.

2.2 Plasma Treatment

Figure 1 shows the APPJ and DBD system setup used during the experiment. For APPJ, a hollow copper rod tube with inner and outer diameters of 4 mm and 6mm was used as the high voltage (HV) electrode. Meanwhile, a copper plate was used as the ground electrode with a position 35 mm away from the tip of the HV electrode. The HV electrode was within the glass capillary tube with an outer diameter and a 20 mm and 1.5 mm thickness, respectively. A petri dish was placed on the ground plate between the HV electrode and the ground plate. The surrounding air is used as working gas at a fixed gas flow rate of 2L/min.



(a)



(b)

Figure 1. (a) APPJ system, (b) DBD system setup for white bread treatment

The plasma discharge was generated by applying an AC high-voltage supply with varying voltage only. A high frequency-high voltage (HF-HV) power supply was connected to the plasma reactor, with the HV electrode connected to the supply's high-voltage terminal and the collar ring connected to the ground terminal. The supply voltage was regulated using a single-phase voltage regulator, ranging from 15 kV to 16.2 kV in increments of 0.6 kV for APPJ. The supply frequency was set at a constant of 9 kHz by using the frequency knob on the HF-HV power supply. The treatment parameter settings are shown in Table 1. For DBD, both HV and ground electrodes were made using stainless steel materials. The gap of these electrodes was 40mm. Two glasses of plates separated the electrodes. The HV power supply setup is the same as the APPJ setup. The voltage for DBD plasma was set to 13.6 kV at 8.3 kHz. The voltage settings differ from those used in APPJ because plasma first became visible at this setting. Increasing the voltage beyond this point causes the bread samples to burn, as shown in Figure 3. The treatment setting for DBD is shown in Table 2.

Figure 3. The condition of white bread when the applied voltage increases more than 13.6 kV.

Table 1. APPJ parameter settings for white bread treatment

HV value (kV)/ duration (s)	Treated Bread		
	60	90	120
15	A1	A2	A3
15.6	B1	B2	B3
16.2	C1	C2	C3

Table 2. DBD parameters setting for white bread treatment

HV value (kV)/ duration (s)	Treated Bread		
	60	90	120
13.6	D1	D2	D3

2.3 Optical Emission Spectrometer (OES)

The production of reactive species by plasma discharge is identified using an optical emission spectrometer (Ocean Optics, Maya 2000 Pro). The measured wavelength ranges from 200-1100 nm using a 25 µm slits width. The spectra monitoring is performed perpendicular to the plasma discharge, and the optical fiber sensor is positioned 50 mm from the plasma.

2.4 Mold Growth Progression Analysis

The control, APPJ-treated, and DBD-treated white bread pieces were analysed to determine the percentage of mold growth. The treated and control pieces of white bread were stored at room temperature for seven days. The picture of mold growth progress on the 7th day of storage was taken using a digital camera. The Image J software was utilised to process the pictures to obtain the percentage of mold growth (MG) as shown in the equation (1):

$$MG\ \% = \frac{Area\ of\ mold\ (mm^2)}{Total\ sample\ area\ (mm^2)} x100 \qquad (1)$$

2.5 Optimal Parameter

The optimal parameter for white bread treatment is determined by which has the lowest mold growth. The frequency (9 kHz and 8.3 kHz for APPJ and DBD, respectively), gas flow rate (2 L/min), and the distance between the sample and plasma nozzle (30 mm) were fixed during the treatment. The applied voltage and treatment time was varied, as shown in Table 1.

3. RESULTS AND DISCUSSION

3.1 OES Spectrum

Figure 2 clearly shows that the most dominant spectrum is the second-positive band of $N_2\ (C^3\Pi_u \rightarrow B^3\Pi_g)$ at 268-546 nm, first-negative band of $N_2^+\ (B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$ at 286-587 nm emission bands, and second diffraction of $N_2\ (C^3\Pi_u \rightarrow B^3\Pi_g)$ at 600-800 nm. The primary components of atmospheric air are nitrogen (N_2), oxygen (O_2) and water vapor (H_2O) due to humidity. The production of $N_2\ (C^3\Pi_u \rightarrow B^3\Pi_g)$ is due to the electron impact excitation collision from the ground state of $N_2\ (X^2\Sigma_g^+)$. The first metastable state $N_2(A^2\Sigma_g^+)$ and $N_2^+(B^2\Sigma_u^+)$ states are generated through electron collisions with high-energy electrons. Thus, based on previous studies [21], [22], the main species generated by air plasma jets are O_3, NO_2, and a small amount of N_2O, HNO, and N_2O_5.

The reactions among these species, as shown below, are based on results obtained from previous studies [23], [24], [25], [26], [27], [28].

$$e + O_2 \rightarrow e + 2O \qquad (2)$$

$$e + N_2 \rightarrow e + 2N \qquad (3)$$

$$O + O_2 + M \rightarrow O_3 + M \qquad (4)$$

$$O_3 + O \rightarrow O_2 + O_2 \qquad (5)$$

$$O_3 \rightarrow O_2 + O \qquad (6)$$

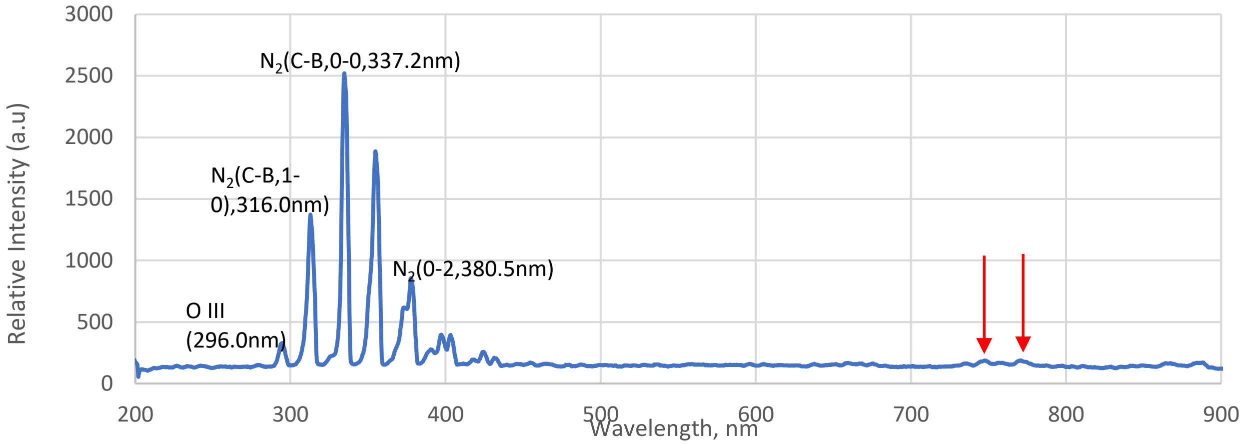


Figure 2. Optical emission spectra of air plasma for 286-440 nm spectrum wavelength

3.2 White Bread Mold Growth Progression

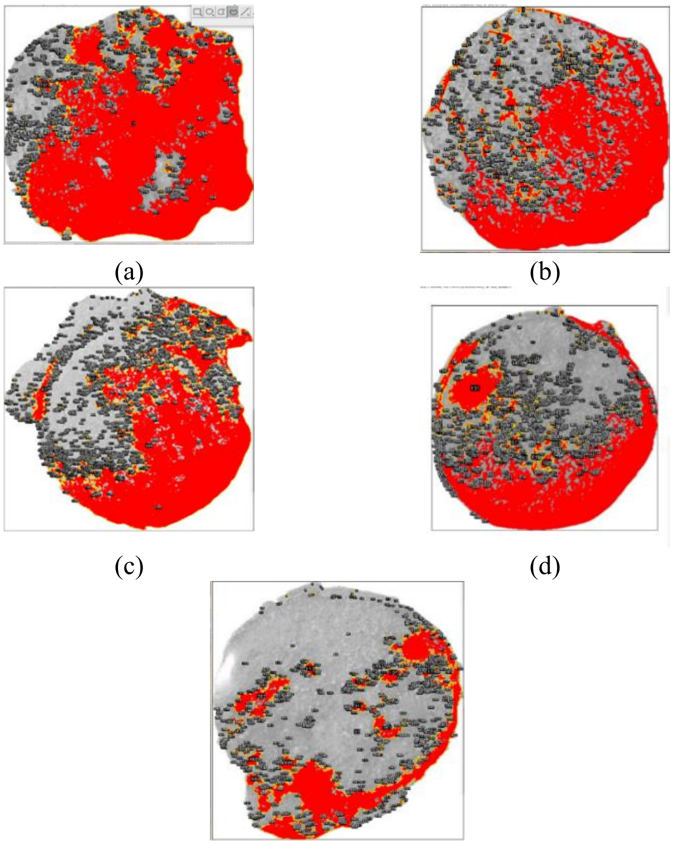
Food contamination is a critical problem in the food industry and can happen during food processing. Cross-contamination can occur during food handling and food storage. Therefore, scientists nowadays are attempting to solve this problem by constantly researching new alternative methods of food preservation. It is crucial to extend the shelf-life of food to avoid food waste as the human population keeps growing. The growth of the human population has caused the problem of hunger more concerning. The findings in this research will contribute to white bread preservation. The high voltage (HV) value and the treatment duration are varied in this research to find which parameter is optimal. The APPJ applied voltage was set to 15 kV, 15.6 kV, and 16.2 kV while the treatment time was set to 60 s, 90 s, and 120 s, as shown in Table 1. The applied voltage for DBD was not varied because the plasma discharge would burn the white bread sample as the applied voltage increased. This is due to the high plasma discharge temperature, especially when using atmospheric air as a working gas. Therefore, for DBD, the treatment time is the only varied parameter, i.e., 60 s, 90 s, and 120 s. The parameter setting for DBD is shown in Table 2, while Figure 3 shows the white bread sample condition when the applied voltage increases more than 13.6 kV.

During the seven days of the white bread post-treatment, the mold growth was observed and recorded by taking the sample picture to monitor the mold progression. The untreated white bread sample took only two days for the mold to grow. The treated white bread sample took a bit longer for mold to grow. In APPJ treatment, sample C3 took 23 days for mold to grow. The shortest mold growth time was observed in sample A1, i.e., three days for mold to visibly grow. The mold growth intensity can be seen reduced when treated by plasma. Table 3 shows the mold growth progression on treated white bread at different APPJ parameter settings.

Table 3. The mold growth progression at different APPJ parameters setting

Sample	Days for mold to grow
Jet/untreated	2
A1	3
A2	4
A3	9
B1	5
B2	6
B3	11
C1	21
C2	23
C3	25

Table 4 shows the impact of DBD plasma treatments on delaying mold growth. Untreated samples consistently showed mold growth within two days. Sample D3 showed that the mold was visibly growing on day 13th, while sample D1 showed a delay in mold growth until day 6. The applied voltage was not varied because the higher voltage will increase the plasma discharge temperature and can negatively impact the food texture, as shown in Figure 3. The data in Table 5 illustrate the effect of plasma jet treatment on the area of mold growth on white bread, while Table 6 shows the percentage growth of mold. The area of mold growth was determined using Image J software as shown in Figure 4. The untreated samples exhibited the largest mold growth area, measuring 1141.187 mm², i.e., 68.88% of mold growth. When treated with a plasma jet, the mold area was reduced to 990.738 mm² (51.23%) in sample A1. However, when increasing the duration to 90s (A2) resulted in a decrease in mold area to 389.187 mm², i.e., 21.39%. Further, samples B1 and B2 have mold areas of 363.585 mm² (19.30%) and 43.141 mm² (2.5%),



(a) (b) (c) (d) (e)

Figure 4. Example of image J application on mold growth progression where (a) and (b) are untreated samples, (c) and (d) are samples A1 and A2, respectively, and (e) is sample D1.

respectively. However, no visible mold growth was observed for A3, B3, C1, C2, and C3 samples.

Table 4. The mold growth progression at different DBD parameters setting

Sample	Days for mold to grow
DBD/untreated	2
D1	6
D2	8
D3	13

Table 5. Area of mold growth progression on day 7 for APPJ treatment

Sample	Area of mold growth on day 7th (mm^2)
Jet/untreated	1141.187
A1	990.738
A2	389.187
A3	0
B1	363.585
B2	43.141
B3	0
C1	0
C2	0
C3	0

Table 6. Percentage of mold growth progression on day 7 for APPJ treatment

Sample	Percentage of mold growth on day 7th (%)
Jet/untreated	68.88
A1	51.23
A2	21.39
A3	0
B1	19.30
B2	2.5
B3	0
C1	0
C2	0
C3	0

Tables 7 and Table 8 revealed the area and percentage of mold growth progression within seven days, respectively. The untreated sample had a 710.443 mm^2 mold growth area, constituting 56.73%. However, the mold growth on D1 has reduced to 24.932 $mm^{2,}$ i.e., 1.70%. As the treatment time increased, samples D2 and D3 showed no mold growth on the white bread.

Table 7. Area of mold growth progression on day 7th for DBD treatment

Sample	Area of mold growth on day 7 (mm^2)
DBD/untreated	710.443
D1	24.932
D2	0
D3	0

Table 8. Percentage of mold growth progression on day 7th for DBD treatment

Sample	Percentage of mold growth on day 7 (%)
DBD/untreated	56.73
D1	1.70
D2	0
D3	0

3.3 Discussion

Several types of mold can grow on the bread, such as *Aspergillus* (*A.nig*er and *A.flavus*), *Penicillium*, and *Fusarium*. Due to the presence of wheat flour as a main ingredient in white bread, it has a high risk of containing mycotoxins (such as *aflatoxin*, *aspergillic acid*, and *aspertoxin*), which are mainly produced by *Aspergillus*. [29]. This is very harmful to humans if being consumed. *Aspergillus*, especially *Aspergillus flavus* (*A. flavus*), favours to grow in warm temperatures, i.e., $28 - 35$ ℃ at high humidity (more than RH = 85%) conditions, which is a typical condition in subtropical and tropical regions [30]. In this research, even though the type of mold growth is not explicitly identified, there is a high possibility of *Aspergillus* contamination due to the environmental conditions of the white bread samples being stored, i.e., Malaysia (Malaysia has high RH and warm temperatures). The untreated bread samples have a high percentage of mold growth, i.e., 56.73 - 68.88%, and it took only two days for the mold to grow. However, after being treated using APPJ and DBD, the mold growth is retarded especially when the treatment has a high setting of applied voltage of the plasma source and longer treatment time. The samples A1 and A2 have a lower percentage of mold growth, i.e., 51.23% and 21.39%, respectively. The mold was grown on the third day of storage for sample A1 and the fourth day for sample A2. The mold growth can be seen taking a longer time. For example, sample B3 took 11 days for mold to grow, and sample C3 took 25 days. For samples treated by DBD, which are samples D1, D2, and D3, the mold grows in 6, 8, and 13 days, respectively. This has shown that the mold had recovered and could grow even after the plasma treatment, indicating that the treatment is not a sterile condition. The mold can still grow, but plasma treatment can reduce its growing intensity. This finding is also supported by Thonglor et al. in 2017, where the mold can be seen growing on day 6th [31]. In other findings, the percentage of mold growth is lower when treated with a 4 kV argon plasma jet, i.e., 14% mold, whereas the untreated bread has 52% mold growth which was reported by Mohammed et al. in 2022 [32]. Starek-Wójcicka et al. reported that the total number of viable cells was 2.71 log lower compared to the control sample after the bread was treated by gliding arc discharge plasma [33]. Therefore, the intensity of the mold growth can be reduced when treated by APPJ and DBD, which extends the shelf life of the bread.

In this research, the most effective to retard the mold growth is by increasing the applied voltage and longer the duration of treatment. Based on data tabulated in Table 3 and Table 4, the mold can grow on the 25th day for sample C3 while sample D3 can be seen on the 13th day. Sample C3 was treated at 16.2kV and 120 s treatment, while sample D3 was treated at 13.6kV and 120 s treatment. This finding can be supported by Lin et al. in 2022, where the authors reported that the reduction of *Aspergillus niger* was 5.76 log CFU/g at 200W for 5 min treatment while *A. flavus* reduce to 4.64 log CFU/g at 200W for 3.5 min of treatment [34]. They also concluded that the mold growth is significantly reduced when higher power and longer treatment time are applied [34]. However, in 2022, Starek-Wójcicka et al. reported that higher mold reduction was when a longer treatment time was applied. The total number of viable cells was reduced by 2.75 logs when treated with plasma for 10 minutes [33]. Their findings are also supported by findings in [31] and [35]. Other research reported that mold growth could be effectively reduced when higher power or voltage is applied in the plasma treatment [32], [36]. Therefore, operational parameters and treatment time can effectively suppress the mold growth on the white bread based on the recent results and previous findings. The effectiveness of plasma decontamination on microbials depends on the setting of operational parameters and the duration of treatment. The operational parameters such as applied voltage, gas flow rate, and frequency would determine the concentrations of RONS generated by plasma, while the duration of treatment would determine the interaction between RONS and microbials. Most previous findings reported that by manipulating one or more operational parameters, the effectiveness of plasma on microbial decontamination would increase, as reported in [37], [38], [39].

The primary reactive species produced by air plasma jets were nitrogen species, atomic oxygen, and hydroxyl radicals [40], [41]. These radicals are believed to be the main factors of microorganism decontamination [42]. Ozone is the most attractive species because it has the advantage of a long life span at room temperature and extreme oxidation actions [41], [43], [44]. It is one of the most powerful species in microorganism decontamination [40]. No matter what type of working gas is used in plasma generation, ozone production is inevitable due to diffuse oxygen from the surrounding air [45]. As shown in Figure 2, the most dominant species are reactive nitrogen species (RNS) such as NO and NO_2. The disruption of macromolecules such as proteins, lipids, and nucleic acids is due to these species, which leads to microbial cell damage. These species are formed when the excited nitrogen species interact with oxygen and reactive oxygen species (ROS) like ozone [41]. According to Dharini et al. [41], the reaction among these species is as follows:

$$N_2 + e^- \rightarrow N_2^+ + 2e^- \quad (7)$$

$$N_2 + e^- \rightarrow N_2^+ + 2e^- \quad (8)$$

$$N + O_2 \rightarrow NO + O \quad (9)$$

$$N_2 + O \rightarrow NO + N \quad (10)$$

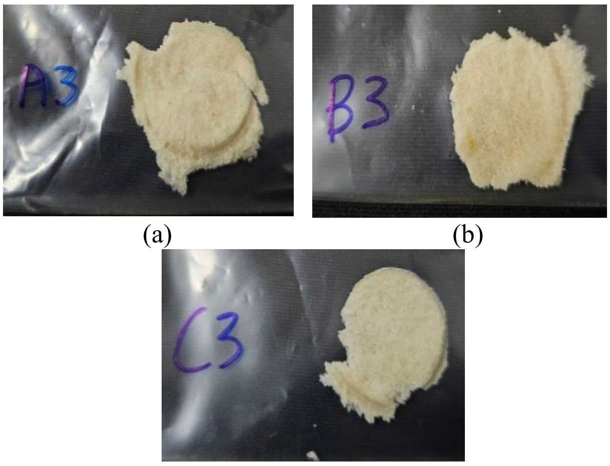
$$N + O_3 \rightarrow NO + O_2 \quad (11)$$

$$NO + O_2 \rightarrow 2NO_2 \quad (12)$$

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (13)$$

The synergistic action of these species, along with ozone, have hindered mold growth on the white bread after being treated by air plasma. The untreated samples exhibited a steep increase in mold percentage, highlighting the rapid proliferation of mold in the absence of treatment. Conversely, the treated sample maintained a substantially lower mold percentage, indicating the treatment's efficacy in suppressing mold development over time. Figure 5 shows the percentage of mold versus days for untreated and treated samples and visually represents the mold growth progression. As the applied voltage and treatment time increased, the intensity of the mold growth was further reduced. The ozone concentration increased as the applied voltage increased [44]. This has caused the slow progression of mold growth on the samples. The synergistic action of RNS and ozone has caused the oxidation of mold cell structures and the interruption of cell composition and metabolism [29]. Thonglor et al. [31] also mentioned that mold growth is reduced to the reactive species' interaction with the fungal cell membrane, which leads to cellular damage after being treated with plasma. In other research conducted by Mohamed et al. in 2022, the cause of the destruction of mold cell walls was due to oxidative ozone, which then reduced mold growth [32]. The authors believed ozone was a mold-growth delaying agent that helped extend bread's edibility. Therefore, the air plasma effectively suppresses the mold growth on the white bread.

The optimal plasma parameters for the present research are the applied voltage of 13.6 kV at 120 s of treatment duration for DBD plasma and the applied voltage of 16.1 kV at 120 s of treatment duration for plasma jet. These optimal parameters are chosen based on the parameters set that have the most reduction of mold growth intensity without causing the bread surface to burn or change in colour. Figure 6 shows the surface of the samples after plasma treatment. As shown in Figure 6, all samples treated with plasma for 120 seconds exhibited no noticeable changes in surface texture or color, which indicates that the treatment preserved the bread's physical integrity. Due to very scarcely research on plasma to treat white bread, there is only one research study on the impact of plasma treatment on bread texture conducted by Starek-Wójcicka A. et al. in 2022. The authors reported that when the bread was treated for 2 minutes, it significantly increased bread hardness, but only by 12%. However, when the treatment increased to 10 minutes, the hardness of bread increased by 28% after three days of storage. Although there is no proper texture analysis of bread samples, the present study provides essential information for future reference.



(a) (b)

(c)

Figure 6. The surface of the samples showed no sign of changes even after plasma treatment (a) sample A3, (b) sample B3, and (c) sample C3.
*The sample is chosen based on the longest treatment time at each varied applied voltage.

The plasma jet treatment demonstrated several advantages and disadvantages in the context of white bread preservation. One of the primary benefits of using plasma jet technology is that the samples are not easily burned during the treatment process. This is a significant advantage because it ensures that the bread's quality and integrity are maintained without the risk of surface damage or charring. Additionally, the plasma jet treatment allows for easier determination of the optimal frequency and voltage settings. This ease of parameter control simplifies the experimental setup and ensures consistent and reproducible results. However, the plasma jet treatment also presents some limitations. One of the main disadvantages is the smaller treatment area compared to DBD plasma. This limited coverage means that the treatment may not be as efficient or effective for larger batches of bread. Furthermore, although plasma jet treatment effectively reduces mold growth, the treated white bread's lifespan is shorter than bread treated with DBD plasma. This reduced shelf life could be a drawback for commercial applications where longer preservation times are desired.

In contrast, DBD plasma treatment offers distinct advantages, particularly in terms of treatment area and shelf life. One of the key benefits of DBD plasma is its ability to treat larger areas effectively. This larger coverage is advantageous for processing multiple bread samples simultaneously, making it more suitable for industrial-scale applications. Moreover, DBD plasma treatment has been shown to extend the lifespan of white bread significantly longer than plasma jet treatment. This extended shelf life is critical for ensuring food safety and reducing food waste. Despite these benefits, DBD plasma treatment also has its challenges. One major disadvantage is the increased risk of burning the samples. The bread is more susceptible to surface damage due to the higher intensity of the treatment, which requires careful monitoring and control. Additionally, determining the optimal frequency and voltage settings for DBD plasma is

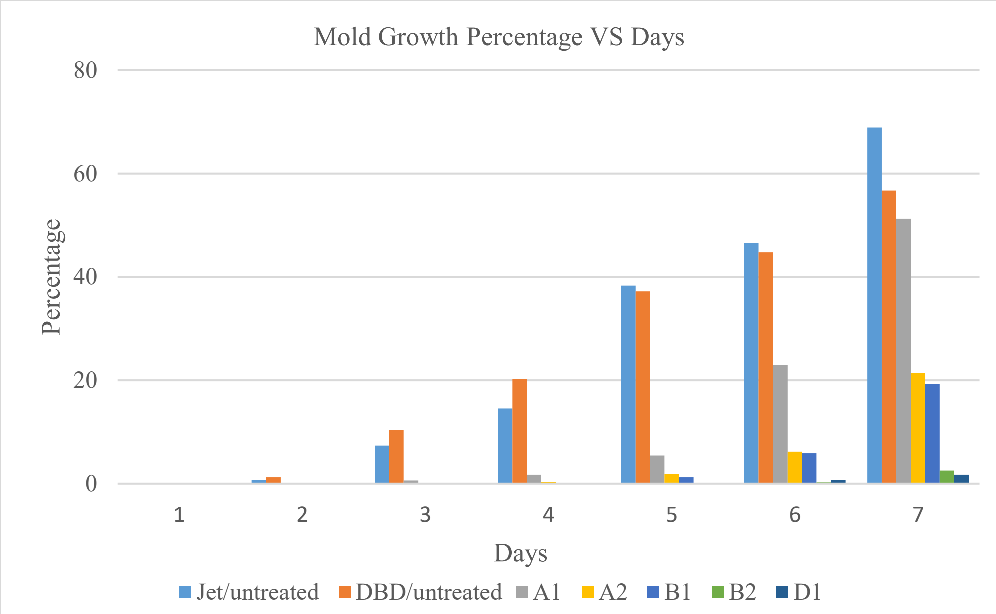


Figure 5. Mold growth percentage versus days progression after DBD and plasma jet treatment

more complex than that of plasma jet treatment. This complexity can lead to variations in treatment efficacy and may require more extensive experimentation to identify the ideal parameters.

4. CONCLUSION

In this work, the white bread is treated by both DBD plasma and plasma jet by varying the applied voltage (plasma jet only) and treatment time. The atmospheric air is used as the working gas. The reactive species are determined by using OES, while the mold growth progression was analysed using Image J. The results show that on day 7, the percentage of mold growth was 51.23% and 21.39% for samples A1 and A2, respectively, while 68.88% of mold growth was for untreated samples. Meanwhile, for sample D1 which was treated by DBD plasma, the percentage of mold growth was 1.70%. Based on the mold growth progression, the optimal DBD plasma and plasma jet treatment parameters for retarding the microbial growth of white bread were 13.6 kV/120 s and 16.1 kV/120 s, respectively. Under the optimal discharge condition, both plasma generators effectively reduce the intensity of mold growth progression. Moreover, plasma-treated white bread's lifespan is longer than untreated white bread's. Furthermore, the DBD plasma treatment is more effective than plasma jet treatment in retarding the microbiological growth of white bread.

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