A comprehensive study on decontamination of food-borne microorganisms by cold plasma

Aasi Ansari\(^a\), Karan Parmar\(^a\), Manan Shah\(^b,^*\)

\(^a\) Department of Nuclear Science, School of Technology, Pandit Deendayal Energy University, Gandhinagar, Gujarat, India
\(^b\) Department of Chemical Engineering, School of Technology, Pandit Deendayal Energy University, Gandhinagar, Gujarat, India

**ARTICLE INFO**

**Keywords:**
- Cold plasma
- Decontamination
- Dielectric Barrier Discharge (DBD)
- Escherichia coli
- Salmonella spp.
- Listeria monocytogenes

**ABSTRACT**

Food-borne microorganisms are one of the biggest concern in food industry. Food-borne microorganisms such as Listeria monocytogenes, Escherichia coli, Salmonella spp., Vibrio spp., Campylobacter jejuni, Hepatitis A are commonly found in food products and can cause severe ailments in human beings. Hence, disinfection of food is performed before packaging is performed to sterilize food. Traditional methods for disinfection of microorganisms are based on chemical, thermal, radiological and physical principles. They are highly successful, but they are complex and require more time and energy to accomplish the procedure. Cold plasma is a new technique in the field of food processing. CP treatments has no or very low effect on physical, chemical and nutritional properties of food products. This paper reviews the effect of plasma processing on food products such as change in colour, texture, pH level, protein, carbohydrate, and vitamins. Cold plasma by being a versatile, effective, economical and environmentally friendly method provides unique advantages over commercial food processing technologies for disinfection of food.

1. Introduction

Over the last few years, people have grown skeptical about the health effects of processed food (Gavahian and Khanegah, 2020; Zhu et al., 2020; Schneider et al., 2009). Therefore, the demand in market for healthy food has considerably increased (O’Beirne et al., 2014; Sagdic, Ozturk, and Torruik, 2013). With the change in consumer demands and food safety guidelines, food processing technologies have changed as well. Ensuring good quality and safety of food has become a difficult task in recent years (Liao et al., 2020). Food surface is easily contaminated by pathogenic microorganisms of manure compost during the process of harvesting. Ready-to-eat products available in the market have been harvested. With that various food borne diseases have also increase recently (Cui, Zhao, and Lin, 2015; Beuchat, 1996) (Fig. 1).

Cleaning and disinfection are crucial processes during food processing to ensure hygienic products and food safety. Different types of chemical and physical processes are used for disinfection of food to prevent pathogenic and harmful microorganisms (Cui et al., 2016). Commercial methods for the inactivation of microorganisms are based on chemical principles (Fernández et al., 2012). Non-thermal methods are preservation of food that are effective at sub-lethal temperatures, thus it minimize negative effects on nutritional value of food (Tiwari, O’Donnell, and Cullen, 2009). These include the application of gamma irradiation, beta irradiation (electron beam), UV treatment, power ultrasound, pulsed light, high hydrostatic pressure and pulsed electric field (PEF). They are effective but limited to certain types of food products and consume more energy and time. Purely physical procedures, such as high hydrostatic pressure, are chemically secure, but they necessitate complicated and costly equipment. (Rastogi et al., 2007), and this can affect the quality of food product (Kruk et al., 2011).

Therefore, several food handling systems are being investigated for use on food packaging surfaces (Kowalonek, Kaczmarek, and Dbrowska, 2010). Cold plasma is a new approach that has drawn the interest of food science and researchers (Basaran, Basaran-Akgul, and Oksuz, 2008; Selcuk, Oksuz, and Basaran, 2008; Vleugels et al., 2005).

The use of cold plasma to decontaminate fresh fruits and vegetables is a new technology (Pankaj et al., 2014). Plasma processing is a flexible method that can be used on a wide range of food items, including cereal, meat, poultry, dairy, fruits and vegetables, as well as packaging. (Critzet al., 2007; Kim et al., 2017; Niemira and Sites, 2008). Cold plasma treatment can inactivate microorganisms on the surface of food products.
Cold plasma includes reactive species such as electrons, free radicals, positive and negative ions, UV photons, and excited or non-excited molecules and atoms, all of which can be used to sterilize food (Hoffmann, Ber-ganza, and Zhang, 2013). Furthermore, the temperature of the plasma glow is low since these active species are not in thermodynamic equilibrium (<60 °C). As a result, it’s known as cold plasma is classified as a non-thermal technology (Misra & Pankaj, 2014).

Chemical washing is done with antimicrobial compounds such as chlorine, hydrogen peroxide, ozone, and managed atmospheric storage are used during the processing of fruits and vegetables to minimize bacterial content (Mahajan et al., 2014). Fresh-cut vegetables are highly bacterial risky due to all operations such as peeling or chopping, dipping or shredding before wrapping (Rico et al., 2007). Thermal therapy is an alternative to microbial food reduction, but heat sensitive vegetables and fruits, which can cause improvement in fruit and vegetable quality attributes. Thus, in comparison to other non-thermal treatment such as ionizing radiations, high hydrostatic strain, pulsed energy champions, oscillating magnetic fields and high performance ultrasound, cold plasma technology offers the opportunity for industrial cost reductions (Tiwari, O’Donnell, and Cullen, 2009). In addition to microbial decontamination, it helps to amend the food content with the desired characteristic and preserves the nutritive and textural properties. Thus, in order to conduct decontamination, it is essential to consider the relationship of cold plasma with the surface of food materials.

Killing of microorganisms is the most essential element for the food safety. There are numerous microorganisms present on food surfaces. *Escherichia coli* is the most common food-borne microorganism found in most of the fruits and vegetables. *Listeria monocytogenes* is another microorganism for food security problem because it is prevalent in the environment (Ukuku et al. 2015). New strawberries, cut apples, and stone fruits such as whole peaches, nectarines, and plums have also been shown to contain *L. monocytogenes*, which can cause a variety of diseases. Plasma-activated atoms and ions induce molecular sandblasting, destroying organic and inorganic pollutants.

2. **Comparison between cold plasma and other decontamination methods**

There are many traditional methods for decontamination of food, such as thermal, chemical, radiation, etc (Ascp and Weber, 1999; Sureshkumar et al., 2010). Food-borne diseases are increased due contamination by viruses, pathogen, parasite, and other microorganism on fruits, vegetable, meat, dairy and fish products.

Thermal technique is one of the most ancient technique for food sterilization (Sureshkumar et al., 2010). Thermal pasteurization of liquid product such as milk are well established and satisfied approach. However, it is not guaranteed for solid product. Many food products are heat sensitive or it has some components which can show unwanted results. Thermal sterilization in medical facilities is not considered an ideal approach. Furthermore, thermal treatment has to be handled carefully or it can be harmful to the personnel. Food packaging can also be used to minimize contamination. If possible, the product could be preheated or pasteurized before packaging to minimize the infection. However, there is still a chance of getting infected by viruses by surface cross-contamination.

Chemical disinfectants are used for recent few centuries. It includes chlorine, alcohols, acids, alkalis, bleach etc (Filipi et al., 2020). Chemical disinfectants are one of the economical method, but it has only short-term effect. It is considered better for surface disinfection, but it can react with the components on food surface and make even more dangers components. Ethanol and Isopropanol are mostly used for surface disinfectants. Human body have many microorganism, which can be killed by chemical disinfectants, but ethanol and many other chemical could be toxic to human body (Moisan et al., 2013).

Antibiotics is one of the most frequently used disinfectants for bacteria. Different antibiotics are available for different bacteria and doses are established, which gives it a natural preference for decontamination. However, it is not considered fully safe for food decontamination. Decontamination from antibiotics can take a long time. Many bacteria can show resistance to antibiotics and can even survive in the presents of an antibodies. Furthermore, if it is applied on human body, it could show side-effect like skin infection, Nausea, Vomiting, Diarrhea, loss of appetite, stomach pain, etc (Mammadova et al., 2019).

Irradiation is one of the physical process, studied thoroughly from last few decades (Section, Atomic, and Agency n.d.). The irradiation processes using gamma, electron beam, infrared and microwave, but again radiation should be handled with precaution or it could be harmful. It can only be used to sterilized pre-packed food material. Hence, it can’t be used directly on food surface, or it could show undesirable effects. Radiation treatment will sterilize the entire body. Thus, it can’t be use for disinfection on a single spot. Radiation treatment should be handled with precaution or it could be harmful to the personnel. Furthermore, radiation sterilization is not cheap. Alcohol is used in sanitizer, has shown good response for flu viruses. Ethyl alcohol is a powerful germicide that is considered better

Fig. 1. (a) Schematic Diagram of DBD, (b) Schematic Diagram of Plasma Jet (Misra et al., 2016).
than isopropyl alcohol and other options. To be effective, any sanitation must contain at least 70% of alcohol solution (Wadhams, 1998). Alcohol sensitization does not show the desired results if the concentration of alcohol falls below 50%. Ethyl alcohol and isopropyl alcohol are two chemical substances that are widely utilized in hospitals. These alcohols are bactericidal and fungicidal (Rutala and Weber, 2013). However, if it is used very often as a disinfectant, alcohol can cause swelling, hardness, cracking, and even color loss. Since, alcohol is flammable it is not 100% safe to be used as a surface decontamination. A 40-year health care worker, experienced hand burn after using alcohol gel sanitizer (O’Leary and Price, 2011). This case demonstrated the possible danger of using alcohol hand gel sanitization, specially for smokers or someone who is working in thermal associated facility.

Cold plasma does not produce radiation, chemical toxicity, high heat, or any other undesirable byproducts, thus considered environmentally friendly. Because it operates under Atmospheric Temperature and Pressure and it is simple to use (Chen et al., 2020; Misra & Patil, 2014; Park et al., 2008; Roosow, Ludewig, and Braun, 2018). It can be operated without vacuum (Sharma et al., 2018). Thermal, chemical and radiation sterilization can’t be used in open, it needs controlled atmosphere. Organic or inorganic impurities are also decontaminated. The use of cold plasma has also been proven to reduce contaminants from the surface of industrial materials such as iron and steel (S. Y. Park and Ha, 2018). Thus, cold plasma can be used to decontaminate heavy metal particles like iron and steel (Ramaswamy et al., 2019). Decontamination of liquid products by cold plasma has shown sufficient log reduction form water, milk, fruits juices, etc (Aggelopoulos and Tsakiroglou, 2021). It is a pollution free technique for bacterial and viral disinfection (Bute et al., 2020). Cold plasma processing had no or little changes on nutritional value or any other physical characteristics. Other advantages of cold plasma therapy include reasonably good food composition preservation, low energy costs, and fast processing. There are many traditional methods that can be used for sterilization, but cold plasma being a versatile, effective, and environmentally friendly method provides unique advantages over commercial sterilization technologies.

3. Plasma physics and chemistry

Plasma is the fourth and final state of matter. It’s a partly ionized gas made up of electron, photons, uncharged atoms and molecules, ozone and free radicals (Hoffman, Berganza, and Zhang, 2013). The antimicrobial effect of this ionized gaseous mixture of active species. Plasma discharges are commonly used in manufacturing and are critical in a variety of technical applications (Milosavljević, Karkari, and Ellingboe, 2007). Cold plasma is operated in less than 60°C (Alves Filho, de Brito, and Rodrigues, 2019). Cold Plasma is an electrically conducting quasi-neutral ‘sea’ of electrons, ions, and reactive and neutral molecules (Claro et al., 2015). Adding gas mixtures can give different reactive atoms and molecules like reactive oxygen, UV photons and nitrogen molecules (Stoffels, Sakiyama, and Graves, 2008). For example, reactivity of oxygen and air can make large amount of atomic oxygen, superoxide, hydroxyl radicals, nitric oxide, hydrogen peroxyde, and many more, which are all considered to kill the microorganism (Liu et al., 2010). Helium can reduce the cost of power requirement as it is easily ionized. However, atmospheric air is more economic since it is abundantly available in nature and less expensive than helium (Niemira, 2012).

Plasma chemistry is a complex science comprising a host of chemical reactions on various scales. Interaction of plasma with food surfaces is difficult to understand because it has numerous chemical reactions amongst 75 different species. The atmospheric plasma technique is effective in the breaking most organic bonds (i.e., C-H, C-C, C=C-C, C-O, and C-N) of surface contaminants. It helps in breaking contaminants with high molecular weight (Donegan, Milosavljević, & Dowling, 2013). The oxygen species produced in the plasma conduct a second purification action (O2, O3, O2, O, O+, and O3−, ionized ozone and free electrons). The radicals lead to the formation of H2O2, CO, CO2 with organic contaminants. The reaction, which ultimately leads to OH production, implemented in the process of DBD are listed below (Foster et al., 2018).

\[ \text{HO}_2 \leftrightarrow \text{O} + \text{H}^+ \]
\[ \text{O} + \text{O}_2 \rightarrow \text{O}_3 \]
\[ \text{O}_3^{-} + \text{H}^+ \rightarrow \text{HO}_3 \]
\[ \text{HO}_3^{-} \rightarrow \text{O}_2 + \text{OH} \]

Cold plasma inactivates microorganisms through three main techniques. First is the chemical reaction of radicals, reactive species, or charged particles with cell membranes. Second is by UV radiation damage to membranes and interior cellular components. Finally, UV produced during plasma species recombination may cause DNA strands to break. However, greatest results are seen by combination of multiple antimicrobial mechanism (Laroussi, 2002; Moisan et al., 2002). Free ions and electrons of plasma are produced by electrode using radio-frequency (RF), microwave (MW), or dielectric barrier discharge (DBD). In other cases, different types of method is used to generate plasma like: Uniform glow discharge plasma (Critzer et al., 2007), Corona Discharge Plasma Jet (Santos et al., 2018), Atmospheric cold plasma (Shi et al., 2017) and many more.

Dielectric barrier discharge is one of the easiest method to producing cold plasma. DBD has a huge anti-microbial potential to kill the contaminants present on the food and increase the shelf life without compromising the food safety or the nutritional value (Feizollahi, Misra, and Roopesh, 2020). DBD is generated by the electrical discharge between two electrodes, normally constructed with copper, which is separated by an insulating dielectric barrier (O’Connor, Milosavljević, and Daniels, 2011). During this process argon, helium or any other noble gas (because they are inert in nature) enclosed within the glass walls act as a dielectric barrier to form cold plasma (Misra et al., 2011).

A sinusoidal voltage is applied to one of the dielectric plates and the other plate is electrically grounded. When high-voltage alternating current is supplied, the electron from the atom are separated forcefully from the atom forming ions and free electrons. This will result in an exponential growth in the number of electrons. This flow of electrons is cold plasma. Glass, quartz, ceramics, and polymers are all popular dielectric materials (Liang et al., 2011). The plasma formed does not react with large particles. However, small entities such as microorganisms or viruses can be eliminated (Moreau, Orange, and Feuillolley, 2008). It also reacts with different compounds to form OH radicals which can be easily separated. This make cold plasma very unique for the decontamination of bacteria, viruses, pathogen or any other types of microorganism. The DBD is considered one of the most energy efficient and economic plasma generator among the various forms of Plasma Generators.

4. Effect of cold plasma on food

4.1. Vegetables

Demand for fresh and natural food is increased in the market recent years. As a basic preservation strategy to assure quality of stored food, atmospheric packaging in addition with refrigeration is increasingly being used. However, because of the use of numerous gases in packaging and refrigeration process, the freshness of many food products is decreasing, and many food-borne diseases are spread between their consumers (Francis, Thomas, and O’Beirne, 1990). Newly harvested vegetables and fruits are mainly decontaminated with chlorine solution. Chlorine traces in food products are done by chemicals that are harmful to humans (Allende et al., 2008; Rico et al., 2007). Organic and inorganic contamination can lead to health risk (X. Chen and Hung, 2017;
the environment (Francis, Thomas, and O’Beirne, 1999). It is rod-shaped Gram-positive bacteria that can cause disease like Meningitis, Septicemia and it can even cause miscarriages (Höh and Nell, 2015; Poukkavenh et al., 2016; Wing and Gregory, 2002). Salmonella is one of the gram-negative rod shaped bacteria. It is faecal associated microorganism thus contamination causes 34% of all worldwide food safety problems (Beuchat, 2002). Every year, bacterial pathogens, viruses with preserving the nutritional value are currently - Luo et al., 2018). Methodologies for inactivation of microorganisms, pesticides, viruses with preserving the nutritional value are currently under evaluation (Cossu et al., 2018; Goodburn and Wallace, 2013; Guo, Huang, and Chen, 2017; Marti, Ferrary-Américo, and Barardi, 2017; Thorn, Pendred, and Reynolds, 2017). Incidents regarding food safety have been increased in recent years due to the increase in use of pesticides and other chemicals (Beuchat, 2002). Every year, bacterial contamination causes 34% of all worldwide food safety problems (Frieden, 2010). E. coli O157:H7, L. monocytogenes, Salmonella phthymium rium KC1TC 1925 are one of the most commonly found food-borne microorganisms. E. coli O157:H7 is found on most of the food surfaces, responsible for majority of foodborne disease. Bovine gastrointestinal track is believed to be the main reservoir of E. coli O157:H7 (Yamada et al., 1993). Thus, food products associated with faeces are considered to be at risk of being contaminated by E. coli O157:H7. L. monocytogenes is considered present nearly everywhere in the environment (Francis, Thomas, and O’Beirne, 1999). It is rod-shaped Gram-positive bacteria that can cause disease like Meningitis, Septicemia and it can even cause miscarriages (Höh and Nell, 2015; Poukkavenh et al., 2016; Wing and Gregory, 2002). Salmonella is one of the gram-negative rod shaped bacteria. It is faecal associated microorganism thus it can contaminate food if sewage water or contaminated water is used for agriculture. Diarrhea, Nausea, Abdominal pain, Vomiting, fever, etc are the symptoms caused by Salmonella microorganism (Gordon, 2008; Kunwar et al., 2013). The types of microorganisms and their disinfection conditions are listed in the Table 1. Vegetables were studied under cold plasma to inactivate L. monocytogenes and E. coli O157:H7 in the studies (mentioned in the table below) related to microorganism inactivation. A DBD plasma device was used within a frequency range of 15–60 Hz and a voltage supply of 60 kV is required to eliminate the E. coli ATCC 25922 type of microorganisms (Misra & Pankaj, 2014; Prasad et al., 2017). However, Salmonella spp. can be eliminated easily at a lower frequency (7 kHz) and voltage (10 kV) (Critzer et al., 2007).  

### Table 1

| Food Product | Type of Plasma | Processing Condition | Microorganisms | Changes | References |
|--------------|----------------|----------------------|----------------|---------|------------|
| Cabbage      | Microwave-powered cold plasma | 400–900 W, 667 kPa, 1–10 min | L. monocytogenes | No change | (Lee et al., 2015) |
| Cucumbers and Carrots and Pears | Plasma jet | 500 V, 30 mA, 1–8 min | Salmonella | Decrease in colour, moisture and vitamin-c | (Wang et al., 2012) |
| Lettuce | ICDPJ | 2.4 kHz, 34.8kV, 5 min | A. hydrophila | No change | (Min et al., 2017) |
| Lamb’s lettuce | Plasma jet | 35 W, 7.12 MHz, 40 s | NA | Decrease in acidity | (Grzegorzewski et al., 2011) |
| Romaine lettuce | DBD | 42.6 kV, 10 min | Escherichia coli O157:H7 | No change | (Min et al., 2017) |
| Red chicory | DBD | 19.15 V, 3.15 A, 15 min | L. monocytogenes | No change | (Trevisani et al., 2017) |
| Iceberg Lettuce | OAUGDP | 9 kV, 6 kHz, 25 °C, 3–5 min | L. monocytogenes | No change | (Critzer et al., 2007) |
| Cherry Tomatoes | DBD | 100 kV, 150 s | E.coli, listeria innocua | No change | (Ziuzina et al., 2016) |
| Tomato | DBD | 15 Hz and 60 kV, from 5 to 30 min | E. coli ATCC 25,922 | No change | (Prasad et al., 2017) |
| Radish | Microwave- powered plasma | 900 W, 667 Pa, 10 min | S. typhimurium | Decrease in the moisture content | (Oh, Young Song, & Min, 2017) |
| Corn | HVACP | 90 kV, 50 Hz, 10 min | Aflatoxins | No change | (Shi et al., 2017) |
| Zain | DBD | 75 V, 10 min | NA | No change | (Dong et al., 2017) |
| Spinach | DBD | 50 Hz, 12kV, 5 min | E. coli ATCC 25,922 | No change | (Klockow and Keener, 2009) |
| Pumpkin | ICDPJ | 17 kV, 20 min | E. coli ATCC 25,922 | Decrease in pH | (Santos et al., 2018) |
| Onion powder | Microwave plasma | 400–900 W, 2.45 GHz, 0.7 kPa, 1 L/min, 10–40 min | A. brasilienis, E. coli O157:H7 | No change | (Kim et al., 2017) |

4.2. Fruits

Fruits, similar to vegetables, they may be infected with pathogenic microorganisms from livestock and manure compost during the irrigation, harvesting, and transportation processes. Traditional postharvest washing and sanitizing methods for food are insufficient. Microbial reductions of less than 2 log units are shown very often by conventional methods in comparison to cold plasma (Niemira, 2012). Research has shown that harmful bacteria may grow on a large scale for fresh and fresh-cut fruit surfaces (Microbiology, 2005). Cold plasma process can promise decontamination of microorganisms and quality enhancement of fruits (Mir et al., 2020). Cold plasma has shown significant reduction in surviving microorganism like E. coli O157:H7 and Salmonella Stanley on surface of Golden Apple (Niemira and Sites, 2008). Inactivation of Salmonella was time dependent, with each increasingly longer treatment giving considerable incremental increases in pathogen inactivation (Niemira and Sites, 2008). In fruits, water content is high, thus most of the fruits are heat sensitive. Due to this surface structure or color may change after thermal treatment. Increment in Color and Vitamin-C content has been seen after cold plasma treatment (Ramazzina et al., 2015). Saccharomyces cerevisiae is one of the persistent microorganism mostly found on Melon and Mango, shown significant reduction in 10 s on mango and 30 s on melon after plasma processing (Perni et al., 2008).

Fresh cut fruits have to be treated in different conditions because the micro-organisms present inside and outside the fruit can be different (Bagheri and Abbaszadeh, 2020). The types of microorganisms that can be eliminated at different processing conditions are listed in the Table 2. In the studies (mentioned in the table below) related to inactivation of microorganisms show fruits processed under cold plasma to decontamination. The fruits have different shapes and they come from different parts of the world. Therefore, they have different micro-organisms. Hence, the processing conditions are different. Several kinds of apples are tested in studies and it is shown that the microorganisms on the surface of the apples can be killed by processing it for 2–5 min. The...
Processing condition for inactivation of microorganisms present on surface of fruits by cold plasma.

| Table 2 |
| --- |

| Food Product | Type of Plasma | Processing Condition | Microorganisms | Changes | References |
| --- | --- | --- | --- | --- | --- |
| Apple | DBD | 150 W, 12.7 kHz, air, 120 min | E. coli O157:H7 | Reduction of antioxidant | (Ramazzina et al., 2016) |
| Golden apple | GACP | 15 kV, 60 Hz, 3 min | Salmonella Stanley and E. coli O157: H7 | No change | (Niemira and Sites, 2008) |
| Granny smith apples | Plasma jet | 40 Hz, 36 kV, 5 min | L. monocytogenes | Changes in apple surface structure | (Ukuku, Niemira, and Ukanalis, 2019) |
| Melon | DBD | 12.5 kHz, 15 kHz, 30 min | NA | Reduction in peroxidase | (Tipp et al., 2016) |
| Banana | Corona electrical discharge plasma | 50 kV/cm, 3 min | Salmonella spp. | Pasting temperatures rise when peak viscosity falls | (Lee, Sun, and Chau, 2018) |
| Cantaloupe | RFP | 9 kV, 6 kHz, 25 °C, 1 min | P. italicum | No change | (Crier et al., 2007) |
| Mandarin | Microwave- powered cold plasma | 2.45 Hz, 0.7 k Pa | No change | Peel has more overall phenolic and antioxidants | (Woo, Lee, and Min, 2017) |
| Mangoes and melons | Cold atmospheric plasma | 12–16 kHz, 30 kHz, 1 min | P. agglomerans, E. coli, Saccharomyces cerevisiae, Gluconacetobacter liquefaciens | No change | (Perni et al., 2008) |
| Kiwi | DBD | 15 kV, 10–20 min | NA | Colour enhancement, improved vitamin-C, and acidity | (Ramazzina et al., 2015) |
| Strawberries | DBD | 50 Hz, 60 kHz, 5 min | Aerobic bacteria and yeasts and moulds | No change | (Misra & Patil, 2014) |
| Blueberry | DBD | 80 kHz, 60 Hz, 5 min | NA | Acidity and colour change | (Sarangapani, O’Toole, Cullen, & Bourke, 2017) |
| Unpeeled almond | Diffuse coplanar surface barrier discharge | 20 kHz | Salmonella | Colour change | (Hertwig et al., 2017) |
| Almond slices | DBD | 15 kHz, 15 min | NA | No change | (Shirani, Shahidi, and Mortazavi, 2020) |
| Groundnuts | Radiofrequency plasma | 60 W, 13.56 MHz | Aspergillus parasiticus, Aspergillus flavus | No change | (Devì et al., 2017) |

| 4.3. Grains |

Grains are produced in large quantity and stored in Godown for later sell and use. While storage grains could be invade by 25 distinct species of fungi (DUAN et al., 2007). Penicillium are one of the most commonly found microorganisms that are responsible for spoilage of food storage. They produce changes in order, color and reduction in nutritional value (Selcuk, Oksuz, and Basaran, 2008) (Table 3).

Decontamination of grains is hard to perform because of their small size (Gupta et al., 2020). In all these studies (mentioned in the table below) related to inactivation of microorganisms show grains tested

| Table 3 |
| --- |

| Food Product | Type of Plasma | Processing Condition | Microorganisms | Changes | References |
| --- | --- | --- | --- | --- | --- |
| Rice, wheat, chick pea, bean, barley, oat, soya beans, lentil, corn, rye, Refined Wheat flour | APP | 20 kV, 300 W, 1 kHz, 5–20 min | Aspergillus spp., Penicillium spp. | Moisture Changed | (Selcuk, Oksuz, and Basaran, 2008) |
| Wheat flour | DBD | 50 Hz, 1–2.5 kHz, 1–5 min | Tribolium castaneum | No change | (Mahendra et al., 2016) |
| Rice starch | RFP | 60–90 kHz, 5–10 min | Penicillium spp. | No change | (Misra et al., 2015) |
| Black gram | RFP | 13.56 MHz, 30–50 W, 5–15 min | Penicillium spp. | No change | (Thirumdas et al., 2017) |
| Brown Rice | RFP | 40–50 W, 13.56 MHz, 5–10 min | Bacillus cereus | Reduction of cooking time, durability, chewiness and humidity | (Thirumdas et al., 2016) |
| Black paper corns | DBD | 9.7–10.6 kV, 15 kHz, 20 min | NA | No change | (Bang et al., 2020) |
| Brown Rice | DBD | 250 W, 15 kHz, 5–20 min | E. coli O157:H7, Bacillus subtilis, Bacillus cereus | Reduction in hardness and pH | (Lee et al., 2016) |

(APP) – Atmospheric plasma jet.
(RFP) – Radio frequency plasma.
under cold plasma to inactivate *Penicillium* spp. For the decontamination of microorganisms of grains DBD and RF are commonly used. The most commonly found microorganism in grains is *Penicillium* spp. The results show that it took more time to decontaminate and kill the microorganisms present in the grains compared with that of vegetables and fruits (Mahendran et al., 2016). It took about 20 min for each bag of grains. However, the processing condition is comparatively less because of the small size. Grains required a frequency and voltage of 1 kHz and 20 kV, respectively (Selcuk, Oksuz, and Basaran, 2008) for the decontamination of *Penicillium* spp. However, study results of flour have shown even lesser input power. It took only 5–10 min and a frequency and voltage of 50 Hz and 2 kV, respectively (Mahendran et al., 2016) for the decontamination of microorganisms like *Penicillium*. Another type of microorganism is *Bacillus cereus* which is mainly found in brown rice. Brown rice is the most easily and heavily contaminated food present in the market. It took 13.56 MHz of frequency (Lee et al., 2016) for the decontamination of *Bacillus cereus*. These microorganisms influence characteristics of food like color, flavor, and composition, which has an impact on the cooking and eating quality. *Bacillus subtilis* contamination of rice-based food items has been linked to food-borne illnesses in humans (Fangio, Roura, and Fritz, 2010). There are many non-thermal characteristics of food like color, flavor, and composition, which has an impact on the cooking and eating quality. *Bacillus subtilis* contamination of rice-based food items has been linked to food-borne illnesses in humans (Fangio, Roura, and Fritz, 2010). There are many non-thermal processes, such as chemical treatment, ultraviolet, ionizing radiation, and high pressure processing that can be used for decontamination. However, these methods have a few disadvantages, such as high application costs, the need for specialized equipment, the creation of unwanted residues, longer processing times and poorer efficiency (Yun et al., 2010). Black gram is one of the most consumed food products in India that contains protein, starch, dietary fibers, sugars and micro-nutrients such as vitamins, minerals, proactive phytochemicals and oil (Singh et al., 2004). However, nutritional value can be reduced due to components present in black gram like tannins and phytic acid, which reducing protein digestion and decreasing mineral bioavailability (Duhan et al., 1989).

### 4.4. Animal product

*Salmonella enteritidis* is a commonly found microorganism in eggs and chicken meat (Wan et al., 2017). A DBD cold plasma jet device are used at a frequency of 2–10 Hz and a voltage supply of approximately 30 kV is sufficient to eliminate *Salmonella enteritidis* type of microorganisms (Dirks et al., 2012; Lee et al., 2011). Chicken skin can be disinfected quickly because it commonly contains *Campylobacter jejuni* which can be killed easily in 1 min at a frequency and voltage of 1 MHz and 3 kV respectively (Rossow, Ludewig, and Braun, 2018). However, chicken thigh, requires more time and power than that of chicken skin (2–3 min) for decontamination (Moutiq et al., 2020). For egg shells, conventional disinfection methodologies are inefficient in removal the existence of Salmonella (Cui et al., 2016; Cui, Ma, and Lin, 2016). Egg shells usually consist *serovar Typhimurium*. Eggs have one of the highest numbers of microorganisms. Therefore, egg shell consumes more time and energy for decontamination than that of vegetables, fruits, grains and chicken thigh or skin. It has to be treated for 15–20 min at a frequency and voltage of 60 Hz and 30–85 kV respectively for the decontamination of *serovar Typhimurium*.

Atmospheric temperature plasma can also be used food packaging for prevention of secondary pollution (Deng et al., 2020). Secondary pollution is rampant in animal products. The pork is studied under two conditions: fresh pork and frozen pork, and both show change in color. Fresh pork took 3 min at a frequency and voltage of 2.45 GHz and 1.2 kHz, respectively (Frohling et al. 2012) for decontamination of *E. coli* by microwave-powered plasma. While frozen pork took 2 min at a frequency and voltage of 58 kHz and 20 kV, respectively (Choi, Puligundla, and Mok, 2016) for the decontamination of *L. monocyctogenes* by corona discharge plasma. Pulsed discharge plasma is used to decontaminates of *Psychrobacter glacincola* from salmon at a frequency and voltage of 16 kHz and 11 kV, respectively, for 1 min (Zhang et al., 2019). A few types of microorganisms such as *Psychrobacter glacincola*, *Brochothrix thermosphaeta*, *Pseudomonas fragi* are mainly found in sea food. Sea food the most heavily contaminated food presents in the market. Decontamination of fish is not arduous; it takes significantly less time for decontamination under the same processing condition. It took 1 min at a frequency and voltage of 16 kHz and 11 kV, respectively, for the decontamination of *Psychrobacter glacincola*, *Brochothrix thermosphaeta*, *Pseudomonas fragi* (Zhang et al., 2019).

### 4.5. Seeds

The process of seed decontamination is done for reducing microorganism that infest the seed surface and tissue or to attack early seedling. A fine seed treatment should be safe for the seed, last for a long time before planting, and tolerate the treatment without leaving hazardous or undesirable residues (Spadaro and Gullino, 2005). Seed sterilization methods include bleach, ethylene oxide, fungicides hot water, aerated steam, etc. All of these techniques can result in a considerable decrease in seed germination. Cold plasma performs at low temperatures, it can decontaminate complex surface structures, it has no chemical toxicity, quick processing time and uniform treatment without destroying seeds (Dhayal, Lee, and Park, 2006). Plasma therapy enhanced plant growth, encouraged normal and healthy physiological performance, and increased plant yield. The utilization of this technique to sterilize seeds before planting might reduce the usage of agrochemicals throughout the crop cycle (Pérez-Pizá et al., 2019). Cold plasma can be used to alter the genes at the transcriptional level through which plant mutation and seed priming can be improved (Jranbaksh et al., 2020). Cold plasma can be used to adjust wettability of plants. This can increase seed germination as germination is dependent on the effect of plasma on seed surface and water absorption (Bormashenko et al., 2015) (Table 4).

Cold plasma has been shown to be safe for use in germination enhancement, production rate, plant growth and other quality of seeds (Pérez-Pizá et al., 2019). It has been observed that seeds require less time for plasma processing compared with that of whole fruits and vegetables. Plasma flow rate and power requirement for the processing condition is also less. Atmospheric plasma can perform decontamination without damaging the DNA (Shapira, Bormashenko, and Drori, 2019). *E. coli, Alternaria brassicicola, Solanum lycopersicum* are one of the most common contamination observed on the surface of seeds. Seeds were selected randomly and processed with a slight modification in the conditions to obtain the favorable condition. To avoid direct contact, seeds are inserted between the two electrodes coated with a 2 mm glass dielectric, then the current is applied at different voltage and frequency under the process condition (Varilla, Marcone, and Annor, 2020) as given in the Table 5.

### 4.6. Liquids products

Sterilization and pasteurization is used conventionally to ensure microbial safety in liquid product (Ozen and Singh, 2020). These process have shown good results, but they could cause quality reduction (Gonzalez and Barrett, 2010). Thermal processing can produce a variety of physical and chemical changes and can reduce nutritional bioavailability (Petruzzi et al., 2017). Non-thermal processing like cold plasma can be used to preserve nutritional and physical properties. Color change in food is an important factor for consumers’ preference. Chemical reactions are responsible for the original color appearance of food, thus any change in color indicates the impact of processing conditions (Barba, Esteve, and Frigola, 2012). Industry uses this factor for quality control since it is the first thing that appears to show a change in nutritional value during food processing. Plasma treatment had no or minor effect on the color of the apple, orange, grape and pomegranate juices (Almeida et al., 2015; Kovacevic, Danjela, & Kljusuric, 2016; Liao et al., 2018; Wang et al., 2018; Pankaj et al., 2017) (Table 6).

The contaminants on the surface of solid food products can be
studies have taken place by improving the geometry. However, large
the protein present in milk (Sharma et al., 2013). Therefore, decontamination of solid surfaces is easier to
execute (Kim et al., 2014). Cold plasma has also shown enhancement of
microorganisms present on surface of Seeds by cold plasma.

### Table 4
Processing condition for inactivation of microorganisms present on surface of Animal product by cold plasma.

| Food Product | Type of Plasma | Processing Condition | Microorganisms                                             | Changes                                | References |
|--------------|----------------|----------------------|------------------------------------------------------------|----------------------------------------|------------|
| Chicken skin| Cold plasma jet| 30–180 s, 1 MHz, 2–3 kV, 2 min | Campylobacter jejuni                                        | No change                             | (Rossow, Ludewig, and Braun, 2018) |
| Chicken thigh| Pulsed gas plasma discharge | 30 kHz, 0.15 W/cm², 100 s | L. monocytogenes                                           | No change                             | (Thammaniphit et al., 2020)       |
| Egg shells   | HVACP          | 85 kV, 60 Hz, 5 to 15 min | Salmonella enteritidis, Salmonella enterica serovar Typhimurium | No change                             | (Wan et al., 2017)               |
| Egg shells   | Cold nitrogen plasma | 400 W, 20 min | Salmonella enteritidis and Salmonella typhimurium | Shelf life increased up to 14 days    | (Cui et al., 2016) |
| Fresh Pork   | Microwave-powered plasma | 2.45 GHz | E. coli O157:H7 | Little change in colour | (Frohling et al., 2012) |
| Frozen pork  | Microwave-powered plasma | 2.45 GHz | L. monocyogenes | No change | (Choi, Puligandla, and Mok, 2016) |
| Pork Loin    | DBD            | 3 kV, 30 kHz, 5–10 min | L. monocytogenes                                           | No change                             | (Patange et al., 2017)         |
| Lamb meat    | DBD            | 80 kV, 50 Hz, 5 min | L. monocytogenes                                           | No change                             | (Kim et al., 2013)            |
| Beef jerky   | RF plasma      | 200 W, 0–10 min     | Staphylococcus aureus                                      | No change                             | (Kim et al., 2014)            |
| Beef loin    | DBD            | 9 kHz, 29.9 W       | Staphylococcus aureus                                      | No change                             | (Bauer et al., 2017)          |
| Ground pork  | Plasma jet     | 7 kV, 25 kHz, 600 W, 60 min | NA                                                        | No change                             | (Lee et al., 2018)            |
| Ham          | CAP            | 13.56 MHz, 150 W, 2 min | L. monocytogenes                                           | No change                             | (Song et al., 2009)           |
| Bacon        | DBD            | 13.56 MHz, 125 W, 1.5 min | L. monocytogenes KCTC3590, E. coli KCTC17682, Salmonella typhimurium KCTC 1925 | No change | (Kim et al., 2011) |
| Bresaola     | Atmospheric temperature plasma | 15–62 W, 1 min | L. innocua                                                | No change                             | (Red et al., 2012)            |
| Salmon       | Pulsed discharge plasma | 16 kHz, 11 kHz, 1 min | Brochothrix thermoplastic, Pseudomonas fragi, Psychrobacter glaciecola | No change | (Zhang et al., 2019) |
| Dried squid shreds | Corona discharge | 58 kHz, 20 kHz, 3 min | Staphylococcus maris vibrio                               | No change                             | (Adhikari et al., 2020) |

Table 5
Processing condition for inactivation of microorganisms present on surface of Seeds by cold plasma.

| Food Product | Type of Plasma | Processing Condition | Microorganisms                                             | Changes                                | References |
|--------------|----------------|----------------------|------------------------------------------------------------|----------------------------------------|------------|
| Cumin seeds  | DBD            | 50 Hz, 2 kHz, 59 mA, 3 min | NA                                                        | Seed germination enhanced             | (Shahskamthali, Sharanyakanth, & Radhakrishnan, 2020) |
| Mung bean seeds | NA             | 5 kHz, 10 kHz, 20 min | E. coli                                                  | Reduction in E.coli                | (Darmanin et al., 2020) |
| Soybean seeds | DBD            | 25 kHz, 5 kHz, 3 min | NA                                                        | Production rate increase              | (Pérez-Piña et al., 2019) |
| Hemp seeds   | DBD            | 8 kHz, 13 kHz, 80 W | NA                                                        | Improved plant early growth           | (Irbakbkhah et al., 2020) |
| Radish seeds | Corona discharge plasma | 7 kHz, 1 kHz, 15 min | Alternaria Brassicola                                      | Surface wettablity and germination increase | (Thammaniphit et al., 2020) |
| Pea seeds    | DBD            | 35 W, 10 min         | NA                                                        | Seedling growth improvement           | (Gao et al., 2019)          |
| Pumpkin seeds | Cold plasma jet | 8 kHz, 6 kHz, 27 min | NA                                                        | Germination accelerated, seed growth improvement | (Volkov et al., 2019) |
| Tomato seeds | Cold plasma jet | 83 kHz, 0.63 kHz, 77 mA, 10 min | Solanum lycopersicum                                     | NA                                    | (Adhikari et al., 2020) |

inactivated easily. However, for food products in liquid form, the plasma
has to be dipped inside the liquid to ensure thorough contact of cold
plasma with the microorganisms. Since cold plasma is dipped inside the solution, the setup of the decontamination of liquid becomes complex. Essentially, it is similar to creating a lightning inside the water or any other liquid. Therefore, decontamination of solid surfaces is easier to execute (Kim et al., 2014). Cold plasma has also shown enhancement of the protein present in milk (Sharma & Singh, 2020). Recently, numerous studies have taken place by improving the geometry. However, large scale disinfection of liquid requires further research (Foster et al., 2018).

5. Changes in food products after cold plasma

5.1. Nutritional value

Sterilizing and maintaining the true nutritional value of food have been a significant source of concern for the food industry. A disinfection technology’s goal is not only decontamination pathogen, but also shelf-life extension while preserving nutritional quality of food. In last decade, people have grown skeptical about the nutritional value of food available in the market (O’Beirne et al., 2014; Sagdic, Ozturk, & Tornuk, 2013). For food industries, cold plasma is a novel technology and a method to perform decontamination to obtain sterilized food without changing the nutritional value.

Vitamins are significantly sensitive and crucial substance for a healthy body. Therefore, it is essential to prevent a change in the vitamin value of the plasma processed food. Cold plasma is a technique which can fulfill that demand for the food industries. Many of previous work focuses on the impact of cold plasma on vitamin C. During plasma therapy with orange juice, a drop in vitamin is detected (Xu et al., 2017) as mentioned in Table 5. Riboflavin (B2), pyridoxine (B6), and biotin are some vitamins that are found stable. In this case, processing condition of
cold plasma can be increased to its limits because the stable vitamins will not be affected during the process. There are a few unstable vitamins such as vitamin – A, C & E and Thiamin (B1) which can be easily altered (Dionisio, Gomes, and Oetterer, 2009). Therefore, it is essential to maintain the processing condition at minimum to ensure that nutritional quality of the food product remains unchanged.

Proteins help to build muscles in the body which makes it necessary to maintain the protein value of the food after plasma treatment. Change in protein value by the effect of cold plasma is rarely seen after the process. It has been observed that the processing condition and time of the plasma processing has to be considerably high to obtain a change in the protein content of the food product. Cold plasma reduced the amount of immobilized water in the protein–dense myofibril network (Amini, Ghorannevis, and Abdijadid, 2017).

Carbohydrates are consumed to provide energy to the body. Carbohydrates define the quality of the food products. Cold plasma treatment resulted in reducing all sugar-related compounds, such as glucose and fructose, as well as non-reducible sucrose (Rodríguez et al., 2017). Cold plasma processing of prebiotic orange juice resulted in a decrease in carbohydrates could cause obesity. Hence, decreasing the in the content of carbohydrates might be considered advantageous.

### 5.2. Color

Cold food plasma processing can lead to color changes in food items. This has been experimentally verified by several studies. Changes in food color was because of chemical reactions due to the availability of noble gas and existence of pigments like chlorophyll or anthocyanin (Ramazzina et al., 2015). Color changes in food vary in different situation with cold plasma treatment condition, such as product category, input voltage, time, energy, gas flow input and conditions of storage are some of the key factors color change. A few studies have reported loss of color after a longer treatment time (Lacombe et al., 2015). However, the color of fruit juices are the least affected and can only be observed by trained eyes (Bursac Kovacević, Putnik, et al., 2016; Xu et al., 2017). According to various researchers, CP treatments of strawberries, apples, kiwifruit, cherry tomatoes, cabbage, and carrots resulted in no noticeable color loss. (Misra & Patil, 2014; Niemira and Sites, 2008; Ramazzina et al., 2015). The total color modification after CP treatment of fruit juices was found to be negligible and undetectable with the naked eye (Bursac Kovacević, Putnik, et al., 2016; Xu et al., 2017). These results have shown cold plasma processing has no or minimum effect on the color. The change in food color after treatment should be minimal because if the food appears unattractive, the consumers might not buy it.

### 5.3. Texture

Texture and color of the food are the most common factors that are noticed at first sight. We cannot compromise the aesthetic value of the food available in the market. Several studies have reported a change in texture of food products after cold plasma processing. We can observe that fruits and vegetables have shown no difference after cold plasma treatment (Misra & Pankaj, 2014; Niemira and Sites, 2008; Tappi et al., 2016). Liquid products also have shown no difference after cold plasma treatment. Increased in texture in high oxygen atmosphere and ozone treatments (Wszelaki and Mitcham, 2000). When DBD is applied to blueberry it shows decrease in firmness, it becomes softer after the treatment (Lacombe et al., 2015; Sarangapani, O’Toole, Cullen, & Bourke, 2017). However, the firmness can be increased in an oxygen rich environment (Misra & Moiseev, 2014). Several studies reported a decrease in crispiness and cooking time (Lee et al., 2016; Sarangapani, O’Toole, et al., 2017; Thirumadas et al., 2016).

### 5.4. pH value

Several studies have reported that liquid products show a significant reduction in ph. It is observed that products with a high percentage of water are prone to reduction in pH (Lee et al., 2016). Furthermore, DBD treatment of pork loin also reported a reduction in pH (Kim et al., 2013). The association of plasma reactive gases, which create radicals, with moisture found in food products causes the pH to change during plasma operation. Plasma species react with the surface water on solid food products which results in decontamination of the surface only, whereas in liquid products, it reacts and produces radicals with the compound present in the solution. However, numerous studies have reported no change in pH of the food product after plasma treatment (Wan et al., 2017; Xu et al., 2017).

| Food Product          | Type of Plasma | Processing Condition | Microorganisms | Changes                           | References                  |
|-----------------------|----------------|----------------------|----------------|-----------------------------------|-----------------------------|
| Water                 | Plasma jet     | 10 Hz, 25 kV         | All the bacteria, viruses, chlorine compound and microorganisms | No change | (Foster et al., 2018) |
| Distilled water       | DBD            | 60 Hz, 186 W, 1 min | *Salmonella enterica serovar Typhimurium* LT2 | Decrease in ph. | (Mahnot et al., 2019) |
| Milk                  | DBD            | 15 Hz, 250 kHz 5 min| *E. coli* ATCC 25,922 | Decrease in ph. | (Kim et al., 2015) |
| Coconut water         | DBD            | 60 Hz, 186 W, 2 min | *Salmonella enterica serovar Typhimurium* LT2 | Decrease in ph. | (Mahnot et al., 2019) |
| Orange juice          | HVACP          | 25 ml, 60 Hz, 90 kHz, 2 min | *Salmonella enterica serovar Typhimurium* | Decrease in ph., vitamin and colour | (Xu et al., 2017) |
| Apple juice           | DBD            | 30-50 W, 1 min      | *E. coli* | Change in colour, toxicity, and ph. | (Liao et al., 2018) |
| Blueberry juice       | GPSDP          | 21.3 kV, 50 Hz, 30 min | *Zygosaccharomyces rouxii* IB and 1130 | Change in colour, toxicity, and ph. | (Wang et al., 2018) |
| Grape juice           | HVACP          | 11 kV, 1000 Hz, 50 L/min, 6 min | *Bacillus sp.* | No changes | (Hou et al., 2019) |
| Pomegranate juice     | Plasma jet     | 25 kHz, 3-7 min     | *Saccharomyces cerevisiae* | Change in ph | (Pankaj et al., 2017) |

(AJP) - Atmospheric jet plasma.
(HVACP) - High Voltage Atmospheric Cold Plasma.
(GPSDP) - Gas Phase Surface Discharge Plasma.
5.5. Acidity

Characteristics of Acidity is not very different from pH. So it is observed that most of the time when there is pH changes acidity also changes. The increases in acidity following plasma treatment are mainly due to the interplay of plasma responsive gases that produce radicals with humidity. Acidity reduction observed in Blueberry by DBD treatment (Sarangapani, O’Toole, et al., 2017). However, it is important to highlight the result of studies related to change in acidity by cold plasma treatment. Sensitivity of Acidity is important for the preservation of the nutritional properties of foodstuffs.

6. Conclusion

Cold plasma has got a huge amount of attention in the food sterilization industry, in recent years. This study has demonstrated that cold plasma can be used to decontaminate surfaces by forming radicals with the components present on the surface. It is clear that cold plasma has no or minimal impact on nutritional quality, pH value, acidity, color, texture. As can be shown, cold plasma is an effective sterilization technique for inactivation of bacteria, viruses, pathogens and other harmful microorganisms. It can tolerate plasma discharges without suffering nutritional damage. However, there are a few studies which have reported a minor change in the food products after plasma processing. Further research can lead to large-scale commercial use of cold plasma sterilization. Cold plasma being an easy, safe, versatile, effective, economical and environmentally friendly method gives a good advantage over commercial decontamination methods. Cold plasma may also be used to eliminate secondary contamination during product packaging. Detailed understanding of cold plasma treatment about the change in food quality should be encouraged, supported and promoted to acknowledge its potential for large-scale decontamination of food products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to Department of Nuclear Engineering and Department of Chemical Engineering, School of Technology, Pandit Deendayal Energy University for the permission to publish this research.

Availability of data and material

All relevant data and material are presented in the main paper.

Funding

Not applicable.

Consent for publication

Not applicable.

References

Adhikari, B., et al. (2020). Cold plasma seed priming modulates growth, redox homeostasis and stress response by inducing reactive species in tomato (Solanum Lycopersicum). Free Radical Biology and Medicine, 156, 57-69. https://doi.org/10.1016/j.freeradbiomed.2020.06.003
Aggelopoulos, C. A., & Tsakiroglou, C. D. (2021). A new perspective towards in-situ cold plasma remediation of polluted sites: Direct generation of micro-discharges within contaminated medium. Chemosphere, 266(xxxx), Article 128969. https://doi.org/10.1016/j.chemosphere.2020.128969
Allemede, F. A., & A. S, et al. (2008). Role of commercial sanitizers and washing systems on epiphytic microorganisms and sensory quality of fresh-cut escarole and lettuce. Food Safety and Quality, 49(1), 155-163.
Almeida Lima, F. D., et al. (2015). Effects of atmospheric cold plasma and ozone on prophytic orange juice. Innovative Food Science and Emerging Technologies, 22, 127-135. https://doi.org/10.1016/j.ifset.2015.09.001
Alves Filho, Elenilson G., Edy S. de Brito, and Sueli Rodrigues. 2019. Advances in Cold Plasma Applications for Food Safety and Preservation Effects of Cold Plasma Processing in Food Components. Elsevier Inc. https://doi.org/10.1016/B978-0-12-814921-8.00008-6
Amini, M., Ghorannevis, M., & Abdeljadi, S. (2017). Effect of cold plasma on crocin extract and volatiles components of saffron. Food Chemistry, 235(5), 290-293. https://doi.org/10.1016/j.foodchem.2017.05.067
Ascp, M T, and David J. Weber. 1999. Concise Communications Sporicidal Activity of a New Low- Temperature Sterilization Technology. 100(July): 514-16.
Bagheri, Hadi, and Sepideh Abbaspour. 2020. Effect of Cold Plasma on Quality Retention of Fresh-Cut Produce. Journal of Food Quality 2020. Bagheri, H., Abbaspour, S., & Safari, A. (2020). Optimization of decontamination conditions for aspergillus flavus inoculated to military rations snack and physicochemical properties with atmospheric cold plasma. Journal of Food Safety, 40
Bang, I. H., Kim, Y. E., Lee, S. Y., & Min, S. C. (2020). Microbial decontamination of black peppercorn by simultaneous treatment with cold plasma and ultraviolet C. Innovative Food Science and Emerging Technologies, 63, Article 102392. https://doi.org/10.1016/j.ifset.2020.102392
Barba, F. J., Esteve, M. J., & Frigola, A. (2012). High pressure treatment effect on meat quality attributes. Journal of Food Science and Technology, 49(13), 307-322.
Basaran, P., Basaran-Akgul, N., & Oksuz, L. (2008). Elimination of aspergillus parasiticus from nut surface with low pressure cold plasma (LPCP) treatment. Food Microbiology, 25(4), 626-632.
Bauer, A., et al. (2017). The effects of atmospheric pressure cold plasma treatment on microbiological, physical-chemical and sensory characteristics of vacuum packaged beef loin. Meat Science, 128, 77-87.
Beuchat, L. R. (1996). Pathogenic microorganisms associated with fresh produce. Journal of Food Protection, 59(2), 204-216.
Beuchat, L. R. (2002). Ecological factors influencing survival and growth of human pathogens on raw fruits and vegetables. Microbes and Infection, 4(4), 413-423.
Bormashenko, E., et al. (2015). Interaction of cold radiofrequency plasma with seeds of hemp (Phascolarctos Vulgaris). Journal of Experimental Botany, 66(13), 4013-4021.
Kovačević, B., Danijela, P. P., et al. (2016). Effects of cold atmospheric gas phase plasma on anthocyanins and color in pomegranate juice. Journal of Food Chemistry, 190, 317-323. https://doi.org/10.1016/j.jfoodchem.2015.05.099
Kovačević, B., Danijela, J. G., Klužnjarć, et al. (2016). Stability of polyphenols in chokeberry juice treated with gas phase plasma. Food Chemistry, 212, 323-331.
Bute, R. K., Chand, N. A., et al. (2020). Cold plasma: Clean technology to destroy pathogenic micro-organisms. Transactions of the Indian National Academy of Engineering, 5(2), 327-331. https://doi.org/10.1007/s41403-020-00133-7
Chen, X., & Huang, Y. C. (2017). Effects of organic load, sanitizer PH and initial chlorine concentration of chlorine-based sanitizers on chlorine demand of fresh produce wash waters. Food Control, 77, 96-101. https://doi.org/10.1016/j.foodcont.2017.01.026
Chen, Z., Garcia, G., Arumugawasami, V., & Witz, R. E. (2020). Cold plasma for SARS-CoV-2 inactivation. Physics of Fluids, 2-6.
Choi, S., Puligundla, P., & Mok, C. (2016). Corona discharge plasma jet for inactivation of Escherichia Coli O157:H7 and listeria monocytogenes on irradiated pork and its impact on meat quality attributes. Annals of Microbiology, 66(2), 685-694.
Choi, S., Puligundla, P., & Mok, C. (2017). Effect of corona discharge plasma on microbial decontamination of dried squid shreds including physico-chemical and sensory evaluation. LWT – Food Science and Technology, 75, 323-328. https://doi.org/10.1016/j.lwt.2016.08.063
Clarø, T., et al. (2015). Cold-air atmospheric pressure plasma against clostridium difficile spores: A potential alternative for the decontamination of hospital inanimate surfaces. Infection Control and Hospital Epidemiology, 36(6), 742-744.
Cosu, A., et al. (2018). Fog, phenolic acids and UV-A light irradiation: A new antimicrobial treatment for decontamination of fresh produce. Food Microbiology, 76 (January), 204-208. https://doi.org/10.1016/j.fm.2018.05.013
Critzer, F. J., Kelly-Wintenberg, K., South, S. L., & Golden, D. A. (2007). Atmospheric plasma inactivation of foodborne pathogens on fresh produce surfaces. Journal of Food Protection, 70(10), 2290-2296.
Cui, H., Ma, C., Li, C., & Lin, L. (2016). Enhancing the antibacterial activity of thyme oil against salmonella on eggshell by plasma-assisted process. Food Control, 70, 183-190. https://doi.org/10.1016/j.foodcont.2016.05.056
Cui, H., Ma, C., & Lin, L. (2016). Synergetic antibacterial efficacy of cold nitrogen plasma and clove oil against Escherichia Coli O157: H7 biofilms on lettuce. Food Control, 66, 11-16. https://doi.org/10.1016/j.foodcont.2016.01.055
Cui, H., Zhao, C., & Lin, L. (2015). The specific antibacterial activity of liposome-encapsulated clove oil and its application in tofu. Food Control, 56, 128-134. https://doi.org/10.1016/j.foodcont.2015.03.026
Darmanin, Martin et al. 2020. “Generation of Plasma Functionalized Water: Antimicrobial Assessment and Impact on Seed Germination.” Food Control 113 (December 2019).
Deng, L. Z., et al. (2020). Recent advances in non-thermal decontamination technologies for microorganisms and mycotoxins in low-moisture foods. Trends in Food Science and Technology, 106(October), 104-112. https://doi.org/10.1016/j.tifs.2020.10.012
A. Ansari et al.

Kim, B., et al. (2011). Effect of atmospheric pressure plasma on inactivation of pathogens inoculated onto bacon using two different gas compositions. Food Microbiology, 28(11), 9–13. https://doi.org/10.1016/j.fm.2010.07.022

Kim, H. J., et al. (2013). Effects of dielectric barrier discharge plasma on pathogen inactivation and the physicochemical and sensory characteristics of pork loin. Current Applied Physics, 13(7), 1420–1425. https://doi.org/10.1016/j.cap.2013.04.023

Kim, H. J., et al. (2015). Microbial safety and quality attributes of milk following treatment with atmospheric pressure encapsulated dielectric barrier discharge plasma. Food Control, 47, 451–456. https://doi.org/10.1016/j.foodcont.2014.07.053

Kim, J. S., Lee, E. J., Choi, E. H., & Kim, Y. J. (2014). Inactivation of Staphylococcus Aureus on the beef jerky by radio-frequency atmospheric pressure plasma discharge treatment. Innovative Food Science and Emerging Technologies, 22, 124–130. https://doi.org/10.1016/j.ifset.2013.12.012

Kim, J. E., et al. (2017). Microbial decontamination of onion powder using microwave-powered cold plasma treatments. Food Microbiology, 62, 112–123. https://doi.org/10.1016/j.fm.2016.10.010

Klockow, P. A., & Keemmer, K. M. (2009). Safety and quality assessment of packaged spinach treated with a novel ozone-generation system. LWT - Food Science and Technology, 42(6), 1047–1053. https://doi.org/10.1016/j.lwt.2009.02.011

Kowalczyk, J., Kuzmiczek, H., & Bhowmik, A. (2010). Air plasma or UV-irradiation applied to surface modification of pectin/poly(vinyl alcohol) blends. Applied Surface Science, 257(1), 325–331

Kruk, Z. A., et al. (2011). The effect of high pressure on microbial population, meat quality and sensory characteristics of chicken breasts fillets. Food Control, 22(1), 6–12. https://doi.org/10.1016/j.foodcont.2010.06.003

Kunwar, R., Singh, H., Mangla, V., & Hiremath, R. (2013). Outbreak investigation: Salmonella food poisoning. Medical Journal Armed Forces India, 69(4), 388–391.

Lacocke, C., Beirne, D. (1999). The microbiological safety of Enterica Senorv Typhimurium. International Journal of Food Microbiology, 152(3), 175–180. https://doi.org/10.1016/j.ijfoodmicro.2011.02.038

Filipi, Arjana et al. 2020. Cold Plasma, A New Hope in the Field of Virus Inactivation. 38 (John Foster, E. M., Jr., M. S., & Blankson, I. M. 2018. Towards high throughput plasma assisted shape-shifting of a flat two-dimensional wheat xerogel and its morphological processing effects on plant cell membrane integrity and relevance to fruit and produce.)

Donegan, M., Milosavljević, N., & Park, S. U. (2006). Using low-pressure plasma for Carthamus Tinctorium L. seed surface modification. Vacuum, 80(5), 499–506.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.

Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food and related genera from different starchy foods. A. Food Science and Technology, 44(2), 247–254.
Petruzzi, L., et al. (2017). Thermal treatments for fruit and vegetable juices and Park, D. J., et al. (2008). Sterilization of microorganisms in silk fabrics by microwave- Misra, N. N., Tiwari, B. K., Raghavarao, K. S. M. S., & Cullen, P. J. (2011). Nonthermal Pankaj, S. K., Wan, Z., Colonna, W., & Keener, K. M. (2017). Effect of high voltage Niemira, B. A., & Sites, J. (2008). Cold plasma inactivates salmonella stanley and Niemira, B. A. (2012). Cold plasma decontamination of foods. Patange, A., et al. (2017). Controlling brochothrix thermosphacta as a spoilage risk using Connor, N., Milosavljevi, V., & Daniels, S. (2011). Development of a real time monitor Moisan et al., 2013. Sterilization/disinfection of medical devices using plasma: The Connor, N., Milosavljevi, V., & Daniels, S. (2011). Development of a real time monitor Patange, A., et al. (2017). Controlling brochothrix thermosphacta as a spoilage risk using...
Food Chemistry: Molecular Sciences 4 (2022) 100098

A. Ansari et al.

Tappi, S., et al. (2016). Cold plasma treatment for fresh-cut melon stabilization. Innovative Food Science and Emerging Technologies, 33, 225–233. https://doi.org/10.1016/j.ifset.2015.12.022

Thammanipit, C., Suwanannar, S., Ruangwong, K., & Srisophon, S. (2020). Effect of Cold Plasma on Alternaria Brasiiicola Morphology and Seed Germinations. 2020 6th International Electrical Engineering Congress.

Thirumadis, Rohit et al. 2016. 37 Innovative Food Science and Emerging Technologies Influence of Low Pressure Cold Plasma on Cooking and Textural Properties of Brown Rice. Elsevier B.V. https://doi.org/10.1016/j.ifset.2016.08.009.

Thirumadis, Rohit, A. Trimukhe, R. R. Deshmukh, and U. S. Annapure. 2017. 157 Carbohydrate Polymers Functional and Rheological Properties of Cold Plasma Treated Rice Starch. Elsevier Ltd. https://doi.org/10.1016/j.carbpol.2016.11.050.

Thor, R. M. S., Pendred, J., & Reynolds, D. M. (2017). Assessing the antimicrobial potential of aerosolised electrochemically activated solutions (ECAS) for reducing the microbial bio-burden on fresh food produce held under cooled or cold storage conditions. Food Microbiology, 68, 41–50. https://doi.org/10.1016/j.fm.2017.06.018

Tiwari, B. K., O’Donnell, C. P., & Cullen, P. J. (2009). Effect of non thermal processing technologies on the anthocyanin content of fruit juices. Trends in Food Science and Technology, 20(3–4), 137–145. https://doi.org/10.1016/j.tifs.2009.01.058

Trevisani, M., et al. (2017). Effects of sanitizing treatments with atmospheric cold plasma, SDS and lactic acid on verotoxin-producing Escherichia Coli and Listeria Monocytogenes in red chicory (radichio). Food Control, 78, 138–143. https://doi.org/10.1016/j.foodcont.2017.02.056

Ukuku, D. O., S. Mukhopadhyay, V. Juneja, and K. Rajkowski. 2015. 9 Handbook of ukuku, Dike O., Brendan A. Niemira, and Joseph Ukanalis. 2019. Nisin-based plasma treatment of refrigerated chicken eggs for control of salmonella enteritidis contamination on egg shell. LWT - Food Science and Technology, 76, 124–130. https://doi.org/10.1016/j.lwt.2016.10.051

Wang, R. X., et al. (2012). Atmospheric-pressure cold plasma treatment of contaminated fresh fruit and vegetable slices: Inactivation and physicochemical properties evaluation. European Physical Journal D, 66(10), 1–7.

Wang, Y., et al. (2018). Inactivation of yeast in apple juice using gas-phase surface discharge plasma treatment with a spray reactor. Lwt, 97, 530–536. https://doi.org/10.1016/j.lwt.2018.07.049

Wing, E. J., & Gregory, S. H. (2002). Listeria monocytogenes: Clinical and experimental update. Journal of Infectious Diseases, 185(SUPPL. 1), 18–24.

Won, M. Y., Lee, S. J., & Min, S. C. (2017). Mandarin preservation by microwave-powered cold plasma treatment. Innovative Food Science and Emerging Technologies, 39, 25–32. https://doi.org/10.1016/j.ifset.2016.10.021

Wrezlak, A. L., & Mitcham, E. J. (2000). Effects of superatmospheric oxygen on strawberry fruit quality and decay. Postharvest Biology and Technology, 20(2), 125–133.

Wu, T. Y., Sun, N. N., & Chau, C. F. (2018). Application of corona electrical discharge plasma on modifying the physicochemical properties of banana starch indigenous to Taiwan. Journal of Food and Drug Analysis, 26(1), 244–251. https://doi.org/10.1016/j.jfda.2017.03.005

Xu, L., Garner, A. L., Tao, B., & Keener, K. M. (2017). Microbial inactivation and quality changes in orange juice treated by high voltage atmospheric cold plasma. Food and Bioprocess Technology, 10(10), 1778–1791.

Yamada, Sumio Takefumi et al. 1993. Detection Gical Testing Escherichia of Verocytotoxin of Patients from with Stool Diarrhea and Serolo by Caused Coli • ONS • o Has Been Extensively Investigated in Europe and H7 of VTEC Has Also Been Isolated Frequently from Stools of the Patients in Outbreaks or Sporadic Diarrhea in Japan. The Most Reliable Procedure with Which to Diag Abbreviations : BSA-PBS , Bovine Serum Albumin in Urawa City , Saitama , Became Affected with over a 40- Day Period, with a Consulted with Diarrhea the Subjects for The. 37(2): 111–118

Yun, H., et al. (2010). Inactivation of listeria monocytogenes inoculated on disposable plastic tray, aluminum foil, and paper cup by atmospheric pressure plasma. Food Control, 21(8), 1182–1186. https://doi.org/10.1016/j.foodcont.2010.02.002

Zhang, Yuxiang et al. 2019. Bactericidal effect of cold plasma on microbiota of commercial fish balls. Innovative Food Science and Emerging Technologies 52 (December 2018): 394–405. 10.1016/j.ifset.2019.01.019.

Zhu, Y., Li, C., Cui, H., & Lin, L. (2020). Feasibility of cold plasma for the control of biofilms in food industry. Trends in Food Science and Technology, 99(March), 142–151. https://doi.org/10.1016/j.tifs.2020.03.001

Ziuzina, D., et al. (2016). Demonstrating the potential of industrial scale in-package atmospheric cold plasma for decontamination of cherry tomatoes. Plasma Medicine, 6 (3–4), 397–412.