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Low- Temperature Cold Plasma and Decontamination of Cereals and Fruits: A Review

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ABSTRACT

Fungi, being an integral constituent of this earth, cause contamination in many food stuffs including dried fruits and nuts. Food or feed control focuses not only on the analysis of natural food components (carbohydrates, proteins, fats, vitamins), but also on the determination of harmful compounds, like mycotoxins. This group of contaminants, produced by fungi (commonly called moulds) can be dangerous to human and animal health causing diseases known as mycotoxicosis. Cold plasma is a novel technology, potentially useful in the agriculture and food processing settings and has gained attention in recent years as a potential alternative method for chemical and thermal disinfection in foods using ambient or moderate temperatures and short treatment times in fruits, vegetables, seeds ect. Cold plasma uses several reactive gaseous species which are likely less ionised for the inactivation of microbe's present in meats, poultry, fruits, and vegetables. This review paper will cover the concepts and underlying principles, applications in food, critical parameters, advantages and limitations when this technique is employed. Otherwise, it provides a critical summary of the studies to decontamination of fruits and cereal products using low-temperature cold plasma technology along with a summary of the mechanisms and characteristics involved. In addition, the review also discusses the effects of this technology on quality of fruits and cereal products. Results suggested that cold plasma may be considered as an alternative method for the degradation and reduction of toxin production by mycotoxigenic fungi in the storage of foods and feedstuffs.

Keywords: *Cereals, Cold plasma, Fruits, Fungi, Contamination*

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1. INTRODUCTION

Fungi have an ability to grow on various foods specially cereals, fruit and nuts, where they cause food spoilage such as toxin production, off-flavor development, discoloration and rotting (Pitt & Hocking, 2009). The blue and green mould encountered during postharvest storage of fruits are *Penicillium italicum* and *Penicillium digitatum*, respectively (Misra et al, 2018). They are the most important postharvest diseases of fruits such as citrus family (Holmes et al., 2015).

Chemical method is one of the most popular methods to protect seeds against pathogens. But, it is high cost as well as a potential harmfulness to humans, animals, and the environment (Wenda-Piesik et al., 2010). Various methods such as radiation, electron beam and ultra violet irradiation, infrared and chlorine dioxide treatment have been used to reduce pathogen contamination of food (Jung et al., 2011; Lee et al., 2015). Although these methods have proven influential at removing pathogenic microorganisms, they may also lead to undesirable chemical and organoleptical changes in foods (Genc and Diler, 2013).

To prevent the fungal spoilage of many fruits, particularly citrus family, postharvest chemical fungicide application by spraying, or wax-coating is a common commercial method. The use of wax treatments in the citrus industry, health and environmental issues associated with chemical residues or the proliferation of pathogenic resistant strains are the common problems.

It is reported that thermal inactivation, irradiation, ultrasound treatment, and biological control agents are effective strategies for the detoxification of mycotoxins and inhibition of fungi growth, which are time consuming and result in reductions in the quality of food products (Basaran et al., 2008). Plasma is termed as the fourth state of matter, which displays various characteristics as compared with a gas, liquid and solid phase (Fig. 1), and is formed at the temperatures at which the ionization potential value is exceeded by the mean values of the particles kinetic energy. In fact, plasma is a quasi-neutral ionized gas state composed of ions, free electrons, atoms and molecules in their fundamental or excited states with a net neutral charge (Pankaj et al., 2013).

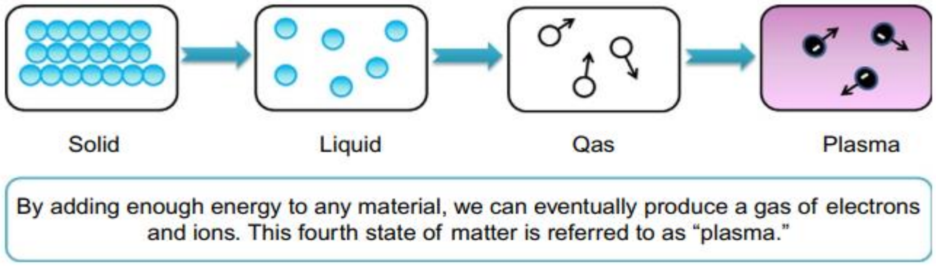

Figure 1. Pictorial representations of the four states of matter.

When the physical properties of the gas change, such as the loss of the insulation and the appearance of the electrical conductivity properties of the ionized gas, is considered to be the border between the state of the gas and plasma (Banu et al., 2012). Plasma technology is commonly used in biomedical, semiconductor manufacturing, displays (e.g. fluorescent, lighting and equipment) (Sarangapani et al., 2015), and decontaminate a wide variety of heat - sensitive instruments (Moisan et al, 2002). The key reason underlying the attractiveness of this technology is that it enables rapid decontamination at ambient temperature and pressure conditions, without causing significant perceivable changes in food quality (Sysolyatina et al., 2014).

Plasma can be classified according to the generation conditions, i.e. atmospheric pressure (low-pressure plasma, high-pressure plasma), temperature (low-temperature plasma, high-temperature plasma), and the composition of plasma-generating gas (one-component plasma, multi-component plasma) (Bourke et al. 2017). Low-temperature plasma consists of highly energetic species, free radicals, UV photons, electrons, negative and positive ions, excited atoms and molecules and UV radiation, which are able to deactivate and kill bacteria, viruses and other microorganisms without significant temperature effects (Guo et al., 2015 ; Fernandez et al., 2011; Bhatt et al., 2018; Schluter et al., 2013). The range of micro-organisms that have been shown to be inactivated using cold plasmas (CP) include Gram positive as well as Gram negative bacteria, bacterial spores, mold, and viruses (Misra et al, 2018). CP is one of the best techniques for disinfecting fruits, vegetables and grains during storage, which the product can be stored for a long time without any damage and microbial contamination.

2. LOW - TEMPERATURE PLASMA MECHANISM

Conventional methods for sterilization such as irradiation with ionizing radiation, fumigation with ethylene oxide, and treatment with super-heated steam and UV radiation are used in food decontamination (Schweiggert et al., 2007). However, each of these techniques include disadvantages such as oxidation of most aromatic components of the spices, loss of flavor and color and decreased qualities of some food ingredients (Sospedra et al., 2010; Sadecka, 2007). Microorganisms are a key target in the study of the CP efficiency, as susceptibility to the sterilization process may vary between microorganisms, even within species and strains (Fig. 2). It largely depends on the structure of cellular envelopes and the microbial growth phase (Liao et al. 2017).

Cell membrane deformations and leakage of the bacterial chromosome were observed in microbial cells treated with atmospheric pressure plasma (Mia-Prochnow et al., 2016). Pulsed electric fields induce electroporation of the cell membranes. Furthermore, plasma acts in a similar way to induce membrane perforations in microorganisms (Abdi et al., 2019). Direct effects of external electric fields on the sterilization and inactivation of microorganisms in plasma are usually negligible, while effects of electric fields associated with movement and accumulation of charged particles are important (Jordan et al., 2013). Plasma operates in the temperature range which can vary from room temperature to the temperature within the range of energy greater than a few electron volts (1 eV = 1,132, 685 oC) (Knoerzer et al., 2012).

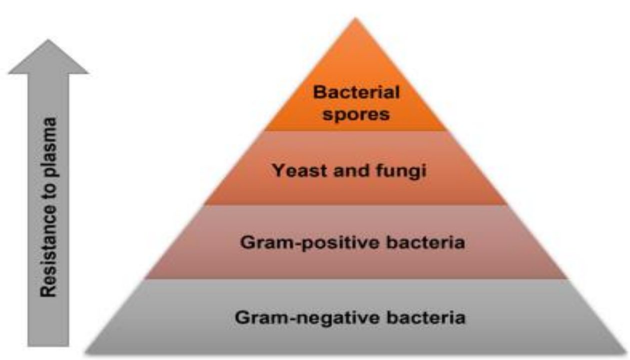

Figure 2. Pyramid of the sensitivity of microorganisms to plasma*.
Based on Klampfl T.G. et al. 2012; and Liao et al. 2017.
* Sensitivity of individual groups of microorganisms can vary depending on the conditions of the process.

CP for the inactivation of microorganisms is mainly associated with the reactive species generated, particularly reactive nitrogen species (RNS) and reactive oxygen species (ROS). Rupturing bacterial cell walls using a build-up of charged particles and/or bombardment of free radicals have been proposed as possible modes of action for bacteria inactivation (Smet et al., 2018). Although greater microbial inhibition is achieved by increasing the non-thermal treatment power and time, in practice a possible negative effect on quality must beaken into account (Kim et al., 2014). Plasma sterilization shows a survival diagram with two or three different linear segments. The analysis of the three single steps in the survival curve suggested many basic mechanisms: (i) direct destruction by UV irradiation of the genetic material of the micro-organism; (ii) erosion of the micro-organism, atom by atom, through intrinsic photodesorption by UV irradiation to form volatile compounds combining atoms intrinsic to the micro-organisms; and (iii) erosion of the microorganism, atom by atom, through etching (Laroussi 2005).

The extent of changes in fungal spores is a function of the level of exposure to plasma species. For example, Panngom et al. (2014) reported that considerable changes in plasma treated spore morphology of *Fusarium oxysporum* were not observed under electron microscopy, although the germination levels decreased, and cells underwent apoptosis. Even when the active species density is not sufficiently high to cause spore structure destruction, the cells could undergo physiological changes because of apoptosis, causing increase in accumulation of lipid bodies (Panngom et al., 2014). A pictorial summary of the mechanisms responsible for inactivation of fungal cells is provided in Figure 3.

Ionization is the first important step for plasma chemistry. Plasma chemistry depends on several factors such as feed gas composition, relative humidity, the power supplied, and treatment time (Devi et al., 2017). Siciliano et al (2016) reported the potential of CP to inactivate toxigenic fungi, leading to the detoxification of nuts. Mendez-Vilas (2013) reported damage in the microbial cellular membrane due to its interaction with active species and a subsequent loss of cytoplasmic material as the final cause of microorganism death. Additionally, DNA molecules - highly sensitive to ions, neutral species, and UV light can be altered when these active species penetrate and reach the nucleus (Jalili et al., 2012; Moreau et al., 2013). Mycotoxin detoxification is mediated by the union of free radicals to the heterocyclic rings in their molecule (Park et al., 2007). In this way, when mycotoxins are irradiated, three possible results can be obtained: first, the resulting structures are more toxigenic than the original molecule; second, the resulting molecules are equally toxigenic as the original toxin; and third, the resulting fragments present lower toxicity compared with the original toxin molecule (Atalla et al., 2004).

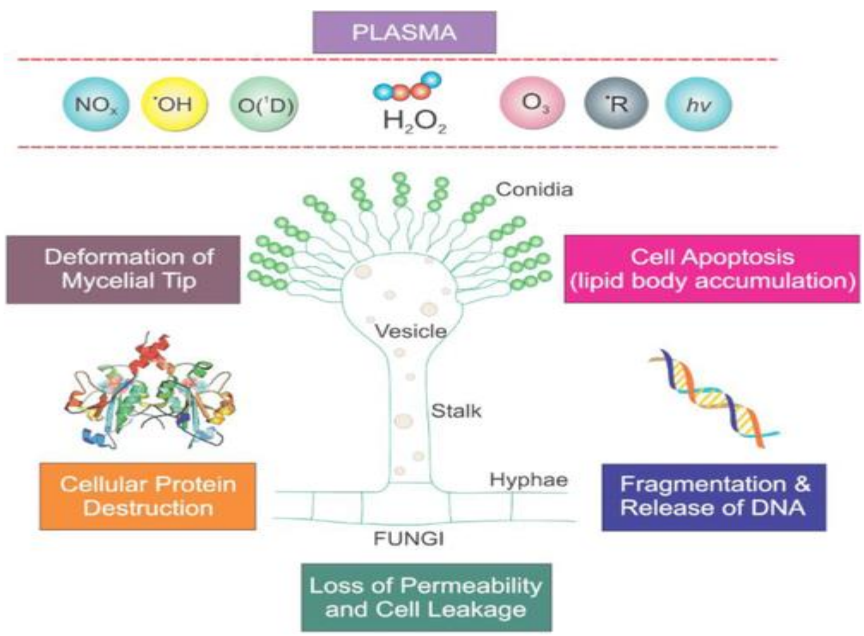

Figure 3. A summary of the effects of cold plasma species on fungal cells resulting in their inactivation.

Recently, Guo et al. (2015) postulated an explanation to justify the role of UV radiation in different plasma conditions. When UV radiation played a major role in the inactivation process, the gases were Ar or a N_2/O_2 mixture in combination with microwave-driven discharge. In this context, the ionization energy of Ar is higher than N_2 and O_2, making N_2 and O_2 ions (i.e. N_2+, N+, O_2+ and O+). In these conditions, the amount of positive nitrogen ions and negative oxygen ions was similar, and NO was generated with more respect to the electric discharge directly in the air. A similar mechanism happens with the excited state of NO. UV radiation in this experimental condition plays a an important role in bacterial inactivation because their doses in the 200–300 nm wavelength range are higher than other experimental conditions.

3. METHODS OF GENERATION OF COLD PLASMA

3.1. Dielectric barrier discharge (DBD)

Dielectric barrier discharge plasma is one of the most popular technique to generate nanthermal plasma, which is made up of a host of high-energy electrons, free radicals, chemically active ions and excited species. This method uses two flat metal electrodes which are covered with dielectric material. Neutral gas or any noble gaseous mixture moves between two electrodes in a closed target chamber and is ionized to generate plasma products as indicated in the Figure 4 (a). One electrode is connected to high voltage circuit and the other is grounded. The power consumption ranges between 10 and 100 W is used for its operation (Shimizu et al., 2018).

3.2. Jet discharge

Plasma jet devices are made up of two concentric electrodes. The outer electrode is grounded and the inner electrode is connected to external energy source such as radio frequency source and creates RF (Radiofrequency) energy. Thus interacts with the working gas in the target chamber causes ionization and exits through nozzle and gives 'jet-like' appearance (Zhang, 2015) as shown in Figure 4 (b).

3.3. Gliding Arc discharge

Gliding arc discharge follows periodic phenomenon that produces an auto-oscillating plasma species between two electrodes submerged in a laminar or turbulent flow. Plasma discharge starts from narrow end (termed as equilibrium stage), where the connecting electrodes of opposite polarity are joined together and it grows between lengths of the interelectrode. The non-equilibrium phase starts when the arc exceeds its critical value. Plasma column undergoes heat loss when begins to exceeds the energy supplied by the power source. At that point, plasma rapidly cools and produces CP (Khalili et al., 2018). Gliding arc discharge is considered as a transition from thermal to nonthermal operation mode combining effects of energetic species generated in thermal mode to the mild effect of plasma in cold nonthermal mode. Figure 4 (c) represents the gliding arc discharge of plasma onto the almonds.

3.4. Corona Discharge plasma

In this process, plasma is produced by non-uniform electric field strength under atmospheric pressure. Corona discharge appears near sharp points and along thin wires and it is represented in Figure 4 (d) shown below. In highly nonuniform electric field, gases exceeds its breakdown strength and produces weakly ionised plasma with some luminosity. Corona discharges are best suited for food sterilization applications (Anatao, 2009).

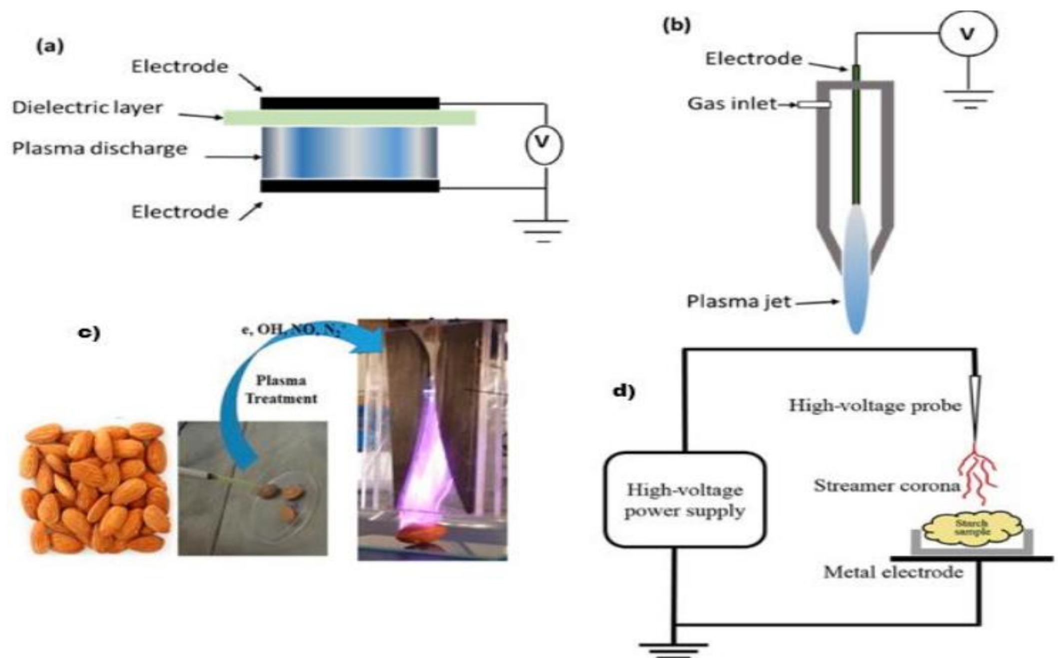

Figure 4. Methods of Discharge of plasma a) Dielectric discharge; b) Jet discharge (Pankaj et al., 2017) c) Gliding arc discharge (Khalili et al., 2018); d) Corona discharge.

4. LOW - TEMPERATURE PLASMA APPLICATIONS

With growing interest in the use of plasma technology in the food industry, CP may have the potential for uses beyond antimicrobial treatment. The demonstrated CP system for treatment of recirculating air in the storage atmosphere has applications in food storage and transportation as antimicrobial agent. The price and complexity of such a system is minimal and, at below 40 W, the system is low energy. The system can be easily powered using inexpensive solar panels incorporated into the air circulation system and produces no chemical waste. (Surowsky et al. 2015). Plasma inactivation capacity depended on many factors such as the type of technology used to generate the plasma, the feed gas, the voltage, the treatment time, the direct or indirect exposure, the species and the concentration of the tested micro-organisms and the structural characteristics of the produce (Li and Farid 2016).

4.1. Cereals

Owing to cereals extensive use as human foods and livestock feeds, the microbiology and safety of grains deserve high importance. The fungal attack in cereal grains could be due to field fungi or storage fungi (Los et al, 2018). According to Selcuk et al. (2008), food grains were investigated for *Aspergillus spp.* and *Penicillum spp.* before and after treatment with plasma products showed significant log reduction after exposure for 15min. In the food processing industry, CP treatment represents an innovative technology, especially since it was proven to be effective against foodborne pathogens and reduction of fungal growth and the various mycotoxins with relatively little effect on food nutritional value (Hojnik et al., 2017 ; Li et al., 2017).

In a study by Dasan et al. (2016), the treatment of, e.g., maize grains contaminated with *A. flavus* und *A. parasiticus* spores resulted in a decrease of 5.5 and 5.2 log CFU/g after 5 min in a non-thermal atmospheric pressure fluidized bed plasma system with air as plasma gas. Plasma technology has the potential to inactivate different mycotoxins, like, e.g., aflatoxin B_1, deoxynivalenol (DON) and nivalenol (Park et al., 2007).

Using ambient air as plasma gas, deoxynivalenol, zearalenone, enniatins, fumonisin B_1, T_2 toxin, and sterigmatocystin were completely degraded within 60s. For zearalenone and sterigmatocystin, the degradation rates were slowed down, but after 60 s, nearly the full amount was removed. For enniatin B and fumonisin B_1 instead, nearly half of the mycotoxins remained intact after 60 s (ten Bosch et al., 2017).

Sterilization of *A. parasiticus* from nuts' surfaces by means of SF_6 with five logarithm effectiveness and one logarithm loss after 5 min plasma sterilization with air was reported by Basaran et al. (2008). The temperature generated during the plasma sterilization process in order to eliminate *Penicillum* spp. and *Aspergillus* spp. from grains and legumes was within room temperature to enable their further growth (Selcuk et al., 2008).

Khan et al. (2017) indicated that combinations of mild heat treatment and dielectric barrier discharge plasma with other food preservation technologies, allow the optimization of microbial inactivation and effectively maintain the quality attributes of food products.

Sterilization effect of fluidized bed plasma treatment on *A. flavus* and *A. parasiticus* inoculated on maize grains was studied by Dasan et al. (2016). A maximum reduction of 5.48 and 5.20 log10 CFU/g in *A. flavus* and *A. parasiticus*, respectively after 5 min plasma treatment was observed. The study has demonstrated that with the prolongation of plasma treatment the number of fungal colonies on the seeds decreases (Filatova et al., 2009; Filatova et al., 2012). Selcuk et al (2008) observed a positive correlation between the use of low-temperature plasma and the reduction of Aspergillus and Penicillium presence in the *Triticum durum* under study. Similar results were obtained by Morar et al (1999). They examined the significance of highly intensive electric field to fungi occurrence on bean seeds and showed a link between an increase of electric field and the decrease in the occurrence of pathogenic fungi on bean seeds. The effect was particularly noticeable in the fungi of the genus Alternaria, Penicillium, Aspergillus, and also Fusarium.

Ouf et al. (2015) contaminated date palm fruits with *A. niger* and treated them for 7.5 min with a double atmospheric pressure cold argon plasma, which resulted in a complete reduction of ochratoxin A (OTA) after 10 days at 25◦C. Ozone has a high antimicrobial potential due to the occurring oxidation of cell components like polyunsaturated fatty acids, enzymes and proteins (Victorin, 1992). The high amount of ozone in the plasmas generated by CO_2 and dry air led therefore probably to a stronger inactivation of *P. verrucosum*, resulting in a reduced ability to produce OTA. Ozone has a direct inactivating effect on the pre-existing mycotoxins by causing chemical modifications leading to a reduced biological activity (Tiwari et al., 2010).

Ye et al. (2012) reported that the spores of *P. expansum* were reduced by corona discharge plasma for approx. one log CFU/Ml after 120 min. *Penicillium spp.* on grain was likewise decreased for 1 log cycle after 5 min of air plasma treatment (Selcuk et al., 2008).

Also, Audenaert et al. (2012) indicated that use of neutralized electrolyzed water reduced the Fusarium microbial count on wheat, but partially increased the amount of produced deoxynivalenol. This was explained by the effect of reactive oxygen species (in this case hydrogen peroxide). In plasma generated by air as process gas, the formation of reactive oxygen species is higher than in plasmas generated by O_2 and CO_2, where instead a higher amount of ozone is released (Hertwig et al., 2017).

Butscher et al. (2015) tested a low-pressure fluidized-bed plasma reactor for the treatment of wheat grains in order to inactivate artificially deposited *Bacillus amyloliquefaciens* endospores on the surface of produce. With this setup, concentration of *B. amyloliquefaciens* endospores was reduced by 2.15 log units within 30 s of effective treatment time, generated at a higher power input of 900 W. Other analyses showed no negative effects of plasma treatment on the flour and baking properties. Later, focusing on the decontamination of grain products, the same research group utilized an atmospheric pressure DBD-generated pulsed plasma treatment for inactivation of *Geobacillus stearothermophilus*.

In the work of Butscher et al. (2016), the reduced inactivation efficacy of plasma, even after an extended treatment time of 60 min, could be attributed to the complexity of the grains surface structure, where microorganisms can be protected by the uneven surface, loose pieces of bran, or hidden deep inside the ventral furrow. Moreover, in case of products with a high surface - volume ratio, the concentration of plasma-generated reactive species tends to decrease during the processing due to interaction with the food surface itself, rather than with the microorganisms on that surface (Hertwig et al., 2015). Table 1 shows the summary of research studies demonstrating inactivation of fungal species in food and model systems using CP.

Table 1. Summary of research studies demonstrating inactivation of fungal species in food and model systems using cold plasma.

Product	Organism(s)	Plasma source	Process parameters	Salient results	Reference
Wheat, barley, oat, rye,corn	*Aspergillus spp.*, *Penicillium spp.*	Inductively Coupled Plasma (ICP)	Pressure: 500 mTorr Gas: Air, SF6 Frequency: 1 kHz Voltage: 20 kV (p-p)	SF6 plasma for 15 min allowed decreasing both species by 3 log10 Seed germination is retained	Selcuk et al (2008)

			Power: 300 W Time: 5,10, 20 min	after plasma treatment	
Wheat and barley	*B. atrophaeus* *P. verrucosum*	DBD	Pressure: 1 atm Gas: Air Voltage: 80 kV, 50 Hz Exposure mode: direct and indirect Time: 5, 10 min	Fungi population decreased on barley surface by 2.1 and 1.5 log10 CFU/ g and on wheat surface by 2.5 and 1.7 after 20 min direct and indirect exposure with 24 hours retention at 15 °C.	Los et al. (2018a)
Maize grains	*Aspergillus flavus*, *Aspergillus parasiticus*	Atmospheric Pressure Fluidized Bed Plasma (APFBP) with stainless steel mesh based on jet from PlasmaTreat GmbH	Pressure: 1 atm Gas: Dry air; N2 Flow rate: 50 L/min Voltage: 5–10 kV Frequency: 18–25 kHz Power: 665 W (maximum) Time: 1–5 min Grain mass: 10 g	Length/Diameter (L/D) ratio of the fluidized bed influenced the decontamination efficacy. After 5 min treatment with air plasma ◦ For L/D = 49 mm/147 mm reductions were: *A. flavus*: 5.48 log CFU/g; *A. parasiticus*: 5.20 log CFU/g ◦ For L/D = 65 mm/195 mm reductions were: ◦ *A. flavus*: 5.08 log CFU/g; *A. parasiticus*: 4.99 log CFU/g ◦ Air was more effective compared to N2	Dasan et al.(2016)
Brown rice cereals	*Aspergillus flavus*	Radio-Frequency atmospheric cold plasma jet	Pressure: 1 atm Gas: Argon Power: 40 W Flow rate: 10 L/min Frequency: 50–600 kHz Voltage: 10 kV (max)	Plasma power of 40 W for 20 min was effective in preventing *A. flavus* growth for 20 days under storage conditions of 25 °C and 100% RH	Suhem et al. (2013)

4.2. Fruits

In-package decontamination of fresh fruits is interesting way to minimize the possibility of post-processing contamination. It reduced background microflora of fruits such as strawberry without significant effect on color and firmness during low temperature plasma (Mirsa et al., 2014). Misra et al. (2014b) studied the effects of CP on packaged strawberries, and they reached a 3 log reduction of the total count (Dirks et al. 2012).

In a study by Lacombe et al. (2015), yeast and molds showed 0.8 to 1.6 log CFU/g order of reduction after 1 day and 1.5 to 2.0 log CFU/g reduction after 7 days. Plasma exposure longer than 60 s was reported to cause considerable reduction in firmness, anthocyanins and color. Sterilization efficacy of in-package indirect CP generated in atmospheric pressure was also reported by Misra et al. (2014a). They observed that a 5 min treatment at 60 kV resulted in 3.3 log cycle reduction of naturally occurring yeasts and molds on strawberry surface after 24 hr of in-pack storage. However, unlike Lacombe et al. (2015), they did not find significant differences in the respiration rate, color, and firmness in plasma treated strawberries.

Won et al (2017) reported the inactivation of *P. italicum* and reduce the disease occurrence by 84% of Mandarins. The inhibition of *P. italicum* was found to depend on many parameters such as gas, power input, and treatment duration. Decontamination of the yeast *Candida albicans* in fresh produce by microwave plasma processed air was reported by Schnabel et al., (2015). They observed complete inactivation of yeast by 6.2 log10 steps on apple peel and strawberry.

According to Nish and Narayanan (2019), the chlorine and water for decontamination of fruits and vegetables can be replace by CP treatment. CP treatments on these products includes berries, cherries, apple, melon, and kiwi were studied. So, microbial decontamination by CP on fruits and vegetables is found to have a positive result with some negative impacts during its storage period. Significant effects of plasma on tomato and carrot color and chlorophyll fluorescence parameters were observed. Also, the CP for apple was more appropriate than the other fruits (Baier et al., 2015).

Matan et al. (2015) reported that integration of CP and other methods is another ways to develop beneficial applications of this novel techniques. The combination of atmospheric CP and green tea extract, extended the shelf life of fresh-cut dragon fruit, without negative effect on the organoleptical properties and nutritional value. Also, according to Irfan et al. (2013), interactions between the plasma and chemical methods such as calcium chloride on the fig storage, can be improved. Similarity, physical methods such as infrared heating and ultraviolet irradiation has good effect on the fig quality (Hamanaka et al., 2011).

Molds, such as *Penicillium spp*., *Aspergillus spp*., *Eurotium spp*., *Alternaria spp*., *Cladosporium spp*., *Paecilomyces spp*., and *Botrytis spp*., are commonly involved in the spoilage of fresh fruits and some processed fruit derivatives. Yeasts, such as *Saccharomyces spp*. *Cryptococcus spp*., and *Rhodotorula spp*. are found in fresh fruits, and *Zygosaccharomyces spp*., *Hanseniaspora spp*., *Candida spp*., *Debaryomyces spp*., and *Pichia spp*. are found in dried fruits (Raybaudi-Massilia et al., 2009). Table 1 shows the summary of effects of cold plasma processing on fungal counts of fruits.

Table 1. Summary of effects of cold plasma processing on fungal counts of fruits.

Sample	Plasma	Microbial Oservation	References
Blueberry	Plasma jet, 47 kHz, 549 W, air, 4–7 cubic feet/min, 7.5 cm, 0–120 s	Upto 2 log10 reduction in total aerobic plate count	Laccombe et al, 2015
Strawberry	DBD, 60 kV, 50 Hz, air, 5 min, indirect exposure	2 log10 reduction in background microflora (aerobic mesophilic bacteria, yeast and mould)	Misra et al, 2014b
Strawberry	DBD, 60 kV, 50 Hz, 65% O2 + 16% N2 + 19% CO2 and 90% N2 + 10% O2, 5 min, indirect exposure	~3.0 log10 reduction in microbes in both gas mixtures	Misra et al, 2014a
Mandarins	Microwave plasma, 2.45 GHz, 900 W, 1 L/min, 0.7 kPa, N2, He, N2 + O2 (4:1), 10 min	Significant inhibition of Penicillium italicum (84% reduction in disease incidence)	Won et al, 2017
Golden delicious apples	Gliding arc plasma, 60 Hz, air, 10–40 L/min, 1–3 min	~3.5 log O157:H7 reduction 10 reduction in *Salmonella* and	Niemira and Sites, 2008
Melon	DBD, 15 kV, 12.5 kHz, air, 30, 60 min	3.4 and 2 log10 reductions in mesophilic and lactic acid bacteria respectively	Tappi et al, 2016
Fresh fruit and vegetable slices (pears, cucumbers and carrots)	Plasma micro-jet, 30 mA, 500 V, 1–8 min	90%, 60% and 40% *Salmonella* inactivation in carrot, cucumber and pear slice, respectively	Wang et al, 2012

5. LIMITATION OF COLD PLASMA TECHNOLOGY

Despite numerous proposed applications of nonthermal plasma, this technology is still in its infancy and its limitations should be considered and addressed prior to its commercialization. Treatment with CP can induce lipid oxidation of food. This may lead to the creation of short-chain fatty acids, thus causing off-flavours and off-odours during storage (Ekezie et al., 2017). Undesirable textural properties, acidity, and discolouration of treated food can occur (Fernandez-Gutierrez et al., 2010). The high cost of installation is also a major drawback. Further research is required to find out the effects of CP on a broad range of quality aspects, including the sensory characteristics of various foods. Furthermore, the impact of CP on the nutritional value of food requires comprehensive investigations. Additionally, the analysis of the marketability/consumer acceptance of CP treated foods is critical, because the potential value of novel food technologies can only be realised if their application does not negatively affect the consumers' purchase decision making. The other limitations are:

1. Treatment of bulky and irregularly shaped food is difficult.
2. Restricted volume and size of the food for treatment.
3. Several ROS species has limited penetration into food products.
4. It may affects the sensory and nutritional attributes of the food to some extent during processing.
5. It may accelerate lipid oxidation and causes negative impact (Coutinho et al., 2018).

6. CONCLUSION

CP is a novel non-thermal technology that has shown significant potential for applications in food industries for food safety and shelf life extension.Nonthermal plasma treatment has attracted the attention of food scientists because of its prospective benefits in enhancing the safety of food. Research has so far revealed that this technique can be used for decontamination of food. The results presented here suggest this method could be a viable option for commercial application in the food industry. In that facet, CP can be versatile technology with great potential to benefit the areas of food industry.

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