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Review

Bactericidal effect of various non-thermal plasma agents and the influence of experimental conditions in microbial inactivation: A review

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ABSTRACT

Microbial inactivation using non-thermal gas discharge at atmospheric pressure has become a subject of significant research effort in the recent years. In this paper, we reviewed the different viewpoints proposed by various researchers, and discussed the reasons for arriving at these conclusions. We summarized some general rules, and offered a proposal to study the reasons behind their conclusions by building mathematical model for prediction of principle factors. The future prospects for the application of plasma are outlined.

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1. Introduction

Non-thermal atmospheric pressure plasma is an innovative technology that has the ability to achieve enhanced gas phase chemistry without increasing the gas temperature. The most attractive features of non-thermal plasma are their low-temperature property, and high efficiency of microbial inactivation, which make them ideal for use in the application of agricultural production and food safety.

To this end, several emerging applications of non-thermal plasma, including microbial decontamination, decontamination of fresh produce and decontamination of storage containers containing seed and food, have been reported over the past decade (Baier et al., 2013; Bermudez-Aguirre, Wemlinger, Pedrow, Barbosa-Canovas, & Garcia-Perez, 2013; Deng et al., 2007; Ehlbeck et al., 2011; Eto, Ono, Ogino, & Nagatsu, 2008; Fernandez, Noriega, & Thompson, 2013; Fernandez & Thompson, 2012; Fridman et al., 2008; Galvin et al., 2013; Misra et al., 2014; Morfill, Shimizu, Steffes, & Schmidt, 2009; Ni et al., 2013; Noriega, Shama, Laca, Diaz, & Kong, 2011; Ragni et al., 2010; Schnabel et al., 2012; Spirov et al., 2013; Zhang, Oh, Cisneros-Zevallos, & Akbulut, 2013).

In principle, plasma can trigger a complex sequence of biological responses in microorganism, initiated by different plasma agents, such as UV radiation, charged particles, and reactive species. Despite the potential uses of non-thermal plasma, the exact mechanism underlying their activity is still not clear. However, future developments in the novel use of these plasma agents require a comprehensive understanding on the role of plasma agents and the mechanism underlying their interaction with microorganism. Thus far, several researchers have proposed different postulates regarding the role plasma in microbial inactivation, making the issue much more complex. Considering the diversity of thoughts and results, we believe that it is highly essential to discuss and analyze the reasons behind their conclusions, despite adopting similar experimental conditions.

It is well known that the interaction mechanisms depend on the way the plasma is generated and the way it is delivered (Shimizu et al., 2008; Stoffels et al., 2006). Therefore, in this paper, we reviewed the different viewpoints concerning the effects of the various plasma-generating agents on the microorganism under different experimental conditions. We also analyzed the different conclusions proposed by different researchers, of which the generality rules are summarized considering the influence of different experimental conditions. These rules could probably be helpful for mechanism research and further development in the use of non-thermal plasma-based approaches in agricultural production and food safety.

2. Principal factors influencing the microbial inactivation effect

Microbial inactivation by plasma is usually affected by several factors. This section presents discussions on the principal factors that influence microbial inactivation and their contributions to the inactivation effect. In the following sections, two types of factors, namely, plasma agents and experimental conditions will be reviewed.

2.1. Plasma agents

2.1.1. UV radiation

The bactericidal properties have been well known and well utilized for quite a long time. In principle, when the photons of UV radiation are incident on a biological cell, the nucleic acid of the cell absorbs the incident photon energy, resulting in the formation of thymine dimers. The formation of thymine dimers inhibits the ability of the bacteria to replicate.

In addition, intracellular repair system proteins play an important role in the UV resistance as well. Recent studies have shown that proteins are the primary cellular targets implicated in the lethal effects of UV-A (Bosshard, Bucheli, Meur, & Egli, 2010; Bosshard, Riedel, et al., 2010). Hence, the irreversibly damage of repair system proteins may has a role in microbicidal UV effect. However, the exact conclusion concerning the role of UV radiation generated in the non-thermal plasma in the inactivation of microorganism is still not consistent. Table 1 summarizes the recent results on the inactivation of microorganism by UV radiation generated in the non-thermal plasma.

Laroussi compared the inactivation kinetics of UV radiation from a low-temperature mercury-vapor lamp and that of non-thermal atmospheric-pressure plasma, and concluded that UV radiation is not the key factor involved in microbial inactivation (Laroussi, 1996). It was later supported by the work of Herrmann, Henins, Park, and Selwyn (Herrmann, Henins, Park, & Selwyn, 1999). They exposed *Bacillus globigii* to the APPJ of which the plasma effluent was blocked by a quartz widow. No substantial reduction in the

Table 1
The role of UV radiation during microbial inactivation process.

Gas composition	Discharge type	Conclusion	References
He	DBD with high voltage (5 kV) at frequency range between 0.3 and 4 kHz	Not major role	Laroussi (Laroussi, 1996)
$He/O_2/H_2O$[a]	APPJ produced at radio frequency 13.56 MHz	Not major role	Herrmann et al. (Herrmann et al., 1999)
He or He/O_2	APPJ produced at 29–37 kHz and 3–15 kV	Not major role	Deng et al. (Deng et al., 2006)
He/N_2 or He/O_2	APPJ produced at 10 kHz and 10 kV	Not major role	Lu et al. (Lu et al., 2008)
He or He/O_2	APPJ produced at 13.56 MHz and 0.9–1.7 kV	Not major role	Kim et al. (Kim et al., 2009)
N_2/O_2	DBD with high voltage (2.5 kV) at frequency 5 kHz	Major role	Eto et al. (Eto et al., 2008)
N_2/O_2	Microwave-driven discharge at 2.45 GHz	Major role	Philip et al. (Philip et al., 2002)
N_2/O_2	Microwave-driven discharge at 2.45 GHz	Major role	Moreau et al. (Moreau et al., 2000)
N_2/O_2	Microwave-driven discharge at 2.45 GHz	Major role	Moisan et al. (Moisan et al., 2002)
N_2/N_2O	Microwave-driven discharge at 2.45 GHz	Major role	Boudam et al. (Boudam et al., 2006)
Air	DBD with high voltage (20 kV) at frequency 2.2 kHz	Not major role	Laroussi and Leipold (Laroussi & Leipold, 2004)
Air	Corona discharge stressed with direct current voltage	Not major role	Timoshkin et al. (Timoshkin et al., 2012)
Air	DBD with high voltage (35 kV) at frequency 12 kHz	Not major role	Fridman et al. (Fridman et al., 2007)
Air	APPJ operated with a direct current	Not major role	Kolb et al. (Kolb et al., 2012)
Ar	Microwave-driven discharge at 2.45 GHz	Major role	Shimizu et al. (Shimizu et al., 2008)
Ar	Microwave-driven discharge at 2.45 GHz	Major role	Sato et al. (Sato et al., 2006)
Ar	APPJ with voltage 0.28 kV at frequency range between 16 and 20 kHz	Not major role	Homma et al. (Homma et al., 2013)
O_2	APPJ applied with direct current voltage of 2.4 kV	Not major role	Li et al. (Li et al., 2013)

[a] A mixture of He, O_2 and H_2O.