2014-3

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Recommended Citation

Misra, NN, Patil, S, Moiseev, T, Bourke, P, Mosnier, JP, Keener, KM, & Cullen, PJ (2013) In-package atmospheric pressure cold plasma treatment of strawberries, Journal of Food Engineering, DOI:10.1016/j.jfoodeng.2013.10.023.

Accepted Manuscript

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PII: S0260-8774(13)00538-4
DOI: http://dx.doi.org/10.1016/j.jfoodeng.2013.10.023
Reference: JFOE 7603

To appear in: *Journal of Food Engineering*

Received Date: 19 March 2013
Revised Date: 12 August 2013
Accepted Date: 17 October 2013

Please cite this article as: Misra, N.N., Patil, S., Moiseev, T., Bourke, P., Mosnier, J.P., Keener, K.M., Cullen, P.J., In-package atmospheric pressure cold plasma treatment of strawberries, *Journal of Food Engineering* (2013), doi: http://dx.doi.org/10.1016/j.jfoodeng.2013.10.023

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.

Keywords

Cold Plasma, Strawberries, Decontamination, Respiration rate, Quality, Nonthermal

Contents

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; Nguyen-the and Carlin, 1994). In addition, to address issues of chemical contamination, most processors seek to minimize 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 at 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, 2002; 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 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 hour 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 gcm^{-3} and was used in the calculations for respiration rate.

2.2. In-package plasma treatment

[Insert Figure 1 here]

A schematic of the experimental set-up employed in the study is presented in Figure 1. The DBD system comprises of two circular aluminium plate electrodes (outer diameter = 158 mm) over polypropylene (PP) dielectric layers (of 2mm thickness) between which a PP package containing the food sample is placed. The high voltage step-up transformer (Phenix Technologies, Inc., USA)

powered at 230V, 50 Hz delivers a high voltage output in the range 0-120kV rms. A single value of the voltage applied across the electrodes of 60 kV_{RMS} at 50Hz 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 micrometres 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. 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 minute and subsequently stored for 24 hours 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 15kV), 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 litre volume), sealed to air tight conditions and stored at 10 °C and 90 % relative humidity (RH). The recommended storage conditions for strawberries are 0-5 °C and ~95 %RH. However, the conditions employed in the present study were selected to account for the temperature abuse that is

commonly encountered during transport and in displays at retail. The change in O_2 and CO_2 gas compositions inside the respirometer were monitored over time using a gas analyser (Systech Instruments, UK). Gas sampling was performed with a hypodermic needle, inserted through an adhesive septum previously fixed to the jar, at a flow rate of 150 mL/min for 10s. The instrument is based on electrochemical sensor to record O_2 concentration and on a mini-IR spectrophotometer to record CO_2 concentrations (accuracy: 0.1 %v/v O_2; 2 %v/v CO_2). Initial experiments showed that sampling had no significant influence on gas concentration in the jar, as the total volume of the jar was much greater than the total volume sampled by the instrument during the experiment.

Two-parameter, non-exponential equations (1), (2) similar to the Peleg's model (Peleg, 1988) were respectively fitted to the average O_2 and CO_2 concentrations of the control and treated packages at different storage time t (in hours), using nonlinear regression analysis.

$$[O_2] = 0.21 - \left[\frac{t}{K_1 t + K_2}\right] \qquad (1)$$

$$[CO_2] = \frac{t}{K_1 t + K_2} \qquad (2)$$

where K_1 and K_2 are the regression coefficients. A similar model has been applied for respiration data of apples by Mahajan and Goswami (2001) and Bhande et al. (2008).

The rate of change of gas concentration was determined from the first derivative of the regression functions as outlined in Equations (3) and (4):

$$\frac{d[CO_2]}{dt} = -K_1 t(K_1 t + K_2)^{-2} + (K_1 t + K_2)^{-1} \qquad (3)$$

$$\frac{d[O_2]}{dt} = K_1 t(K_1 t + K_2)^{-2} - (K_1 t + K_2)^{-1} \qquad (4)$$

At each sampling time, the respiration rates R_{CO_2} and R_{O_2}, defined in terms of CO_2 evolution and O_2 consumption, were calculated using Equations (5) and (6), respectively.

$$R_{CO_2} = \frac{d[CO_2]}{dt}\frac{V}{W} \qquad (5)$$

$$R_{O_2} = -\frac{d[O_2]}{dt}\frac{V}{W} \qquad (6)$$

where V and W are the free gas volume (mL) and weight of the strawberries (kg), respectively.

2.7. Colour measurement

The colour was quantified using a L*-a*-b* colorimeter (Colour Quest XE Hunter Lab, Northants, UK). The colour measurements were performed along four symmetrical sections on each strawberry and the average value is reported. The instrument was calibrated using white (L* = 93.97, a* = 0.88 and b* = 1.21) and green (L* = 56.23, a* = 21.85, b* = 8.31) standard tiles, respectively. Hunter colour readings were recorded. The L* parameter (lightness index scale) ranges from 0 (black) to 100 (white). The parameter a* measures the degree of red (+a) or green (-a*) colour and the b* parameter measures the degree of yellow (+b) or blue (-b*) colour.

2.8. Firmness

Four strawberries from each of the control and ACP treated groups were measured. The force necessary to cause a deformation of 3 mm with a speed of 0.2 mm/s was recorded using an Instron texture analyser (Instron 4302 Universal Testing Machine, Canton, MA, USA), with a 3.5-mm-diameter flat-faced cylindrical probe. Data were analysed with the Instron series IX software for Windows.

2.9. Statistical Analysis

The non-linear regressions were carried out using the Gauss-Newton numerical method available from the Minitab software package (Minitab® ver. 16, Minitab Ltd.). The coefficient of determination (r^2) and the root mean squared error (RMSE), defined by equation (7) below, were used as criterion to evaluate the adequacy of model fitting.

$$RMSE = \sqrt{\sum_{i=1}^{n_t} \frac{\left(y_{\exp i} - y_{pred}\right)^2}{n_t - n_p}} \quad (7)$$

where $y_{\exp i}$ are experimental observations, y_{pred} are model predictions, n_t are number of experimental data points and n_p are number of estimated model parameters. One-way ANOVA was performed to determine the significance of differences among the colour parameters and firmness of control and treated strawberries at 95% level of confidence.

3. Results and Discussion

3.1. Discharge characteristics

The I-V waveforms and the Q-V characteristics for the discharge with and without strawberries are shown in figures 2(a, b) and 3(a, b), respectively. The I-V waveforms indicate the presence of a filamentary-type discharge without noticeable differences between the empty package and the package with produce. The use of high voltage permits generation of a stable discharge, even at large gaps of 4cm. The Q-V characteristics of figure 3 (a, b) take the shape of closed-loop parallelograms, where along the sides A-B and C-D the discharge is idle while during B-C and D-A it goes through breakdown transferring charges trough the gap for applied voltage values between V_{min} (corresponding to breakdown voltage) and V_p (peak voltage).

[Insert Figure 2 (a) and (b) here]

The electrical performances of the discharge derived from the Q-V measurements according to the method developed by Manley (1943), Falkenstein and Coogan (1997) are shown in Table 1[Insert Table , where C_d is the dielectric capacitance, C_{gap} is the capacitance of the discharge gap, P is the discharge power, ΔQ is the total charge transported over a cycle and Δt is the duration of the discharges per half voltage cycle. The capacitances are calculated from the slopes of the Q-V parallelogram obtained as Lissajous figure with C_d and C_{cell} (total capacitance of the discharge cell) indicated in Figure 3 (a, b) while C_{gap} is given by $C_{gap} = \frac{C_d \times C_{cell}}{(C_d - C_{cell})}$. The transported charge is calculated as $\Delta Q = 2.C_0.Q$; and $\Delta t = \frac{1}{2\pi f}\left[\pi / 2 - \sin^{-1}\left(\frac{V_{\min}}{V_p}\right)\right]$ with C_0 the measurement capacitor, f the frequency (50 Hz) and $V_{\min}$ the breakdown voltage, V_p the peak voltage and charge Q indicated in Figure 3b. The discharge power is calculated as the product of the area of the Lissajous charge-voltage loop and the frequency of applied voltage. The discharge performance is not affected in any way by the presence of fresh produce as electrical parameters for the box with and without produce have close values, within the range of estimation errors.

[Insert Table 1 here]

[Insert Figure 3 here]

3.2. Ozone concentrations

When high voltage is applied across the electrodes, the electric field generated produces the phenomenon of dielectric barrier discharge (DBD) (Amjad et al., 2012; Kogelschatz, 2003; Kogelschatz et al., 1997). This discharge generates energetic electrons that dissociate oxygen molecules by direct impact. The single O atom from the dissociation combines with oxygen molecule (O_2) to form ozone gas. Ozone is considered as one of the most chemically stable and active species generated in DBD because of its relatively long lifetime and high oxidation potential. Ozone

concentrations, inside the package containing strawberries, were measured to be (1000 ± 100) ppm immediately post-treatment. We have observed that ozone concentration, generated in similar conditions but without strawberries, can be as high as (1500 ± 100) ppm after 2 min. The comparatively lower ozone concentration for packages loaded with product could be due to the ozone solubilising by reacting with the water at the produce surface and also the smaller volume of available air in the produce packages, i.e. lower initial volume of oxygen. It is worth noting that ozone has been granted GRAS (generally recognized as safe) status by the U.S. Food and Drug Administration as a direct additive to food (FDA, 2001; Rice and Graham, 2001). Besides ozone, the plasma apparatus employed here has also been found to generate reactive nitrogen species (Misra et al., 2013).

3.3. Microbial inactivation

The total mesophilic and yeasts/mould counts for untreated samples were 4.99 and 4.96 $\log_{10}$ cfu/g, respectively. The storage at 10° C for 24 h of untreated control samples had no effect on the reduction of viable population on strawberry surfaces, where the total mesophilic count recorded was 4.92 $\log_{10}$ cfu/g. Yeast and mould counts also showed similar trend and was 5.06 $\log_{10}$ cfu/g. The effect of ACP treatment on the reduction of total mesophiles and yeasts/moulds on strawberry surface is shown in Table 2[Insert Table . In-package, indirect ACP treatment of strawberries for 5 min achieved reductions of 2.4 and 3.3 log cycles of total mesophiles and surface yeasts/moulds, respectively.

[Insert Table 2 here]

Critzer et al. (2007) have also reported the ability of atmospheric plasma for reduction of inoculated microbial populations on fresh produce surfaces. Recently, Fernandez et al. (2013) investigated cold atmospheric gas plasma inactivation of *Salmonella enterica* serovar Typhimurium on fresh produce. The reported study achieved 2.72, 1.76 and 0.94 log-reductions of *S. Typhimurium* on lettuce,

strawberry and potato, respectively, in 15 min of plasma treatment time. The type of produce and its intrinsic characteristics like waxy cuticles, stomata of lettuce and the convolutions of strawberry surfaces were suggested to contribute to different inactivation rates. Similarly, Perni et al. (2008) observed a reduced efficacy of ACP in inactivating bacteria and yeast inoculated on freshly cut fruit surfaces compared to that on inert filter membranes.

In this work reductions in total mesophiles and yeasts/moulds were found, which are primary contributors to spoilage. The efficient reduction of microorganism in a sealed package suggests the elimination of a possible post-process contamination of the treated products. The fact that temperatures that could cause microbial inactivation were never reached, suggests that the microbial reductions were solely due to unique chemical species obtained in plasma state (Pankaj et al., 2013). This was verified using a handheld infrared thermometer (IR-102, Maplin Electronics, UK) which recorded a maximum rise of 8±2 °C after 5 minute of treatment. Previous studies in our laboratory have revealed absence of any residual ozone after at least 24 h post-treatment, under ambient room temperature conditions (Misra et al., 2012). Therefore, it is likely that active species of ACP, including ozone, are retained inside the package for varying times, dependent on the species lifetime, leading to significant reductions in microbial load. However, this requires further investigation into the kinetics of degradation of post-plasma gaseous species inside the sealed package.

3.4. Respiration rate of cold plasma treated strawberries

It is well-known that processing of fresh horticultural produce promotes a faster physiological deterioration, biochemical changes and microbial degradation of the product even when only mild processing operations are used (O'Beirne and Francis, 2003; Rico et al., 2007). This is because fresh produce is often subjected to stress during the processing steps (Watada et al., 1996). When a treatment process damages the tissue or induces stress in the produce, it exhibits a higher respiration rate during processing which can even last after the completion of the process (Laties,

1978; Mitcham and McDonald, 1993). Practical experience reveals that tissues with high respiratory rates and/or low energy reserves have shorter postharvest lives (Eskin, 1990).

In this study, the respiration rate was observed to decrease with time for control as well as treated strawberries (figure 4, 5 and Table 3). This decline is due to the decreasing O_2 concentration and increasing CO_2 concentration in the gaseous environment. The respiration rate of the treated produce was found to be lower than that of the control following an initial delay which is most likely due to the decreased microbial count. Based on these observations it can be said that ACP does not induce significant stress in strawberries treated within the set of conditions employed.

[Insert Figure 4 here]

[Insert Table 3 here]

[Insert Figure 5 here]

3.5. L*-a*-b* colour of strawberries

Colour is the most obvious parameter for consumers (Del-Valle et al., 2005) and plays a key role in food choice, food preference and acceptability, and may even influence taste thresholds, sweetness perception and pleasantness (Clydesdale, 1993). A change in the L*-a*-b* colour parameters of ACP treated strawberries was observed (Figure 7). However, the changes in individual colour parameters viz. lightness, redness or greenness were statistically insignificant ($p > 0.05$) in comparison to the untreated control stored under same conditions.

[Insert Figure 6 here]

3.6. Firmness

Texture is a critical quality attribute in the consumer acceptability of fresh fruits. The firmness of control, untreated strawberries stored at 10 °C for 24hr as well as for ACP treated strawberries are

shown in figure 8. A significant ($p \leq 0.05$) decrease in firmness of strawberries was recorded within 24hr. The difference in firmness among untreated control and treated group was found to be statistically insignificant ($p > 0.05$). Strawberry is a soft fruit that suffers a rapid loss of firmness during storage, which contributes greatly to its short postharvest life and susceptibility to fungal contamination (Hernández-Muñoz et al., 2008). Furthermore, the ability of ozone to retain the texture of strawberries has already been reported in the literature (Runguang, 2011). Besides instrumental colour and firmness, no obvious change in the flavour or edible quality of the strawberries relative to control was noticed.

[Insert Figure 7 here]

4. Conclusions

In-package decontamination of fresh foods is desirable as this minimises the possibility of post-processing contamination. In order to achieve this, atmospheric cold plasma was generated inside a sealed package containing strawberries, using a dielectric barrier discharge in the filamentary regime. The electrical characteristics of the discharge were diagnosed using Q-V measurements and indicated that the discharge behaviour and performance are not affected by the presence of the produce.

The behaviour of plasma, its action on micro-organisms and the resulting changes in food quality are largely determined by the plasma chemistry. Plasma chemistry and the resultant dynamics can be very complex involving a large number of different species at any given point of time. For example chemistry of plasma in air is believed to comprise of more than 75 species and almost 500 reactions (Gordillo-Vázquez, 2008). These active species of post-plasma discharge inactivate the micro-organisms before reverting back to their original or stable states (Ziuzina et al., 2013). Although the modified gas composition induced through complex plasma chemistry may persists for several hours (< 24 h) inside the package, a drastic change in respiration rate of strawberries does not occur. Thus,

this work demonstrates the ability of in-package ACP to reduce the background microflora present on strawberries without inducing significant physiological (respiratory) stress or adversely affecting the colour and firmness. The DBD system achieved these desired effects with a power input of only 15-20 W, without increasing the temperature of the samples significantly.

Future studies will focus on inactivation of inoculated bacteria inoculated on surface of fresh produce. Additionally, in order to assess the long term effects of ACP on food quality, shelf-life studies will be conducted.

Acknowledgements

The research leading to these results has received funding from the European Community´s Seventh Framework Programme (FP7/2007-2013) under grant agreement number 285820. The authors also acknowledge support from the Irish Research Council (IRC).

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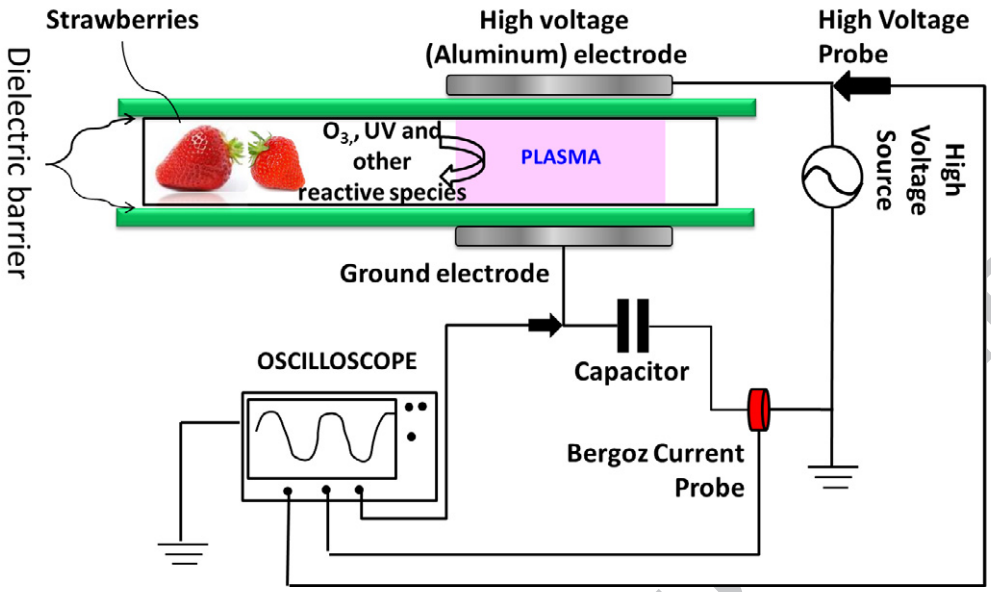

Figure 1

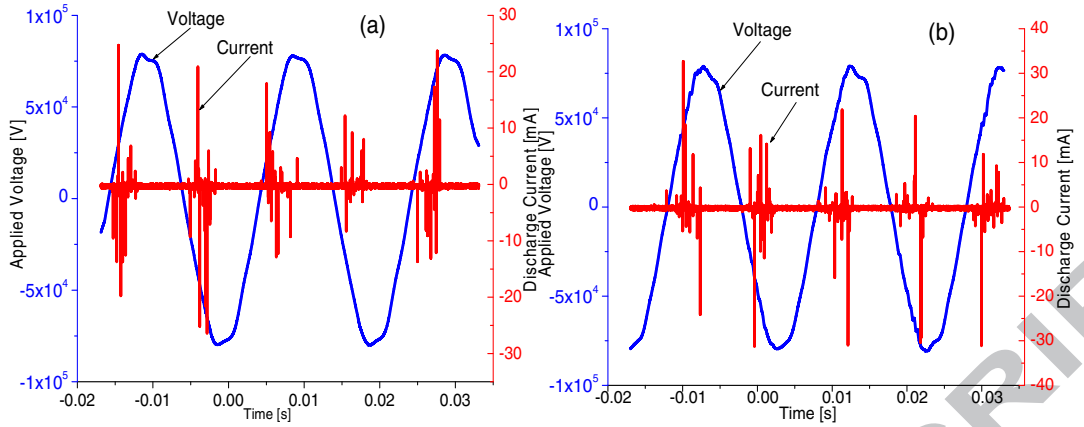

Figure 2 (a) and 2(b)

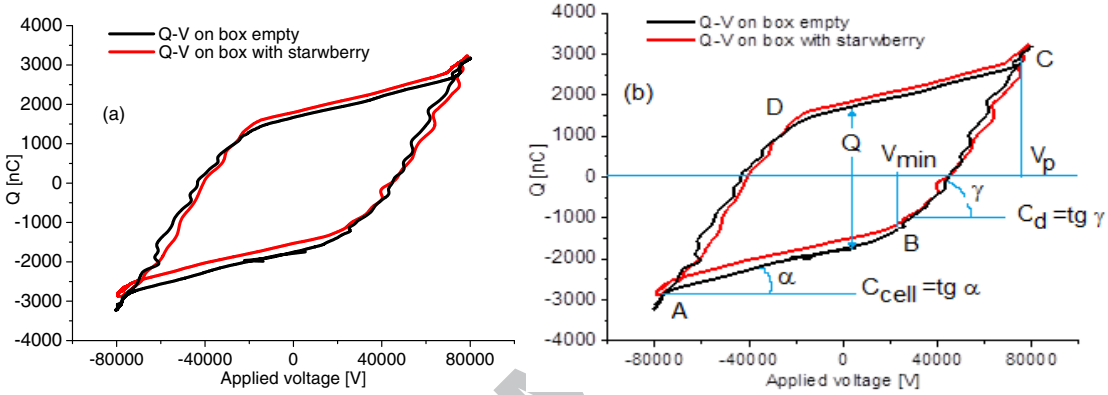

Figure 3

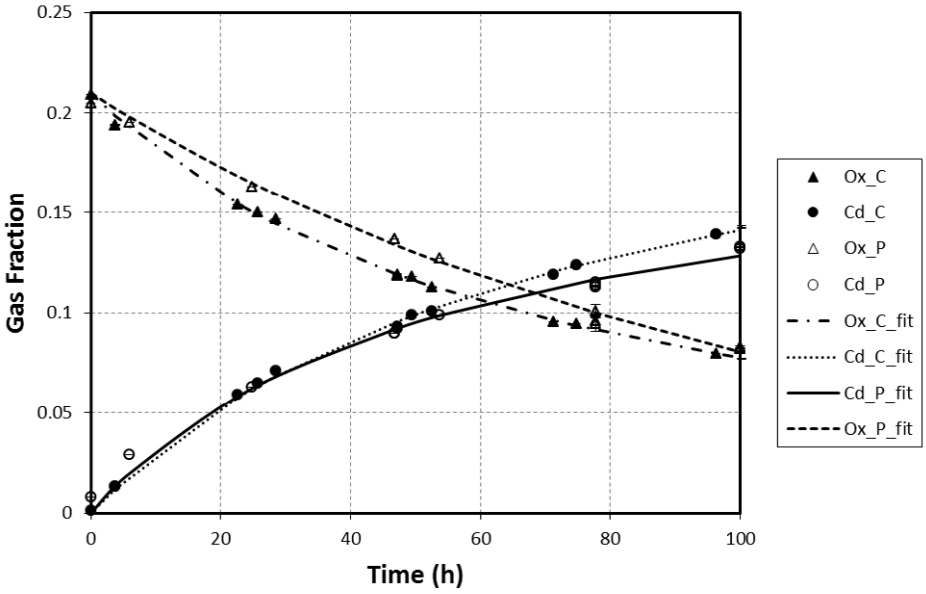

Figure 4

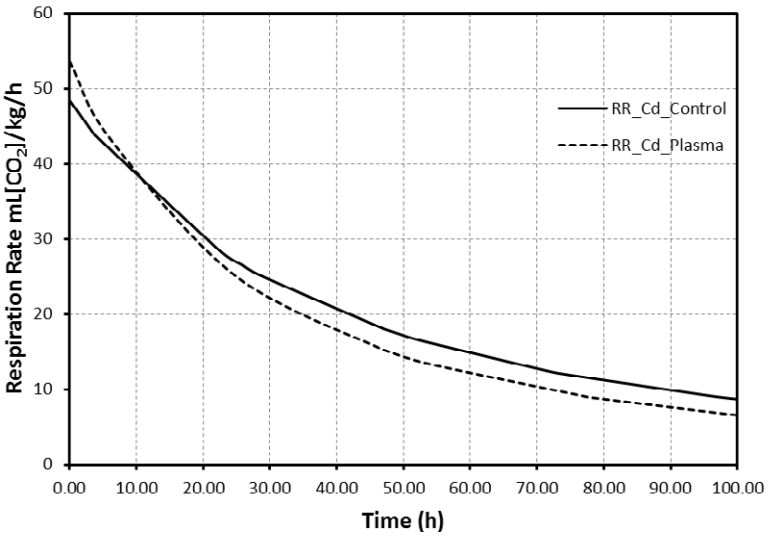

Figure 5

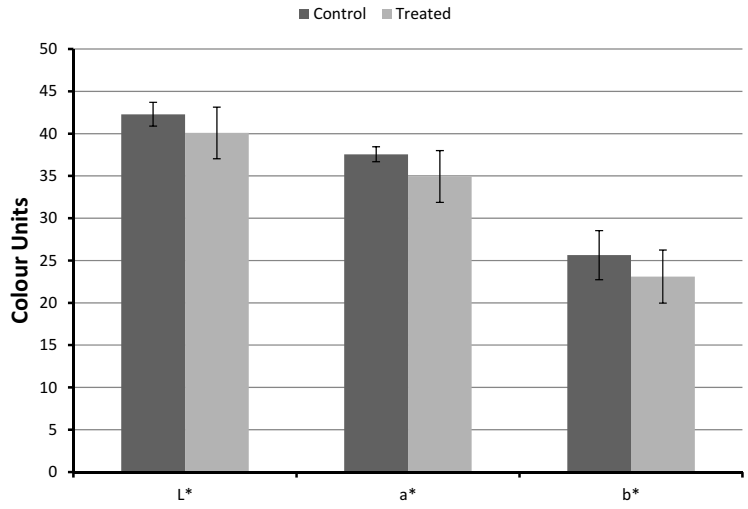

Figure 6

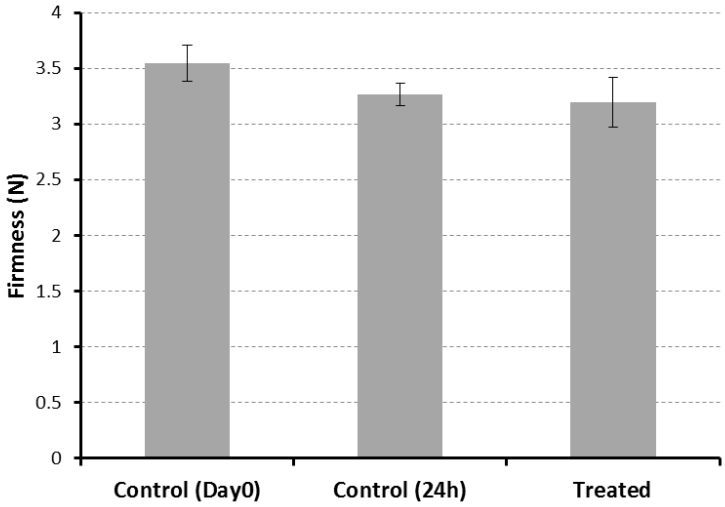

Figure 7

Table 1 Discharge electrical parameters derived from Q-V measurements.

Parameter	**Empty box**	**Box containing Strawberry**
C_d [pF]	89 ± 6	83
C_{gap} [pF]	1.62	1.58
P [W]	17.43	17.03
ΔQ [nC]	8098	7924
Δt [ms]	3.6	3.7

Table 2: Microbial reductions on strawberry surface by indirect atmospheric cold plasma (ACP) treatment in air

Microorganisms	Initial population (log_{10}cfu/g) untreated	Untreated control stored at 10° C for 24h	ACP treated surviving population (log_{10}cfu/g)
Total mesophiles	4.99±0.02	4.92±0.14	2.56±1.82 (12-85% reduction)
Yeast/moulds	4.96±0.08	5.06±0.04	1.56±1.29 (44-95% reduction)

Table 3 Regression coefficients K_1 and K_2 (s) of equations (1) and (2) for O_2 consumption and CO_2 evolution, respectively.

Package	Principle undertaking the respiration rate	Regression coefficients		Coefficient of determination	RMSE
		K_1	K_2		
Control	CO_2 evolution	4.0787	300.67	0.99	0.00182
	O_2 consumption	4.4978	306.96	0.99	0.00203
5 min ACP treated	CO_2 evolution	5.0637	272.27	0.98	0.00488
	O_2 consumption	2.9615	476.76	0.99	0.00355

Highlights

- In-package cold plasma ~~processing~~ treatment of strawberries based on dielectric barrier plasma discharge.
- Electrical characterisation of the plasma discharge revealed a filamentary regime and ozone production.
- A significant background microflora reduction was achieved.
- No adverse changes in respiration rates, texture and colour of treated strawberries.