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Research review paper

Nonthermal plasma — A tool for decontamination and disinfection

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ABSTRACT

By definition, the nonthermal plasma (NTP) is partially ionized gas where the energy is stored mostly in the free electrons and the overall temperature remains low. NTP is widely used for many years in various applications such as low-temperature plasma chemistry, removal of gaseous pollutants, in gas-discharge lamps or surface modification. However, during the last ten years, NTP usage expanded to new biological areas of application like plasma microorganisms' inactivation, ready-to-eat food preparation, biofilm degradation or in healthcare, where it seems to be important for the treatment of cancer cells and in the initiation of apoptosis, prion inactivation, prevention of nosocomial infections or in the therapy of infected wounds. These areas are presented and documented in this paper as a review of representative publications.

Contents

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Introduction

The consumers' increasing demand for increased food quality improvement focuses mainly on lower preservative and other chemical contents. The production of minimally processed, pre-packed, ready-to-eat fruits and vegetables or salads has also increased rapidly in recent years. Prevention of food-borne infections requires permanent care starting from the acquisition of raw food materials to food consumption by consumers. A number of methods limiting microbial contamination are used in food production, based on changing the properties of foods such as water content or pH, on diverse methods of heating and on the effect of various types of radiation or high pressure. These methods provide good results in a number of cases, however, sometimes they are expensive, there is a lack of effectiveness, or they are too slow. Some methods, moreover, adversely alter food properties such as color, taste and smell, or damage their structure. Other adverse effects sometimes occur, namely a decrease of the valuable nutritive content, or even the formation of toxic by-products. The disadvantages of the methods used so far initiated a search for new approaches.

The use of nonthermal plasma (NTP) may remove some of the shortcomings mentioned. NTP which was recently tested for microorganism inactivation, ready-to-eat food preparation, or biofilm degradation, seems to be an emerging antimicrobial technology predominantly for decontaminating of infected surfaces and potentially of volumes. In healthcare, plasma treatment was applied to cancer cells and in the initiation of apoptosis, prion and other biomolecule inactivation, prevention of nosocomial infections or the therapy of infected wounds. Among the new methods for the inactivation of the undesirable micro-flora, NTP provides a sufficient effectiveness accompanied by minimized damage of exposed biomaterial, such as plant and animal tissues, and processed foods or thermo-sensitive packaging materials. So far, it appears that at least in some cases, the minimal damage of antioxidants in food and the minimized content of residues of the substances with disinfectant effect introduced into food may be expected after plasma treatment. This paper concurs the six year old review of Moreau et al. (2008), published in this journal. Since the publication of the manuscript, a number of papers have appeared including review papers in the areas of plasma decontamination (e.g., De Geyter and Morent, 2012; Misra et al., 2011; Ehlbeck et al., 2011), plasma and food system interactions (e.g., Surowsky et al., 2014b; Pankaj et al., 2014) and plasma medicine (e.g., Kong et al., 2009; Morfill et al., 2009). Recent publications also include books (Laroussi et al., 2012; Fridman and Friedman, 2013) and compendia based on congress proceedings (Hensel et al., 2012). However, the recent review summarizing and pointing out the practical applications of NTP for the food industry and biotechnology is missing. This work presents a short introduction to NTP and a review of representative publications documenting the food industry practically oriented point of view. We conclude, that this review will be the source of both the inspiration and useful information for decontamination and disinfection advances in biotechnology and also in the rapidly developing field of plasma medicine.

Plasma and its generation

Plasma is a partially or fully-ionized gas. Generally there are two types of plasma recognized, thermal and nonthermal plasma. For more details see the classical books by Loeb (1960) and Raether (1964), or the more contemporary book by Fridman and Kennedy (2004). A nice introduction into plasma physics and plasma generation is also in the book devoted to plasma medicine (Laroussi et al., 2012), or in a review paper (Tendero et al., 2006). In thermal plasma, the electrons are at nearly the same temperature as heavy particles (ions, neutral molecules and atoms), the plasma is in a local equilibrium state and its temperature reaches the values of several thousands of Kelvins. In contrast, nonthermal plasma (NTP) can be generated if most of the coupled energy is transmitted into the electrons and only their temperature reaches the high values; plenty of various plasma-chemical reactions are induced. In this case, the neutral particles and ions bear only negligible energy and stay cold. The low macroscopic temperature is the main feature of NTP and enables the treatment of thermolabile materials. NTP can be generated by electrical discharges in gases under either low or atmospheric pressure.

The discharges burning at atmospheric pressure are mostly used in presented areas, because the costly vacuum techniques are absent and the manipulation with treated object is, therefore, easier. The discharges burn most often in the atmosphere of natural or synthetic air, nitrogen, oxygen, helium, hydrogen, argon or their admixtures. Other types of atmosphere are used only rarely. NTP generated at atmospheric pressure consists of various active agents, namely UV photons, and particles as neutral or excited atoms and molecules, negative and positive ions, free radicals and free electrons. In commonly used sources, the majority of reactive species are the following:

- electronically and vibrationally excited oxygen O_2 and nitrogen N_2,
- active form of oxygen molecules and atoms (reactive oxygen species, ROS) such as atomic oxygen O, singlet oxygen $^1O_2$, superoxide anion O_2^- and ozone O_3,
- reactive nitrogen species (RNS) such as atomic nitrogen N, excited nitrogen $N_2(A)$, nitric oxide NO•,
- if humidity is present H_2O^+, OH^- anion, OH• radical or hydrogen peroxide (H_2O_2) is also generated.

However, the composition and abundance of these agents vary substantially with the type of plasma source. Moreover, it is very hard to understand the real interaction of plasma agents with the material applied on, for details see e.g., Yousfi et al. (2010, 2011). Recent extensive reviews (Graves, 2012; Kelly and Turner, 2013) describe several opinions of the plasma reactive nitrogen and oxygen species interaction with biomaterials, the physiologic processes and the possible therapeutic responses. The common electrical discharges used to generate nonthermal plasma are the corona discharge, the dielectric barrier discharge, the microwave discharge, and a special arrangement called plasma jet. A detailed description can be found in a book by Raizer (1991), in the first chapters of Laroussi et al. (2012), or in a review paper by Tendero et al. (2006). To see how the discharges look, three discharge types are schematically depicted in Fig. 1.

Corona discharge

Corona discharge is usually generated on sharp electrodes, such as tips, pitpoints, or thin wires, with imposed high voltage. The electric field of high intensities is formed close to such points and the active region of corona and plasma generation occurs. In recent years there are also frequently tested modified forms of corona-based discharges, e.g., transient spark.

Dielectric barrier discharge (DBD)

Dielectric barrier discharge (DBD) is alternating current generated discharge burning between two electrodes separated by a solid dielectric material (glass, plastic). The dielectric avoids the charge transport (i.e., current) and the discharge burns due to the electric induction