Trends in Food Science & Technology 64 (2017) 74–86

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: http://www.journals.elsevier.com/trends-in-food-science-and-technology

Review

Applications of cold plasma technology for microbiological safety in meat industry

N.N. Misra [a, *], Cheorun Jo [b]

[a] GTECH, Research & Development, General Mills India Private Limited, Mumbai 79, India
[b] Department of Agricultural Biotechnology, Center for Food and Bioconvergence, and Research Institute of Agriculture and Life Science, Seoul National University, Seoul 08826, South Korea

A R T I C L E I N F O

Article history:
Received 10 November 2016
Received in revised form
17 April 2017
Accepted 18 April 2017
Available online 25 April 2017

Keywords:
Plasma
Decontamination
Pasteurisation
Meat
Poultry
Hygiene
Electrical
Nonthermal
Nitrite

A B S T R A C T

Background: Elimination of microbiological contamination of meat and meat products is of paramount importance for consumer food safety. Cold plasma is a rapid, effective nonthermal technology for food applications which possesses several of the typical traits desired by the industry from a decontamination intervention to ensure food safety. The rapid microbiological inactivation achieved with cold plasma has led to an explosion of interest in this subject.

Scope and approach: This review provides a critical summary of the studies pertinent to decontamination of meat and meat products using cold plasma technology along with a summary of the mechanisms involved. In addition, the review also discusses the effects of cold plasma on quality of meat and meat products, highlights some emerging applications of plasma technology in the meat sector, and lays directions for future research.

Key findings and conclusions: Majority of the studies have demonstrated the successful application of cold plasma for decontamination of meat and meat products. With rapid on-going developments in plasma science, plasma technologies could be used to replace conventional decontamination technologies in meat industry in the near future.

1. Introduction

Over the past few decades, the food sector has experienced an increase in the demand for meat and meat products, which has resulted from a rise in the household incomes (Nam, Jo, & Lee, 2010). This is particularly true in the eastern hemisphere, where the rise is also due to globalisation and the introduction of western meat based foods into these growing markets. However, among the food sectors, meat sector has been found to be least trusted by consumers (EC, 2010) and this has been partly associated with the rising food scares (Grasso, Brunton, Lyng, Lalor, & Monahan, 2014). Food safety, in general, is an issue of concern for government authorities, industry as well as consumers. A particular challenge in decontamination of meat and meat products arises from the fact that the composition of meat not only makes it highly perishable, but also imparts very high sensitivity in terms of loss of sensory attributes, when subjected to common sterilization processes. Pathogens such as *Listeria monocytogenes*, *Escherichia coli* O157:H7, *Campylobacter jejuni* and *Salmonella* spp. can easily thrive on meat causing severe foodborne illness in consumers.

Typical food processes employed by the meat industry include freezing, cooling, dehydration, and several thermal approaches. Other common approaches include the use of hurdle technology, involving modulation of pH and water activity depressors (salts, sugars), antimicrobials, spices, and active packaging (Barbosa-Canovas, Medina-Meza, Candogan, & Bermudez-Aguirre, 2014). In thermal processing of meat, the change in food structure and loss of texture is common; additionally, lipid oxidation is a major cause of rancidity and off-flavours during subsequent storage. This is particularly the case for meats like chicken that contain significant amounts of unsaturated fatty acids. In addition, when meat is subjected to traditional thermal processing operations, the formation of undesirable process-induced compounds (e.g. polycyclic aromatic hydrocarbons (PAHs), heterocyclic amines, and N-nitroso compounds) occurs (Behsnilian, Butz, Greiner, & Lautenschlaeger, 2014). In the era of rapid spread of information, consumers are becoming increasingly concerned about the plausible health issues and cancer causing agents that they might be exposed to on

* Corresponding author.
E-mail address: misra.cftri@gmail.com (N.N. Misra).

http://dx.doi.org/10.1016/j.tifs.2017.04.005

consuming thermal processed meat products (Chiang & Quek, 2017). Although gamma irradiation is an effective solution for food decontamination, its low consumer acceptability discouraged its wide adoption among the meat processors (Hugas, Garriga, & Monfort, 2002). In addition, reports also indicate that irradiation adversely affects fatty acid profile and sensory attributes of meat, which are crucial to consumer acceptance (Barba, Santa-Maria, Herraiz, & Calvo, 2012). Finally, the use of chlorine for disinfection is being scrutinized because of toxicity issues and disinfection by-products when used in excess, besides the requirement of large quantities of water (Casani, Rouhany, & Knøchel, 2005).

In order to ensure that the growing demand for safe, high-quality meat products is successfully fulfilled, it is necessary to develop and implement advanced technologies in the meat industry, and in the food industry in general. Over the past 25 years, food scientists and engineers have largely devoted their research activities towards advancement of nonthermal processes. These developments are largely driven by the undesirable effects confederated with thermal treatments of food matrices. High pressure processing (HPP) (Barba, Terefe, Buckow, Knorr, & Orlien, 2015; Hugas et al., 2002; Hygreeva & Pandey, 2016), the use of pulsed electric fields (PEF) (Barba, Parniakov, et al., 2015; Gudmundsson & Hafsteinsson, 2001), high pressure carbon dioxide (HPCD) treatments (Ferrentino & Spilimbergo, 2011), and the use of essential oils (Jayasena & Jo, 2013) are some of the non-thermal approaches that have been well-researched for meat processing applications. HPP is in use for several years at commercial scale for the decontamination of meat products (Shigehisa, Ohmori, Saito, Taji, & Hayashi, 1991). In addition to opening the opportunity to produce significantly higher quality foods with improved safety, alternative technologies like cold plasma also allow addressing a spectrum of issues that conventional technologies cannot.

Among the non-thermal approaches, cold plasma treatment for safety and quality of meat and meat products is a very recent innovation. Plasma can be described as a gas that is at least partially ionized, and is an ensemble of a myriad of sub-atomic, and molecular entities, besides quanta of electromagnetic radiation (UV photons and visible light). Depending on the state of thermodynamic equilibrium between electrons and ions, plasmas can be classified into thermal (hot) or cold. Unlike thermal plasma, in cold plasma, the electron temperature (T_e) is much higher than the global gas temperature ($T_e \gg T_g$) and the temperature of constituting ions, which is why these are also referred to as non-equilibrium plasma. Conversely, much of the energy in cold plasma is stored in the free electrons (Scholtz, Pazlarova, Souskova, Khun, & Julak, 2015). Cold plasmas can be induced and sustained by means of an electric discharge in a gas at atmospheric or low pressures, using the corona, dielectric barrier discharge (DBD), or the gliding arc discharge configurations. In simple words, cold plasma is an ionized gas generated under atmospheric or low pressure conditions.

An important feature of non-equilibrium cold plasma is its ability to generate a unique 'one pot' cocktail of biologically active agents, such as reactive oxygen species (ROS) and reactive nitrogen species (RNS), while remaining close to ambient temperature, which enables its safe application to biological materials, including foods. The reactive species and their concentration in the plasma would vary depending on many factors, including the gas in which plasma is induced, the configuration of the plasma source, power input to the gas, duration of treatment, and the humidity levels (Moiseev et al., 2014). There are several excellent reviews and books discussing the fundamental physics and chemistry of plasma (Fridman, 2008; Kogelschatz, Eliasson, & Egli, 1997; Lieberman & Lichtenberg, 2005; Schutze et al., 1998) and the diagnostics of plasma sources (Aragón & Aguilera, 2008; Reuter, Sousa, Stancu, & Hubertus van Helden, 2015).

Several recent studies have demonstrated the potential of cold plasma technology as a novel intervention for ensuring meat safety, including pork (Fröhling et al., 2012; Kim, Yong, Park, Choe, & Jo, 2013), chicken (Dirks et al., 2012; Lee et al., 2011), and beef (Kim, Lee, Choi, & Kim, 2014). This is due to the ability of cold plasma to effectively inactivate a broad range of micro-organisms, including spores (Patil et al., 2014), biofilms (Jahid, Han, & Ha, 2014; Niemira, Boyd, & Sites, 2014) and even some viruses (Bae, Park, Choe, & Ha, 2015; Puligundla & Mok, 2016) in an array of foods. One can appreciate this from some of the recent reviews describing the cold plasma led inactivation of food-borne pathogens (Misra, Tiwari, Raghavarao, & Cullen, 2011; Niemira, 2012; Shaw, Shama, & Iza, 2015; Surowsky, Schlüter, & Knorr, 2014) and decontamination, in general (Moreau, Orange, & Feuilloley, 2008; Scholtz et al., 2015). In addition, a detailed account of the fundamentals and applications of cold plasma technology in food and agricultural sciences is available in a recent book (Misra, Schlüter, & Cullen, 2016).

In this review, we will discuss a) the decontamination mechanisms in cold plasma treatments; b) antimicrobial efficacy of cold plasma; c) quality changes in plasma treated meat; d) cold plasma applications for meat processing; and e) future trends and research needs.

2. Decontamination mechanisms in cold plasma treatments

Before delving into the mechanistic aspects of antimicrobial action of plasma and changes in food composition resulting from plasma treatments, it is important to understand the plasma chemistry in gas and liquid phases, which is quite complex, involving thousands of reactions and dozens of species; cf. Gaens and Bogaerts (2013) for a kinetic model with 1880 reactions and 84 species. Depending on the gas used, examples of reactive oxygen species (ROS) species commonly associated with antimicrobial activity and the inactivation cascades include hydrogen peroxide (H_2O_2), ozone (O_3), superoxide anion ($O_2^{\bullet -}$), hydroperoxyl ($HO_2^{\bullet}$), alkoxyl ($RO^{\bullet}$), peroxyl ($ROO^{\bullet}$), singlet oxygen ($^1O_2$), hydroxyl radical ($^{\bullet}OH$), and carbonate anion radical ($CO_3^{\bullet -}$). Likewise, examples of reactive nitrogen species (RNS) include nitric oxide ($NO^{\bullet}$), nitrogen dioxide radical ($^{\bullet}NO_2$), peroxynitrite ($ONOO^-$), peroxynitrous acid (OONOH), and alkylperoxynitrite (ROONO) (Arjunan, Sharma, & Ptasinska, 2015). In addition, several other atoms, metastables, radicals, electronically and vibrationally excited molecules, including short- and long-lived neutral reactive species, could contribute to the antimicrobial processes. For a good exposure to the details on non-equilibrium plasma chemistry of significance to biological applications, we recommend the exhaustive review by Lu et al. (2016).

In Fig. 1, we have attempted to present a summary of the mechanisms underlying plasma led inactivation of micro-organisms subjected to plasma treatments. The plasma source shown is exemplary of a dielectric barrier discharge (DBD) based plasma jet, where one can note that there are two distinct regions- the active region and the remote region. Such demarcation of the plasma is important for practical reasons; researchers employ direct (i.e. active) and indirect (i.e. remote) plasma treatments in food and bio-decontamination studies. The key difference is that within the active region, the material being treated and the micro-organisms are exposed to the electric field and the very short life time (quasi-stable) species, in addition to the usual long lived positive and negative ions of the plasma.

The ROS from plasma detrimentally interact with vital cellular biomolecules, such as DNA, proteins and enzymes in cell. ROS could potentially alter the function of biological membranes via