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In-package atmospheric pressure cold plasma treatment of strawberries

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ABSTRACT

The ability to generate low temperature plasma at atmospheric pressure offers new opportunities to decontaminate biological materials, including fresh foods. In this study, strawberries were treated with atmospheric cold plasma (ACP), generated with a 60 kV dielectric barrier discharge (DBD) pulsed at 50 Hz, across a 40 mm electrode gap, generated inside a sealed package containing ambient air (42% relative humidity). The current–voltage characteristics revealed that the plasma operated in the filamentary regime. The background microflora (aerobic mesophillic bacteria, yeast and mould) of strawberries treated for 5 min was reduced by 2 $\log_{10}$ within 24 h of post-ACP treatment. The respiration rate of ACP treated produce, measured by the closed system approach, showed no significant increase. The effect of ACP on strawberry colour and firmness was insignificant.

1. Introduction

Strawberries are known for their flavour and nutritional value. Strawberries are rich in bioactive compounds such as phenolic compounds, including their abundant anthocyanins, which impart the bright red colour to the fruits. Freshly harvested strawberries are very susceptible to mechanical injury, dehydration, decay and physiological deterioration. For this reason, strawberries are harvested and packed in the field directly into retail clamshell containers that are delivered to the supermarket. However, post-harvest spoilage of strawberry can be mainly attributed to the high incidence of yeast and mould growth (Garcia et al., 2011; Narciso et al., 2007).

Chlorine-based washing for decontamination is widely used by fresh produce processors. However, in some European countries including Germany, The Netherlands, Switzerland and Belgium the use of chlorine for washing fresh and fresh-cut products is prohibited (EU Directive 2092/91, 1991; Nguyen-the and Carlin, 1994). In addition, to address issues of chemical contamination, most processors seek to minimise or avoid the use of conventional preservatives and chemical antimicrobials (Misra et al., 2011a). Consumer demands and the shortcomings of the existing technologies are thus stimulating the development of alternative and preferably non-thermal approaches to processing of fresh produce (Deliza et al., 2003; Jeyamkondan et al., 1999). Food industries are seeking suitable technologies to ensure optimum microbiological safety and quality of minimally processed foods (Castenmiller et al., 2008; Misra et al., 2011a).

Nonthermal technologies such as high pressure processing (HPP) and pulsed electric field (PEF) technologies have already commercialised and provide good results (Suzuki, 2002). However, the equipment and set-up for HPP is capital intensive (Hugas et al., 2002), while PEF is only suitable for liquid foods. Nonthermal approaches for achieving decontamination of fresh whole fruits and vegetables include pulsed light processing (Gómez-López et al., 2007), ionising radiation, ultrasound or ozone assisted washing (Bilek and Turantas, 2008; Pangloli and Hung, 2013) and use of other chemical or packaging approaches (Ramos et al., 2013). Challenges of adoption of such technologies include; the shadowing effect in UV light processing, consumer acceptance and facility set-up for ionising radiation and the lack of suitable industrial scale processing units for ultrasound processing (Deora et al., 2013). Washing methods combined with chemical approaches have provided some success; nevertheless, this demands large volumes of water at industrial scale. Considering these aspects, research to develop suitable food processing technologies aiming to overcome such limitations is desirable and timely.

In this context, atmospheric pressure cold plasma (ACP) offers distinct advantages for decontamination of foods. The term "plasma" refers to an overall electrically neutral gas composed of molecules, atoms, ions and free electrons. In ACP, the electron temperature is much larger than the ion and neutral temperatures which are typically equal and close to room temperature ("cold" or non-thermal). The ACP gas is at atmospheric pressure, e.g. ambient

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air, thus obviating the need for vacuum chambers and pumps. Various aspects concerning the inactivation of food-borne pathogens using cold plasma technology have been reviewed by Misra et al. (2011b) and Niemira (2012). Until recent advances in the development and applications of atmospheric pressure plasma systems, cold plasma processes were carried out under vacuum and thus incompatible with food processing. While cold plasmas are used in industrial processes such as electronics cleaning (Korner et al., 1995), bonding of plastics (Vlachopoulou et al., 2009) or binding of dye to textile fibres (Naebe et al., 2010), their potential remains untapped in the food industry. Plasma generation at atmospheric pressure is of interest, both technically and commercially to the food industries because this can be implemented at ambient conditions, reduces cost, increases treatment speed and enables industrial applicability (Misra et al., 2011b).

The present study involves use of a dielectric barrier discharge (DBD) to generate cold plasma from humid atmospheric air inside a package. DBD is a well-established technique to generate ACP plasma (Kogelschatz, 2003) and has attracted the interest of a range of scientists in recent years because of its unique advantages (Xu, 2001; Huang et al., 2010). In this work, an evaluation of the potential use of atmospheric air cold plasma for the decontamination of strawberries inside a closed package was conducted. Some of the discharge features were obtained from charge–voltage (Q–V) and current–voltage (I–V) measurements. The quality of the treated produce was evaluated based on the strawberry respiration rate within a closed system and change in colour and firmness.

2. Materials and methods

2.1. Produce characteristics

Fresh strawberries (*Fragaria ananasa*, var. Elsanta) were purchased from the local wholesale fruit market (Dublin, Ireland) and stored under refrigerated conditions for 1 h before the beginning of the experiments. The density of the strawberries was determined by the volume displacement method using toluene instead of water, to avoid floating (AOAC, 1998). The choice of toluene was also based on the fact that it interacts to a lesser extent with the fruit (Ferrando and Spiess, 2003) and can efficiently fill the shallow dips of strawberries due to its low surface tension. The temperature of the liquid was registered using a thermometer to be 20.0 ± 0.2 °C. The mean density of the strawberry samples was found to be 0.938 ± 0.004 g cm^{-3} and was used in the calculations for respiration rate.

2.2. In-package plasma treatment

A schematic of the experimental set-up employed in the study is presented in Fig. 1. The DBD system comprises of two circular aluminium plate electrodes (outer diameter = 158 mm) over polypropylene (PP) dielectric layers (of 2 mm thickness) between which a PP package containing the food sample is placed. The high voltage step-up transformer (Phenix Technologies, Inc., USA) powered at 230 V, 50 Hz delivers a high voltage output in the range 0–120 kV_{RMS}. A single value of the voltage applied across the electrodes of 60 kV_{RMS} at 50 Hz was used for these experiments. The rigid PP package had dimensions of 310 mm × 230 mm × 40 mm and also served as a dielectric material. Boxes with strawberry samples were sealed inside polymeric film of 50 μm thickness (Cryovac BB3050) with very low gas transmission rates, in order to prevent leakage of the plasma-generated reactive species. This film served as an additional layer of dielectric (Pankaj et al., 2013b). The atmospheric air condition at the time of packaging and treatment was 42% relative humidity (RH) and 25 °C, as measured using a humidity-temperature probe connected to a data logger (Testo 176 T2, Testo Ltd., UK). The strawberry samples were subjected to indirect ACP treatment for 5 min and subsequently stored for 24 h at 10 °C and 90% RH. Indirect exposure refers to placement of strawberries away from area of field between electrodes (at least 2.5 cm from the circumference of field in this study). These operating conditions were selected based on previous experiments conducted in our laboratory. All treatments and further evaluations were done in triplicate.

2.3. Electrical characterisation of the plasma

The electrode bias voltage was monitored using a high voltage probe (North Star PVM-6) coupled to a 10:1 voltage divider to allow recording of the full voltage waveforms on an Agilent InfiniVision 2000 X-Series Oscilloscope (Agilent Technologies Inc., USA). The discharge characteristics were monitored using Q–V measurements by connecting a capacitor C_0 = 8.8 nF in series on the ground side of the discharge. The voltage drop across the capacitor was recorded using a 1000:1 high voltage probe (Testec-Electronik TT-HVP 15 kV), while a current transformer probe (Bergoz CT-E1.0S) was used to measure the current waveforms. The charge on the capacitor was plotted versus the applied voltage to obtain Lissajous figures from which the capacitance of the discharge gap, the capacitance of the dielectric, the total power delivered to the plasma, the transferred charge and discharge–on time (duration of the discharge per half cycle) were calculated, respectively.

2.4. Measurement of ozone concentration

Ozone concentrations within the package were measured, immediately following ACP treatments, using Gastec short-term ozone detection tubes (Product No. 18M, Gastec, Japan). These tubes contain a reagent which changes colour after coming in contact with the specified gas and are calibrated for specific sampling volumes. 10 mL of gas was pulled out of the package, through the tube, using a gas pump (Gastec, Japan) and a hypodermic needle. To avoid leakage of the gas, a silicone septum with adhesive was used at the point of gas sampling.

2.5. Microbial enumeration

For microbial count estimations, untreated control samples, untreated control samples stored at 10 °C for 24 h and atmospheric cold plasma (ACP) treated samples stored at 10 °C for 24 h were analysed, respectively. Strawberry samples were placed in stomacher® bags (Seward 80 bags, UK), two strawberries (weighing approximately 10–15 g) were placed in each separate bag, containing 10 ml of sterile maximum recovery diluent (MRD, Scharlau Chemie, Spain) and hand rubbed for 2–3 min. The resulting wash fluid was serially diluted in MRD. Total aerobic mesophiles and yeasts/moulds count were determined by surface plating of appropriate aliquots in duplicate on plate count agar (PCA, Scharlau Chemie, Spain) and potato dextrose agar (PDA, Scharlau Chemie, Spain) respectively. PCA plates were incubated at 37 °C for 24–48 h. The PDA plates were incubated at 25 °C for 3–7 days before yeast/mould colonies were counted. All experiments were conducted in duplicate and each microbial count was the mean of four determinations.

2.6. Respiration rate measurement

After 24 h in-pack storage, ACP treated strawberries were carefully moved into a gas jar (2.365 L volume), sealed to air tight conditions and stored at 10 °C and 90% relative humidity (RH). The