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Review

A review on recent advances in cold plasma technology for the food industry: Current applications and future trends

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ABSTRACT

Background: Cold plasma (CP) is an emerging technology, which has attracted the attention of scientists globally. It was originally developed for ameliorating the printing and adhesion properties of polymers plus a variety of usage domains in electronics. In the last decade, its applications were extended into the food industry as a powerful tool for non-thermal processing, with diverse forms for utilization.
Scope and approach: This review presents an overview of recent studies on the application of cold plasma in the food industry. Specific areas discussed include microbial decontamination of food products, packaging material processing, functionality modification of food materials and dissipation of agro-chemical residues. The application of CP has also been expanded into areas, such as hydrogenation of edible oils, mitigation of food allergy, inactivation of anti-nutritional factors, tailoring of seed germination performance and effluent management. In addition, the paper provides a summary of plasma chemistry and sources, factors influencing plasma efficiency and strategies for augmentation. Furthermore, key areas for future research are highlighted and salient drawbacks are discussed.
Key findings and conclusions: The recent studies conducted on the interaction of reactive species with food contact surfaces establish plasma processing as an eco-friendly technique with minimal changes to food products, making it a befitting alternative to traditional techniques. Active researches focused on up-scaling for commercial applications are urgently required.

1. Introduction

Besides thermal techniques such as cooling (McDonald, Sun, & Kenny, 2000, 2001; Sun, 1997; Sun & Brosnan, 1999; Sun & Zheng, 2006; Wang & Sun, 2004; Zheng & Sun, 2004), freezing (Cheng, Sun, & Pu, 2016; Cheng, Sun, Zhu, & Zhang, 2017; Kiani, Zhang, Delgado, & Sun, 2011; Ma *et al.*, 2015; Pu, Sun, Ma, & Cheng, 2015; Xie, Sun, Xu, & Zhu, 2015; Xie, Sun, Zhu, & Pu, 2016) and drying (Delgado & Sun, 2002; Ma, Sun, Qu, & Pu, 2017; Pu & Sun, 2016, 2017; Qu *et al.*, 2017; Sun, 1999; Yang, Sun, & Cheng, 2017) that are commonly used in food processing, non-thermal processing techniques have gained their popularity in recent years for the food industry. Cold plasma (CP) technology is an emerging non-thermal food processing technique, which has attracted the attention of many researchers across the globe. CP was originally employed for ameliorating the printing and adhesion properties of polymers, increasing surface energy of materials and a variety of usage domains in electronics. It is commonly used to treat textiles, glasses, paper, and other products. A new research trend suggests that CP technology is a powerful and profitable technology for the food industry. The non-thermal technology is highly advantageous for microbial decontamination of food products including sporulating and spoilage/pathogenic organisms; owing to the ample amount of reactive oxygen species (ROS) contained in the quasi-neutral plasma gas (Butscher, Zimmermann, Schuppler, & Rudolf von Rohr, 2016; Choi, Puligundla, & Mok, 2017; Devi, Thirumdas, Sarangapani, Deshmukh, & Annapure, 2017; Jung

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et al., 2017; Min *et al.*, 2017; Patange, Boehm, Bueno-Ferrer, Cullen, & Bourke, 2017; Sohbatzadeh, Mirzanejhad, Shokri, & Nikpour, 2016). As an illustration, atmospheric plasma at 18 kV can kill *Salmonella* spp. on strawberry samples by 1.7–2.3 log CFU/sample (Ma *et al.*, 2015). Likewise, using dielectric barrier discharge (DBD) plasma at 80 kV for 5 min successfully decontaminated cherry tomatoes containing *Escherichia coli, Salmonella typhimurium,* and *Listeria monocytogenes* by up to 3.5, 3.8, and 4.2 log CFU/tomato, respectively (Ziuzina, Patil, Cullen, Keener, & Bourke, 2014). Therefore, sterilization using CP proffers low cost and minimal changes to food products, thus a befitting alternative to heat-based techniques.

CP have also been employed for the processing of packaging materials in order to improve barrier properties and bestow antimicrobial activity (Oh, Roh, & Min, 2016; Puligundla, Lee, & Mok, 2016). Other documented pathways for the utilization of CP technology in food processing includes functionality modification of food components, enhancement of seed germination performance, improved physiochemical properties of grains and degradation of agrochemical residues (Mir, Shah, & Mir, 2016; Sarangapani, O'Toole, Cullen, & Bourke, 2017a, Sarangapani, Yamuna devi *et al.*, 2017b; Sivachandiran & Khacef, 2017; Yepez & Keener, 2016). One might refute the need for another review since some reviews have already been published on the applications of CP in these specific areas. However, CP is a trending area of research with a significant number of research output in the past two years, as the technology is new and has not been fully exploited in the food industry. Thus, it is also important that consistent generalizations are made to drive the technology's awareness, point out future research needs and promote its acceptability. Interestingly, our latest literature survey also shows that CP application has recently been expanded into hydrogenation of vegetable oils to yield *trans*-free edible oils, inactivation of anti-nutritional factors, control of food allergens, *etc*. (Mohamed, Al Shariff, Ouf, & Benghanem, 2016; Yepez & Keener, 2016).

Therefore, this review summarizes recent developments in the applications of non-equilibrium plasma for the food industry. An overview of plasma chemistry and generation sources, equipment and apparatuses are first presented. Existing and novel areas for the applications of CP in the food industry, their underlying principles and mechanical pathways are then elucidated. Pre-requisites and challenges that must be subdued including future directions for research are also discussed. It is hoped that the current review will encourage early adoption of this eco-friendly technology by the food industry and food regulatory agencies; so that its full potential for industrial applications could be established.

2. Fundamentals of cold plasma technology

2.1. Plasma chemistry and sources

Plasma is the fourth state of matter, which is an ionized gas containing an array of active species, *i.e*., electrons, free radicals, ions, *etc* (Ekezie *et al.*, 2017; Dasan *et al.*, 2017). Plasma exists in either ground or its excited state, possessing a net neutral charge. It is induced under varying temperatures and pressures by energizing a neutral gas, thus being classified into thermal and non-thermal plasma. Thermal plasma requires extreme pressure levels (≥105 Pa) and up to 50 MW of power for its propagation, which is also distinguished by a thermodynamic equilibrium between the electrons and heavier species due to uniform gas temperature for all constituents (Scholtz, Pazlarova, Souskova, Khun, & Julak, 2015). Whilst, non-thermal plasma is produced at low levels of pressures and power, without a localized thermodynamic equilibrium, thus designated as non-equilibrium plasma. In general, the supplied energy disassociates the gas into a manifold of reactive species, following other reactions such as excitation, de-excitation and ionization. For the applications in the food industry, non-thermal plasma induced by electrical discharges is of primary interest due to its potential relevance in processing foods at low temperatures. Moreover, the specific method exercised during cold plasma generation determines the trajectory for application alongside magnitude and composition of reactive species. It is therefore important to first delineate the technological pathways for plasma generation, which includes those induced by atmospheric pressure and those operating under reduced pressure.

2.1.1. Plasma generated at atmospheric pressure

Contemporary innovations in plasma engineering brought about plasma sources that can operate at atmospheric pressure. They include dielectric barrier discharges (DBD), gliding arc discharge, corona discharge, and radio frequency plasma. DBD plasma is generated by an alternating current emitted when two metal electrodes are kept apart using a dielectric material such as plastic, quartz or ceramic at a discharge gap ranging from 100 mm to several centimeters. The dielectric thwarts the formation of sparks due to movement of charges. The expediencies of DBD includes relative simplicity, employment of different gases, reduced gas flow rate, flexibility owing to varying electrode geometries, and uniform discharge ignition over several meters. However, the approach requires high ignition voltages of 10 kV, therefore adequate precautionary measures are required. Typical areas of applications include ozone generation, ultraviolet (UV) generation in excimer lamps and CO_2 lasers.

Gliding arc discharges (GAD) are created in a reactor containing two or more diverging metallic electrodes operating at a high potential difference of 9 kV and 100 mA in alfresco conditions. Generally, an inlet gas consisting of humid air is pumped into the discharge gap between the electrodes, leading to an arc formed in between the narrowest inter-electrode area, which is subsequently blown away by the inlet gas into the diverging area. Typically, GAD produces both thermal and non-thermal plasmas, depending on the conditions. This technique possesses excellent adaptability for both surface and liquid treatments and has been utilized for experimental investigations involving degradation of chemical contaminants like organic constituents, solvents and industrial wastes present in water and for bacterial decontamination.

Corona discharge plasma is a diffused route for plasma ignition that develops around sharp pointed electrodes, containing substantial electric field for expediting the ionization energy of arbitrarily produced electrons to that of milieu gas atoms or molecules (Scholtz *et al.*, 2015). It is usually generated at high voltage and occurs predominantly on one electrode. Additionally, the technique is inexpensive and simple to implement. Corona discharges have been exploited for microbial decontamination, surface treatment, electro-precipitation, *etc*., however it is restricted to non-homogeneous diminutive areas. In contrast, radio frequency plasma is usually achieved when a gas is placed within an oscillating electromagnetic field, produced by an induction coil or distinct electrodes kept outside the reactor. Analogous to microwaves, this class of plasma leverages on well-known sophistication and operates at frequencies covering Hz to MHz.

2.1.2. Plasma generated at reduced pressure

Non-thermal plasma generated under low pressure is basically delineated by microwave powered (MP) plasma, driven by electromagnetic waves at frequencies over hundreds of MHz. As opposed to electrode-based methods, microwave discharges are generated using a magnetron that supplies microwaves into a process chamber guided by a coaxial cable. The irradiation is