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Characteristics and Applications of Cold Atmospheric Plasma – Review

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Abstract – **Cold atmospheric plasma technology is an emerging, green process offering many potential applications for packaging and preservation of food and in medical and industrial purposes. While it was originally developed to increase the surface energy of polymers, enhancing adhesion and printability, it has recently emerged as a powerful tool for surface decontamination of both foodstuffs and food packaging materials. New trends aim to develop in-package decontamination, offering non-thermal treatment of foods post-packaging. This paper provides an overview of cold plasma theory, equipment and summarises recent advances in the modification of polymeric food packaging materials along with potential applications in the food industry.**

Keywords – **Cold Atmospheric Plasma, Non-thermal Processing, Food Preservation, Mechanism, Applications.**

I. INTRODUCTION

CAP: Cold atmospheric plasma, a non-thermal plasma technology, is proposed as a potential alternative to traditional methods for decontamination of foods [1-2-3-4]. That contains reactive species, such as: electrons, positive and negative ions, free radicals, gas atoms and photons [5-6]. This technology does not require extreme process conditions and offers great opportunities for food product preservation [7-5]. The inactivation of pathogens and removal of chemical and biological contaminants has remained an area of great interest in the fields of food. An optimal decontamination process can be considered as one that is safe, fast, cost-efficient, nontoxic and nonhazardous, environmental friendly.

The technology of atmospheric plasma (ionized gas), widely used in material processing, offers one of the most significant breakthroughs in food and agri-material processing. This technology allows for the generation of bactericidal molecules very efficiently with low power requirements. Non-thermal atmospheric plasma has been used to effectively decontaminate surfaces, but it has received limited investigation for in-package decontamination [8].Over the last decade, considerable research has been conducted on atmospheric cold plasmas (ACPs) as a decontamination method [9].

There are a lot of methods to destroy these microorganisms, such as: thermal technologies, e.g. sterilization, pasteurization, etc. [10]. For the past few decades the trend of replacing traditional materials such as glass, metals and paper by polymeric materials has been growing continually within the various process industries, including the food industry. the fact that physical and chemical characteristics of polymers are on a par with conventional materials in terms of functionality. In addition, polymeric packaging materials provide greater flexibility, transparency, adequate chemical inertness, have low specific weights and typically cost less. However, in most cases polymeric surfaces are hydrophobic in nature and are often characterized by a low surface energy[11].

Since the past two decades, considerable efforts have been made by the scientific and technological community to generate, sustain and utilize ANTP because of their numerous scientific and industrial applications. Growth and importance of atmospheric cold plasma technology can be realized by the fact that the scientific and technological utilization of ANTP has multiplied by several factors and its applications have expanded into a large number of fields such as in environmental engineering, aeronautics and aerospace engineering, biomedical field, textile technology, analytical chemistry, and several other areas too[12].

II. MECHANISM OF PLASMA

In the microbial inactivation plasma process, a key role is attributed to reactive species (atomic oxygen, singlet oxygen, ozone, superoxide, hydrogen peroxide, hydroxyl radicals, nitric oxide and nitrogen dioxide) generated by electron collision. The atmospheric cold plasma treatment can effectively inactivate a wide range of microorganisms including spores and viruses, through permeabilization of the cell membrane, damage of the intracellular proteins and the nucleic acids and the inactivate of some enzymes[5].The bacterial killing occurs via three different mechanisms: (a) direct permeabilization of the cell membrane or wall, leading to leakage of cellular components, including potassium, nucleic acids and proteins; (b) critical damage of intracellular proteins from oxidative or nitrosative species and (c) direct chemical nucleic acids damage [13].The plasma generates different level of lethal effects on microorganisms through interaction with microbial surrounding environments (water, pH, nutrients, osmotic stability and temperature) [14]. CP could be employed in inactivation of the microorganisms on the surface of fresh and processed foods. The accumulation of charged particles can rupture the cell membrane. Oxidation of the lipids, amino acids and nucleic acids with reactive oxygen species and nitrogen species cause changes that lead to microbial death or injury. Contribution of mentioned mechanisms depends on plasma characteristics and on the type of microorganisms [15-16].

Cold plasma (CP) induces several chemical and physical processes within the plasma volume and on the plasma-polymer interface, which modify the surface properties. This phenomena is exploited in surface functionalization to impart selective and tune able surface energies to the packaging polymers for promoting adhesion or sometimes anti-adhesion [17]. As can be improved printability, imparting antimist properties and improving the polymer's resistance to mechanical failure. Using plasma deposition of barrier layers, the barrier properties of the packaging materials towards gases (oxygen, carbon-dioxide) and chemical solvents can be improved [18]. Gas plasma reactions also establish efficient inactivation of micro-organisms (bacterial cells, spores, yeasts and moulds) adhering to polymer surfaces within short treatment times. Packaging materials such as plastic bottles, lids and films can be rapidly sterilized using cold plasma, without adversely affecting their bulk properties or leaving any residues [19].

The plasma treatment can effectively inactivate a wide range of microorganisms, including spores and viruses. Cold plasma can be used for decontamination of products where micro-organisms are externally located. Unlike light (e.g. ultraviolet light decontamination), plasma flows around objects, which means 'shadow effects' do not occur ensuring all parts of a product are treated. For products such as cut vegetables and fresh meat, cold plasma could be used for this purpose. Cold plasma could also be used to disinfect surfaces before packaging or included as part of the packaging process. The plasma generates different level of lethal effects on microorganisms through interaction with microbial surrounding environments "water, pH, nutrients, osmotic stability and temperature" [20]. The bacterial killing occurs via three different mechanisms: (a) direct permeabilization of the cell membrane or wall, leading to leakage of cellular components, including potassium, nucleic acids and proteins; (b) critical damage of intracellular proteins from oxidative or nitrosative species and (c) direct chemical nucleic acids damage [21].

III. PLASMA CHARACTERISTICS

Plasma, a quasi-neutral gas, is considered to be the fourth state of matter, following the more familiar states of solid, liquid & gas and constitutes more than 99% matter of the universe. It is more or less an electrified gas with a chemically reactive media that consists of a large number of different species such as electrons, positive and negative ions, free radicals, gas atoms and molecules in the ground or any higher state of any form of excited species It can exist over an extremely wide range of temperature and pressure. It can be produced at low-pressure or atmospheric pressure by coupling energy to a gaseous medium by several means such as mechanical, thermal, chemical, radiant, nuclear, or by applying a voltage, or by injecting electromagnetic waves and also by a combination of these to dissociate the gaseous component molecules into a collection of ions, electrons, charge-neutral gas molecules, and other species[12].

The term "plasma" refers to a quasi-neutral ionized gas, primarily composed of photons, ions and free electrons as well as atoms in their fundamental or excited states with a net neutral charge. Plasma discharges are widely used for processing and are indispensable for many technological applications [22]. Through their wide variety of operational conditions, plasma sources offer a tremendous freedom in the generation of radiation and the creation of chemical compositions. As a result the field of technological and industrial plasma applications is expanding strongly. Several plasma applications have been identified in literature: high-efficiency light sources (the rich plasma UV source for surface sterilization), material processing, such as deposition, cleaning and surface modification [23]. Spectrochemical analysis (analytical chemistry e plasma spectral emission can be used for element detection with very low detection limits, waste treatment (e.g. detoxification e use of thermal plasma torches, cascaded arc plasmas, or microwave plasmas for the production of negative ions) [6]. Plasma is an effective, economical, environmentally safe method for critical cleaning. The vacuum ultraviolet (VUV) energy is very effective in the breaking most organic bonds (i.e., CeH, CeC, CeC, CeO, and CeN) of surface contaminants. This helps to break apart high molecular weight contaminants [24].

Electrons trajectory is spiral vertically along the magnetic field lines. Magnetic field strength is 875 Gauss with a dome shaped contour. The electrode which holds food packaging could be a RF power supplied and is used to generate direct current (DC) bias independently of plasma ionisation. In ECR electrons travel far enough to gain sufficient energy to strike gas molecules and cause ionisation. Electron density (ion flux) is over an order of magnitude higher than for CCP or ICP plasma tools, and therefore may be more efficient for surface treatments of packaging, i.e. surface functionalisation, surface cleaning, etching, and/or surface deposition [6].

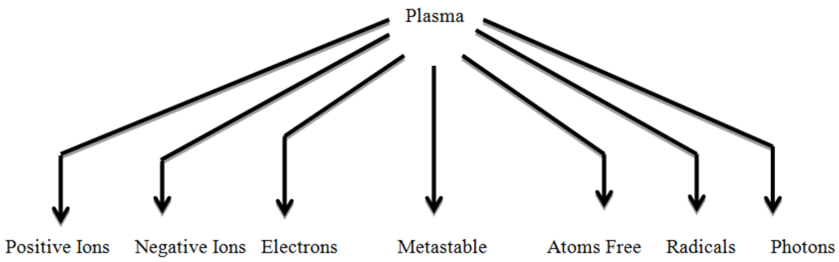

Fig. 1. Constituents of plasma [12].

The chemistry which takes place in a plasma is usually quite complex and involves a large number of elementary reactions. The main types of reactions occurring in volume plasma are divided into homogenous and heterogenous reactions. Homogenous reactions occur between species in the gaseous phase as a result of inelastic collisions between electrons and heavy species or collisions between heavy species; whereas, heterogenous reactions occur between the plasma species and the solid surface immersed or in contact with the plasma. These typical reactions have been listed in table 1 and 2. The heterogenous reactions are particularly important in the processing of semiconductor materials.[12].

Table 1: Gas phase reactions involving electrons and heavy species

Name	Reactions	Description
Excitation of atoms ormolecules	$e+A_2\rightarrow A_{2+}e$ $e+A\rightarrow A_{+}e$	Leads to electronically excited state of atoms and molecules by energetic electron impact.
De-excitation	$e+A_2\rightarrow A_{2+}e+hv$	Electronically excited state emits electromagnetic radiations on returning to the ground state.
Ionization	$e+A_2\rightarrow A_2^++e$	Energetic electrons ionize neutral species through electron detachment and positively charged particles are formed.
Dissociation	$e+A_2\rightarrow 2A_{+}e$	Inelastic electron impact with a molecule causes its dissociation without ions.
Dissociative attachment	$e+A_2\rightarrow A^++A+e$	Negative ions are formed when free electrons attach themselves to neutral species.
Dissociative ionization	$e+A_2\rightarrow A+e$	Negative ions can also be produced by dissociative ionization reactions.
Volume recombination	$e+A+B\rightarrow A+B$	Loss of charged particles from the plasma by recombination of opposite charges.
Penning dissociation	$M+A_2\rightarrow 2A+M$	Collision of energetic metastable species with neutral leads to ionization dissociation.
Penning ionization	$M+A\rightarrow A^++M+e$	
Charge exchange	$A^++B\rightarrow B^++A$	Transfer of charge from incident ion to the target neutral between two identical or dissimilar partners.
Recombination of ions	$A^-+B^+\rightarrow AB$	Two colliding ions recombine to form a molecule.
Electron–Ion recombination	$e+A^+{}_2+M\rightarrow A_2+M$	Charge particles are lost from the plasma by recombination of opposite charges.
Ion-ion recombination	$A^++B^-+M\rightarrow AB+M$	Ion-ion recombination can take place through three body collisions.

Table 2: Surface reactions

Name	Reactions	Description
Etching	$AB+C_{solid}\rightarrow A+BC_{vapour}$	Material erosion.
Adsorption	$M_g+S\rightarrow M_s$ $R_g+S\rightarrow R_s$	Molecules or radicals from a plasma come in contact with a surface exposed to the plasma and are adsorbed on surfaces.
Deposition	$AB\rightarrow A+Bsolid$	Thin film formation.
Recombination	$S-A+A\rightarrow S+A_2$ $S-R+R_1\rightarrow S+M$	Atoms or radicals from the plasma can react with the species already adsorbed on the surface to combine and form a compound.
Metastable de-excitation	$S+A\rightarrow A$	Excited species on collision with a solid surface return to the ground state.
Sputtering	$S-B+A^2\rightarrow S^2+B+A$	Positive ions accelerated from the plasma towards the surface with sufficient energy can remove an atom from the surface.
Polymerization	$R_g+R_s\rightarrow P$ $M_g+R_s\rightarrow P_s$	Radicals in the plasma can react with radicals adsorbed on the surface and form polymers.

IV. APPLICATIONS OF ATMOSPHERIC COLD PLASMA

Table 3: Applications of Atmospheric Cold Plasma in various industries

NO.	Application	References
1	Food industry	[7-25-26-6-4]
2	Medical and clinical	[27-28-29-30-24]
3	Materials processing	[23-31]
4	Material analysis	[31]
5	Surface modification	[23-31-6]
6	Light source	[24-31]
7	Microplasma chip	[31]
8	Decontamination of foods	[32]
9	Decontamination of fresh produce	[33-34]
10	Treat a variety of vegetables: fresh tomatoes	[35-36- 6]
11	Decontamination of cucumbers and broccoli. The tomatoes and the lettuce were easier to decontaminate than the carrots, probably because of the surface structure	[35]
12	ACP is used to reduce the microorganisms on strawberries	[36]
13	Apples, melons and mango. ACP can successfully decontaminate of the fresh meat and poultry and cheese.	[25]
14	ACP it is able to control the microorganisms in the cereal industry.	[25-37]
15	Inactivate enzymes from fruit or vegetable sources.	[6]
16	ACP is a powerful tool for surface decontamination of not only foods but also food packaging materials	[6-26]
17	ACP technology can be combined with the essential oil (e.g. clove oil) to decontaminate the cellulose-based food packaging.	[38]
18	Inhibition of bacteria, treatment of tooth decay and composite fillings and tooth whitening.	[39]
19	CP has been applied in the food industry including for decontamination of raw agricultural products (apple, lettuce, almond, mangoes and melon), egg surface and real food system (cooked meat, cheese)	[40]
20	using Cold atmospheric plasma in cancer therapy	[41]

V. CONCLUSIONS

The atmospheric cold plasma, by far, is one of the newest technologies used in food industry for microbial inactivation and for medical and industrial purposes. It has many interesting applications in the food industry: decontamination, especially of fruits and vegetables, spice, nuts, raw and meat products, cheese, or decontamination of the food packaging materials and newer, can be combined with some antimicrobial agents such as essential oils. This technology is considered to be a very promising alternative to thermal new processing technologies. However, more information's are needed to clarify the microbial inactivation mechanisms and to confirm that no harmful by-products are generated by atmospheric cold plasma treatment.

REFERENCES

[1] Bárdos L., Baránková H. Cold atmospheric plasma: Sources, processes, and applications, Thin Solid Films, 518, 2010,pp, 6705–6713.

[2] Niemira B.A. Cold Plasma Decontamination of Foods, Annual Review of Food Science and Technology, 3, 2012,pp, 125-142.

[3] Afshari R., Hosseini H. Non-thermal plasma as a new food preservation method, Its present and future prospect, Journal of Paramedical Sciences, 5(1), 2014,pp, 116-120.

[4] Ziuzina D., Patil S., Cullen P.J., Keener K.M., Bourke P. Atmospheric cold plasma inactivation of Escherichia coli, Salmonella enterica serovar Typhimurium and Listeria monocytogenes inoculated on fresh produce, Food Microbiology, 42, 2014,pp, 109-116.

[5] Stoica, Maricica, Petru Alexe, and Liliana Mihalcea. Atmospheric Cold Plasma as new Strategy for Foods Processing-An Overview. Innovative Romanian Food Biotechnology 15, 2014,pp 1-8.

[6] Pankaj S.K., Bueno-Ferrer C., Misra N.N., Milosavljevi V., O'Donnell C.P., Bourke P., Keener K.M., Cullen P.J. Applications of cold plasma technology in food packaging, Trends in Food Science & Technology, 35 (1), 2014,pp, 5-17.

[7] Fernández A., Shearer N., Wilson D.R., Thompson A. Effect of microbial loading on the efficiency of cold atmospheric gas plasma inactivation of Salmonella enterica serovar Typhimurium, International Journal of Food Microbiology, 152 (3), 2012,pp, 175–180.

[8] Misra.N.N, Ziuzina D., Cullen P. J., Keener K.M.Characterization of a Novel Atmospheric Air Cold Plasma System for Treatment of Biomaterials. American Society of Agricultural and Biological Engineers Vol. 56(3), 2013,pp, 1011-1016.

[9] Laroussi, M. Nonthermal decontamination of biological media by atmospheric-pressure plasmas: Review, analysis, and prospects. IEEE Trans. Plasma Sci. 30(4), 2003,pp, 1409-1415.

[10] Afshari R., Hosseini H. Non-thermal plasma as a new food preservation method, Its present and future prospect, Journal of Paramedical Sciences, 5(1), 2014, pp, 116-120

[11] Vesel, A., & Mozetic, M. Surface modification and ageing of PMMA polymer by oxygen plasma treatment. Vacuum, 86, 2012,pp, 634- 637.

[12] Nehra, V., Kumar, A., & Dwivedi, H. K. Atmospheric non-thermal plasma sources. International Journal of Engineering, 2(1), 2008,pp, 53-68.

[13] Mai-Prochnow, A., Murphy, A. B., McLean, K. M., Kong, M. G., & Ostrikov, K. K. Atmospheric pressure plasmas: infection control and bacterial responses. International journal of antimicrobial agents, 43(6),2014,pp,508-517.

[14] Ryu, Y. H., Kim, Y. H., Lee, J. Y., Shim, G. B., Uhm, H. S., Park, G., & Choi, E. H. Effects of background fluid on the efficiency of inactivating yeast with non-thermal atmospheric pressure plasma. PLoS 1, 8(6), 2013, e66231.

[15] Mendis, D. A., Rosenberg, M., & Azam, F. A note on the possible electrostatic disruption of bacteria. IEEE transactions on plasma science,28(4), 2000. pp 1304-1306.

[16] Laroussi, M., & Leipold, F. Evaluation of the roles of reactive species, heat, and UV radiation in the inactivation of bacterial cells by air plasmas at atmospheric pressure. International Journal of Mass Spectrometry, 233(1), 2004,pp, 81-86.

[17] Poncin-Epaillard, F., Brosse, J. C., & Falher, T. Reactivity of surface groups formed onto a plasma treated poly (propylene) film. Macromolecular Chemistry and Physics, 200(5), 1999,pp, 989-996.

[18] Schneider, J., Akbar, M. I., Dutroncy, J., Kiesler, D., Leins, M., Schulz, A., ... & Stroth, U. Silicon oxide barrier coatings deposited on polymer materials for applications in food packaging industry. Plasma Processes and Polymers, 6(S1), 2009,pp,700-704.

[19] Muranyi, P., Wunderlich, J., & Heise, M. Sterilization efficiency of a cascaded dielectric barrier discharge. Journal of applied microbiology,103(5), 2007,pp,1535-1544.

[20] Ryu Y-H., Kim Y-H., Lee J-Y., Shim G-B., Uhm H-S., Park G., Choi E.H. Effects of Background Fluid on the Efficiency of Inactivating Yeast with Non-Thermal Atmospheric Pressure Plasma, PLoS ONE, 8(6), 2013, e66231.

[21] Mai-Prochnow A., Murphy A.B., McLean M., Kong M.G., Ostrikov K. Atmospheric pressure plasmas: Infection control and bacterial responses, International Journal of Antimicrobial Agents, 43 (6), 2014,pp, 508–517.

[22] Milosavljević, V., S. K. Karkari, and A. R. Ellingboe. "Characterization of the pulse plasma source." Plasma Sources Science and Technology 16. 2007,pp,304.

[23] Law VJ, O'Neill FT, Twomey B, Milosavljevi V, Kong MG, Anghel SD, Dowling DP. Electrical power dissipation within a helium APPJ flowing afterglow and its impact on spatial-temporal properties. IEEE Transitions on plasma science. 40(11) 2012, pp, 2994-3002.

[24] Donegan, Mick, Vladimir Milosavljević, and Denis P. Dowling. "Activation of PET using an RF atmospheric plasma system." Plasma Chemistry and Plasma Processing 33,5, 2013, pp, 941-957.

[25] Shakila Banu M., Sasikala P., Dhanapal A., Kavitha V., Yazhini G., Rajamani L. Cold plasma as a novel food processing technology, International Journal of Emerging trends in Engineering and Development, 4 (2), 2012,pp, 803-818.

[26] Surowsky, B., Fischer, A., Schlueter, O., & Knorr, D. Cold plasma effects on enzyme activity in a model food system. Innovative Food Science & Emerging Technologies, 19, 2013,pp, 146-152.

[27] Terrier O., Essere B., Yver M., Barthélémy M., Bouscambert-Duchamp M., Kurtz P., VanMechelen D., Morfin F, Billaud G., Ferraris O., Lina B., RosaCalatrava M., Moules V. Cold oxygen plasma technology efficiency against different airborne respiratory viruses, Journal of Clinical Virology, 45 (2), 2009,pp, 119–124.

[28] Isbary G., Stolz W., Shimizu T., Monetti R., Bunk W., Schmidt H.-U., Morfill G.E., Klämpfl T.G., Steffes B., Thomas H.M., Heinlin J., Karrer S., Landthaler M., Zimmermann J.L. Cold atmospheric argon plasma treatment may accelerate wound healing in chronic wounds: Results of an open retrospective randomized controlled study in vivo, Clinical Plasma Medicine, 1 (2), 2013,pp, 25 30.

[29] Hoffmann, Clotilde, Carlos Berganza, and John Zhang. "Cold Atmospheric Plasma: methods of production and application in dentistry and oncology."Medical gas research 3(21), 2013,pp1-5.

[30] Arora V., Nikhil V., Suri N.K., Arora P. Cold Atmospheric Plasma (CAP) in Dentistry, Dentistry, 4 (1), 2014,pp, 189-193.

[31] Sato R., Yasumatsu D., Kumagai S., Takeda K., Hori M., Sasaki M. An atmospheric pressure inductively coupled microplasma source of vacuum ultraviolet light, Sensors and Actuators A: Physical, 215 (15), 2014,pp, 144–149.

[32] Misra N.N., Patil S., Moiseev T., Bourke P., Mosnier J.P., Keener K.M., Cullen P.J. In package atmospheric pressure cold plasma treatment of strawberries, Journal of Food Engineering, 125, 2014b,pp, 131–138.

[33] Kabir Jahid I., Han N., Ha S.D. Inactivation kinetics of cold oxygen plasma depend on incubation conditions of Aeromonas hydrophila biofilm on lettuce, Food Research International, 55, 2014,pp, 181–189.

[34] Ziuzina D., Patil S., Cullen P.J., Keener K.M., Bourke P. Atmospheric cold plasma inactivation of Escherichia coli, Salmonella enterica serovar Typhimurium and Listeria monocytogenes inoculated on fresh produce, Food Microbiology, 42, 2014,pp, 109-116.

[35] Bermúdez-Aguirre D., Wemlinger E., Pedrow P., Barbosa-Cánovas G., Garcia-Perez M. (2013) Effect of atmospheric pressure cold plasma (APCP) on the inactivation of Escherichia coli in fresh produce, Food Control, 34 (1), 2013,pp, 149-157.

[36] Misra, Nrusimha Nath, Kevin M. Keener, Paula Bourke, Jean-Paul Mosnier, and Patrick J. Cullen. In-package atmospheric pressure cold plasma treatment of cherry tomatoes. Journal of bioscience and bioengineering 118, 2, 2014,pp, 177-182.

[37] Suhem K., Matan N., Nisoa M., Matan N. Inhibition of Aspergillus flavus on agar media and brown rice cereal bars using cold atmospheric plasma treatment, International Journal of Food Microbiology, 161, 2013,pp, 107–111.

[38] Matan, Narumol, Mudtorlep Nisoa, Nirundorn Matan, and Tanong Aewsiri. "Effect of cold atmospheric plasma on antifungal activities of clove oil and eugenol against molds on areca palm (Areca catechu) leaf sheath."International Biodeterioration & Biodegradation 86, 2014,pp, 196-201.

[39] Arora, Vipin. "Cold Atmospheric Plasma (CAP) in Dentistry. Dentistry,4(1) 2014, pp 1-5.

[40] Deng S, Ruan R, Mok CK, Huang G, Lin X, Chen P. Inactivation of Escherichia coli on almonds using nonthermal plasma. Journal of food science. 2007,72(2):M62-6.

[41] Keidar, Michael, Alex Shashurin, Olga Volotskova, Mary Ann Stepp, Priya Srinivasan, Anthony Sandler, and Barry Trink. Cold atmospheric plasma in cancer therapya). Physics of Plasmas (1994-present) 20, 2013, 057101.

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