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Atmospheric gas plasma treatment of fresh-cut apples

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ABSTRACT

In this study we pioneered the use of gas plasma for the treatment of fresh-cut apples and its potential application in the agri-food precesses. Treatments were conducted on fresh-cut Pink Lady® apples using a Dielectric Barrier Discharge (DBD) generator and considering three different times: 10, 20 and 30 min. Main quality (soluble solid content, titrable acidy, colour by computer vision system and texture) and metabolic parameters (polyphenol oxidase PPO activity, respiration and heat production) were assessed immediately after the treatment and during a storage of 24 h (10 °C, 90% RH). In terms of browned areas, a significant decrease was observed in treated samples compared to the control ones (up to about 65% for 30 min and after 4 h of storage). PPO residual activity decreased linearly by increasing the treatment time (up to about 42%). In general the treatment appeared to slow down the metabolic activity of the tissue. Other qualitative parameters were only slightly affected by the treatment.

Industrial relevance: The potential application on in-packed cold plasma technology and its known effect on microbiological decontamination of foods makes this technique very encouraging for fresh-cut fruit stabilization. However very important aspects have to been clarified in order to deeply understand gas plasma effect on fresh-cut apple quality and on the metabolic response of the tissue.

1. Introduction

Factors controlling the quality maintenance of fresh-cut fruits are a result of a complex process, concerning a number of physico-chemical and biochemical modifications, that mainly affect flavour, colour and texture (Mencarelli & Massantini, 1994). The disruption of the cellular structure due to peeling and cutting puts enzymes and their substrates in direct contact. Several reactions can be promoted, and a sudden increase in the respiration rate and in the metabolism, leading to a faster tissue deterioration, can be observed. These reactions involve negative changes in fundamental characters highly appreciated by consumers, as the visual quality (mainly changes in colour) and the texture (tissue softening) (Toivonen & Brummell, 2008).

For fresh-cut apples the most important phenomenon responsible of its quality degradation is the enzymatic browning (Rocha & Morais, 2003). It is worth noting that apple tissue cutting allows the interaction between the polyphenol oxidase (PPO) with the polyphenolic substrate, in the presence of oxygen (Martinez & Withaker, 1995). Cut-edge browning is due to two PPO catalyzed reactions, the hydroxylation of monophenols to diphenols and the oxidation of diphenols to quinones, which in turn involve melanin accumulation (Toivonen & Brummell, 2008).

At date different chemical and physical techniques were explored to control enzymatic browning of fresh-cut apples. Chemical techniques that act to inactivate the enzyme are based on dipping procedures and on the use of organic acids in combination with calcium salts, carboxylic acids, thiol containing compounds and phenolic acids (Oms-Oliu et al., 2010). Edible coatings, as carriers of the anti-browning chemical agents, were also extensively studied (Baldwin, Níspero-Carriedo, Chen, & Hagenmaier, 1996) and several researches were focused on the contribution of modified atmosphere packaging (MAP) on browning inhibition (Aguayo, Requejo-Jackman, Stanley, & Woolf, 2010; Rocculi, Romani, & Dalla Rosa, 2004).

Recently different innovative treatments were tested to inhibit browning reactions. For fresh-cut apples, UV-C light (200–280 nm) exposure (Manzocco et al., 2011) and short term exposure to nitric oxide (NO) gas (Pristijono, Willis, & Golding, 2006) showed high potentialities.

Among advanced techniques, gas plasma is currently used for biotreatments; it is an ionized gas characterized by active particles such as electrons, ions, free radicals, and atoms which are both in ground and excited states; the excited species emit a photon (including UV photons) when they get to the ground state (Moreau, Orange, & Feuilloley, 2008). The ionization occurs by applying energy to a gas mixture and particularly to electrons which in turn transmit the energy to the heavy species by collisions. Non-thermal or non-equilibrium plasmas are produced at low pressure (e.g. atmospheric), and the behaviour of electrons and ions is in turn influenced by the excitation frequency. When atmospheric air is used as working gas to generate non-equilibrium plasma

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discharges, reactive oxygen species (ROS) and reactive nitrogen species (RNS) are formed. Ozone (O_3), atomic oxygen (O) and hydroxyl radical (OH), are the main generated ROS active components. OH radicals are produced from the direct dissociation of the water molecules by electronic impact (Moreau et al., 2007). Excited molecules of N_2 and nitric oxide radical (NO) are the main RNS species characterizing a non-equilibrium plasma and having a role in the decontamination. The oxidative species produced during the discharge can cause lipid peroxidation, and protein and DNA oxidation (Montie, Kelly-Wintenberg, & Roth, 2000). Main biological applications of non-thermal plasmas are undoubtedly medicals (Fridman et al., 2008) and regard the microbial decontamination of complex and expensive heat-sensitive medical devices (Weltmann et al., 2008), the sterilization of living tissues and wound healing (Kong et al., 2009). In the medical field, protein destruction (bovine serum albumin) was also observed by treating medical surgical instruments with atmospheric gas plasma (Deng, Shi, Chen, & Kong, 2007; Deng, Shi, & Kong, 2007).

Recently, non-thermal plasma was used for the decontamination of agricultural products and its inactivation power was studied with respect to several microbial species (Shama & Kong, 2012). In terms of microbiological lethal power, main results showed that this technique can be a valuable alternative to the washing procedures with chemicals such as those used for fresh fruits and vegetables such as apples, cantaloupe, lettuce (Critzer, Kelly-Winterberg, South, & Golden, 2007), mango, melons (Perni, Liu, Shama, & Kong, 2008), and pears (Berardinelli, Vannini, Ragni, & Guerzoni, 2012). Other studies regarding the food sector were conducted on the decontamination of shell eggs (Ragni et al., 2010), chilled poultry wash water (Rowan et al., 2007), food packaging materials such as polyethylene terephthalate bottles (Koulik, Begounov, & Goloviatinskii, 1999) and sealed packages (Keener et al., 2012).

Fundamentals of cold plasma technology and its applications to the decontamination of foods have been reviewed by Misra, Tiwari, Raghavarao, and Cullen (2011) and Niemira (2012). Unlike research for food-borne pathogen inactivation, few studies have been conducted to this end to evaluate the effect of cold gas plasma on fresh-cut fruit and vegetable quality aspects.

Grzegorzewski, Rohn, Kroh, Geyer, and Schlüter (2010) and Grzegorzewski, Ehlbeck, Schluter, Kroh and Rohn (2011) studied the effect of non-thermal plasma on lamb's lettuce morphology and chemical composition, particularly on phenolic compounds content. According to their findings, leaf surfaces were significantly affected by the treatment, showing a degradation of epicuticular waxes and an increase in hydrophilicity proportional to plasma exposure time. They also found that generally the treatment caused a reduction of the leaf phenolic content, although the plant matrix acted as a protection against oxidation of bioactive compounds by reactive species generated by plasma.

Baier et al. (2013) tested the antimicrobial efficacy and the physiological effect of non-thermal plasma treatment applied with different power intensities on lamb's lettuce. Results showed that the treatment can cause an inhibition of photosynthetic activity that became more severe and permanent with increased power settings. The impact on tissue physiology was attributed both to the thermal damage, particularly at the higher power, and to the stress brought by charged particles and/or reactive species generated by plasma treatment.

More recently, the effect of cold plasma on tomato peroxidase (Pankaj, Misra, & Cullen, 2013), on polyphenol oxidase and peroxidase in a model food system (Surowsky, Fischer, Schlueter, & Knorr, 2013), was evaluated. Although the results obtained in these studies underline the potential of cold plasma treatments for enzyme inactivation, further researches are needed to assess the effect on more complex systems such as fresh-cut fruit and vegetable.

Since the product temperature during the treatment is very close to the ambient one, this technique could be suitable for fresh-cut product processing, where temperature and pressure must be controlled in order to preserve the product quality.

Given that the application of cold gas plasma treatment on fresh-cut fruit and vegetable is in its infancy, in the present work we have pioneered the study of its effect on fresh-cut Pink Lady® apple quality and endogenous metabolic activity during controlled storage. Particular attention has been given to colour modification and PPO inhibition, considering that enzymatic browning is the most important phenomena limiting the product shelf-life.

2. Materials and methods

2.1. Raw material, handling and storage

Apples (*Malus domestica* cv. 'Pink Lady®') grown in the Emilia–Romagna region of Italy were harvested in November 2012. Fruits were stored at 2 ± 0.5 °C and approximately 100% RH in air, in plastic bins for 2 months. 20 kg of fruits free from defects was selected and transported to our laboratory and placed in a closed refrigerated chamber at 4 °C and saturated atmosphere in darkness for one week. When the experiments were performed, apples had a dry matter content of 15.73 g ($\pm$0.29) 100 g fw^{-1}, a soluble solid content of 14.27 ($\pm$0.35) °Brix and a titrable acidity of 0.39 mg ($\pm$0.03) of malic acid g fw^{-1}.

2.2. The gas plasma generator

A Dielectric Barrier Discharge (DBD) generator was used for the treatment of Pink Lady® apple slices (Fig. 1). Within the low frequency plasma sources, the DBD configuration is one of the most investigated and industrialized non-equilibrium plasma generator. It presents numerous advantages in terms of flexibility of geometrical configurations (planar or cylindrical), operating parameters (medium, frequency and voltage), costs and characteristics of the power supply (Kogelschatz, 2003; Morgan, 2009).

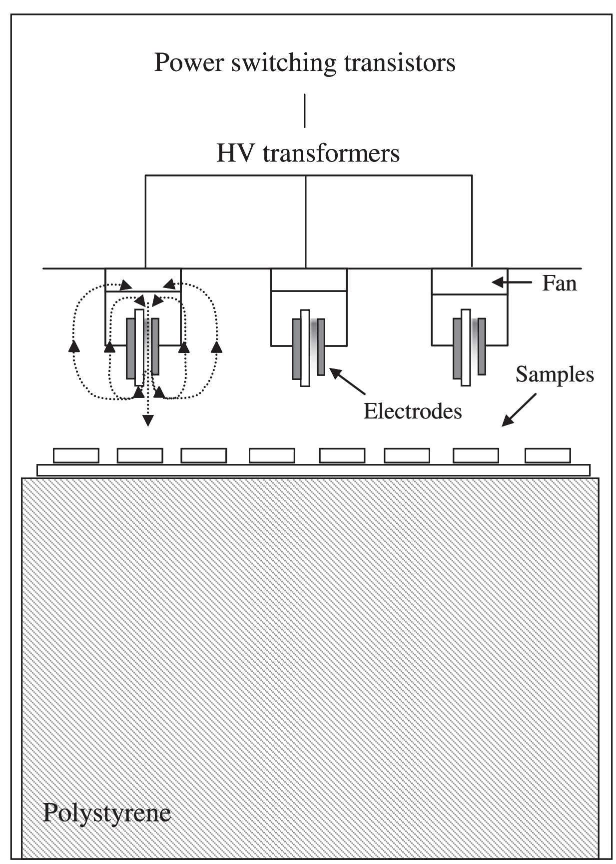

Fig. 1. Layout of the DBD gas plasma generator.