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ORIGINAL ARTICLE

Effect of cold plasma technique on the quality of stored fruits - A case study on apples[1]

Efeito da técnica de plasma frio na qualidade de frutas armazenadas - Estudo de caso em maçãs

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HIGHLIGHTS:
Cold plasma treatment at high pressure and short immersion time gave the highest quality to apple slices.
The moisture content of apple slices increased when treated with filtered water at a longer immersion time.
Apple slices maintained color quality when treated with cold plasma during storage.

ABSTRACT: The consumption of fresh fruits has increased nowadays due to the lifestyle of the consumers. Maintaining the quality and nutritional value of cut fruits during storage is difficult compared to whole fruits. Deterioration of internal and external quality usually occurs in freshly harvested fruits. It is necessary to use different techniques to maintain the quality and increase the shelf life of the freshly cut product. This research studied the effect of treating apple slices with cold plasma once and with filtered water again on quality characteristics (hardness, moisture content, sugar content, carbohydrate content, and color) after being stored for five days. The best treatment was determined using two different pressures of the plasma jet (1 and 5 atm) and two different immersion times (3 and 6 minutes). It was verified the superiority of cold plasma treatment at 5 atm and 3 minutes immersion time in all studied traits, while treatment with filtered water and 6 minutes immersion time was superior concerning the moisture content of apple slices. There is an inverse relationship between L* and a direct relationship between the a* and b* values with the storage time. Therefore, the use of cold plasma treatment is promising in storing cut fruits, extending their shelf life, and improving their quality and safety, which provides fresh fruits.

Key words: apple slices, filtered water, hardness, immersion time, plasma jet

RESUMO: O consumo de frutas frescas tem aumentado atualmente devido ao estilo de vida dos consumidores. Manter a qualidade e o valor nutricional dos frutos cortados durante o armazenamento é difícil em comparação com os frutos inteiros. A deterioração da qualidade interna e externa geralmente ocorre em frutas recém-colhidas. Para manter a qualidade e aumentar a vida útil do produto recém-cortado, é necessário utilizar diferentes técnicas. Nesta pesquisa, foi estudado o efeito do tratamento de fatias de maçã com plasma frio uma vez e com água filtrada novamente nas características de qualidade (como dureza, teor de umidade, teor de umidade, teor de carboidratos e cor) após armazenamento por 5 dias. O melhor tratamento foi determinado utilizando duas pressões diferentes do jato de plasma (1 e 5 atm) e dois tempos de imersão diferentes (3 e 6 min). Verificou-se superioridade do tratamento com plasma frio a 5 atm e tempo de imersão de 3 min em todas as características estudadas, enquanto o tratamento com água filtrada no tempo de imersão de 6 min foi superior no teor de umidade das fatias de maçã. Existe uma relação inversa entre o valor da cor L* e uma relação direta entre o valor de a* e b* com o tempo de armazenamento. Portanto, o uso do tratamento com plasma frio é promissor no armazenamento de frutas cortadas, prolongando sua vida útil e melhorando sua qualidade e segurança, o que proporciona frutas frescas.

Palavras-chave: fatias de maçã, água filtrada, dureza, tempo de imersão, jato de plasma

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Introduction

The main purpose of properly storing fruits is to maintain their quality and extend their shelf life. Several factors influence fruit storage, including appropriate conditions such as temperature and humidity. Generally, good storage practices are essential for maintaining the quality and integrity of fruits and maximizing their shelf life (Lamikanra et al., 2000; Al-Aani & Sadoon, 2023). Good storage practices include separating fruits and vegetables, proper packaging, ideal temperature, clean storage space, refrigeration, proper handling, and monitoring of ripeness (Khan et al., 2017).

Therefore, most foods require specific processing operations to maintain their quality, and this processing may alter the functional composition of fruits (Muhammad et al., 2018). However, processing fruits for postharvest processes such as washing, peeling, and cutting can cause mechanical damage to the tissues and lead to negative consequences like a high microbial load, browning of the cut surface, texture destruction, and unpleasant odor during storage. Processed fruits can facilitate the reduction of the growth of certain pathogenic bacteria and spoilage microorganisms (Liu et al., 2020). As a result, the food industry is seeking alternatives to heat treatment. Therefore, research may focus on new nonthermal food preservation technologies. These nonthermal technologies aim to preserve food with minimal loss (Lin et al., 2019; Rauuf & Aadim, 2023).

This research aims to study the effect of cold plasma treatment, first alone and then combined with filtered water, on certain internal and external characteristics of apple slices (hardness, moisture content, sugar content, carbohydrate content, and color). It aims to determine the most suitable treatment using two different pressures of cold plasma (1 and 5 atmospheres) and two different immersion times (3 and 6 minutes).

Materials and Methods

Ionized water was prepared, and measurements were taken in the Plasma Laboratory, Department of Physical Sciences, College of Science, University of Baghdad, Baghdad, Iraq (33° 16' 12" N, 44° 22' 54" E). The ionized water treated by jet plasma is the main medium for immersing the fruit and studying its effects. The ionized water was prepared by placing 5 ml of deionized water in a glass beaker and then introducing it into the DC jet plasma system. In this system, the cathode electrode is connected to the needle outlet. On the other hand, the anode electrode is connected to a stainless steel plate immersed in the water within the beaker. Stainless steel is safe to use; it does not release harmful oxidizing substances to human health.

A voltage difference is applied between the two electrodes. This voltage is sufficient to ionize the metal within the water, leading to the acquisition of ions by the water. Ionization occurs when the gas pressure used in the preparation is set at 1 and 5 L per minute, with an ionization time of 5 minutes. This process results in the creation of a suitable medium for immersing the fruit and assessing the effects of increased ionization during immersion, achieved by elevating the pressure. This increase leads to more electrons for the gas, thereby intensifying the ionization process within the water. Figure 1 shows a DC plasma jet device (Aadim & Abbas, 2023; Jihad & Aadim, 2022).

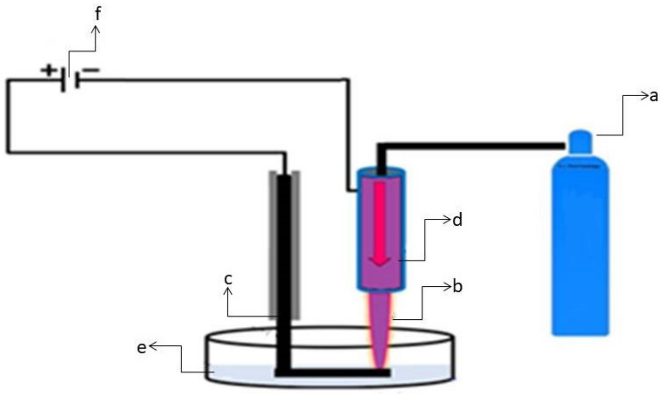


Figure 1. DC plasma jet schematic

The specifications of the DC plasma jet device are as follows:

a. Gas supply = Argon gas, 40 L;
b. Plasma jet = non-equilibrium;
c. Anode electrode;
d. Cathode electrode;
e. Water sample = 5 mL;
f. Voltage difference = 14 KV.

The optical properties of deionized water prepared with plasma jets were measured using a UV-VIS spectrophotometer to determine the concentration of substances dissolved in water. The absorbance of the purified water was meticulously measured at 1 nm intervals in the wavelength range 196 - 320 nm. UV-Vis absorption at 400 nm was chosen to represent the concentration, as this wavelength demonstrates the lowest absorption coefficient of deionized water.

After preparing plasma water, fruits of the 'Golden Delicious' apple variety obtained from local markets - in Baghdad, Iraq, were purchased. Apple samples were selected while considering their equal degree of ripeness in terms of hardness and color levels; then, they were sliced. Table 1 displays the characteristics of apple slices employed in the experiment.

Apple slices were immersed after processing in cold plasma at two different pressures (1 and 5 atm) once and in filtered water again at two different immersion times (3 and 6 minutes). After immersing the apple slices in the different treatments, they were stored in a refrigerator at a temperature of 5 °C and a humidity of 50% for five days.

After five days of storage, the following measurements were taken: moisture, sugar, and carbohydrate contents. These were measurements using an Apocket SCiO molecular scanner (Consumer Physics Ltd., Illinois, USA) with an accuracy of 78% (Al-Sammarraie et al., 2022). Additionally, the degree of hardness was measured using a Mini fruit hardness meter, with

Table 1. Characteristics of apple slices used in the experiment

Slice thickness (mm)	10
Slide diameter (mm)	60-70
Hardness (kg f cm^{-2})	5.11
Sugar content (Brix)	11.5
Carbohydrate content	14
Moisture content	84
L*a*b*	67.07*2.25*16.59

the average measurement ranging from 0.2 to 15 kgf cm^{-2} and an accuracy of ±2%. Also, the values of L*a*b* were measured using a fiber optic sensor, and the sample size was thirty-six.

Data were submitted to the analysis of variance and means were compared by LSD test. All calculations were performed at a $p \leq 0.05$ using the Minitab statistical software. Regression equations and determination coefficients were calculated to highlight the relationship between different coefficients and the L*a*b* values.

Results and Discussion

The absorption of water prepared in the UV-visible region (300-1100 nm) exhibits high absorption at longer wavelengths (Figure 2).

Regarding the study of the impact of cold plasma on the internal and external characteristics of apple fruits, Table 2 presents the moisture content of apple slices obtained from various treatments.

The highest moisture content occurred when treated with filtered water for 6 minutes (Table 2). In contrast, the cold plasma treatment at 5 atm pressure and 3 minutes immersion time yielded the lowest moisture content. Doubling the immersion time led to a 0.14% increase in the moisture content. Furthermore, a transition from 5 atm to 1 atm pressure resulted in a 1.55% rise in moisture content, and immersing in filtered water compared to cold plasma treatment at 1 atm pressure led to a 2.62% increase, rising to 4.22% at a pressure of 5 atm.

Cold plasma water can induce drying of the surface of apple slices, as plasma can enhance drying processes (Du et al., 2022). Previous research findings also suggest the potential of cold plasma treatment in fruit drying (Loureiro et al., 2021).

The moisture content of apple slices affects their sugar content. Table 3 presents the analysis of variance for the sugar content of apple slices obtained from various treatments.

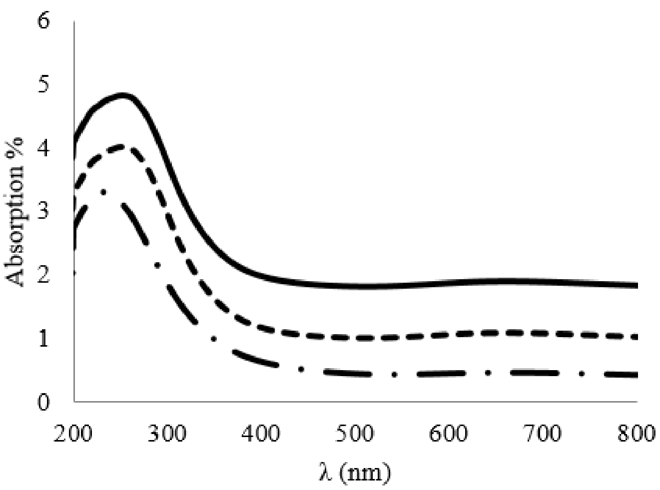


Figure 2. Absorption of deionized water by plasma Jet gas flow

Table 2. Moisture content of apple fruits

T (minutes)	P_5	P_1	Filtered water	Average
3	80.17 a	82 a	83.8 a	81.99 a
6	80.83 a	81.5 a	84 a	82.11 a
Average	80.5 a	81.75 a	83.9 a	

P_5=5 atm, P_1=1 atm

Table 3. Sugar content (brix) of apple fruits

T (minutes)	P_5	P_1	Filtered water	Average
3	17.5 a	12.83 a	12.83 a	14.39 a
6	14.08 a	13.58 a	12.75 a	13.47 a
Average	15.79 a	13.21 a	12.79 a	

P_5=5 atm, P_1=1 atm

The highest sugar content occurred with the treatment with cold plasma at a pressure of 5 atm and an immersion time of 3 minutes (Table 3). In contrast, immersion in filtered water with a duration of 6 minutes yielded the lowest sugar content. Doubling the immersion time resulted in a 6.39% decrease in the sugar content. Similarly, reducing the pressure of the cold plasma treatment from 5 to 1 atm led 16.33% reduction in the sugar content. Moreover, immersing in filtered water, compared to cold plasma treatment at 1 atm pressure, caused a decrease of 3.17%, whereas, at a pressure of 5 atm, this decrease was 18.99%.

This phenomenon could be attributed to the fact that cold plasma aids in drying fruits. This aligns with prior studies to establish a connection between fruit dryness and their sugar content. Drying reduces moisture content, increasing sugar levels (Keast & Jones, 2009). Also, some studies have indicated that cold plasma treatment can increase the sugar content of fruits (Dong & Yang, 2019).

Previous research findings indicate a relationship between the sugar content of fruits and their carbohydrate content. As fruits that contain a high percentage of sugar tend to contain a higher percentage of carbohydrates, there is a direct relationship between the sugar content of fruits and their carbohydrate content (Yahia et al., 2019). Table 4 shows the analysis of variance of the carbohydrate content of apple slices obtained from different treatments.

Based on the results in Table 4, the highest carbohydrate content was achieved through cold plasma treatment at a pressure of 5 atm and an immersion time of 3 minutes. Conversely, immersing in filtered water for 6 minutes yielded the lowest carbohydrate content. Doubling the immersion time resulted in a 2.1% decrease in carbohydrate content. Similarly, reducing the pressure of the cold plasma treatment from 5 to 1 atm pressure led to a 7.17% decline in the sugar content. Additionally, immersing in filtered water, compared to cold plasma treatment at 1 atm pressure, caused a 10.82% reduction, while at a pressure of 5 atm, this reduction was 17.88%.

As time progresses, the hardness of the fruits diminishes, likely attributed to the deterioration of cell walls, changes in pectin and cellulose content, and alterations in enzymatic activity (Choi et al., 2013). Table 5 shows the analysis of variance for the hardness of apple slices obtained from different treatments.

Table 4. Carbohydrate content of apple fruits

T (minutes)	P_5	P_1	Filtered water	Average
3	18 a	16 a	14.5 a	16.17 a
6	16.83 a	16.33 a	14.33 a	15.83 a
Average	17.42 a	16.17 ab	14.42 b	

P_5=5 atm, P_1=1 atm

Table 5. Means of hardness for apple fruit

T (minutes)	P_5	P_1	Filtered water	Average
3	3.67 a	2.87 a	2.82 a	3.12 a
6	3.57 a	3.15 a	2.76 a	3.16 a
Average	3.62	3.02	2.79	

P_5 =5 atm, P_1 =1 atm

Cold plasma treatment at a pressure of 5 atm and an immersion time of 3 minutes yielded the highest hardness, whereas immersion in filtered water for 6 minutes yielded the lowest hardness value (Tabel 5). Doubling the immersion time led to a 1.28% increase in hardness. On the other hand, reducing the pressure of the cold plasma treatment from 5 to 1 atm caused a 16.5% decrease in the hardness, leading to a 7.61% reduction. This reduction was more pronounced at 5 atm, reaching 22.92%.

The effectiveness of cold plasma treatment in preserving the hardness of apple slices can be attributed to its capability to inactivate the enzymes found in apples. These enzymes contribute to the softening and cell wall breakdown during the ripening process. (Punia Bangar et al., 2022; Mayookha et al., 2022). Cold plasma treatment also induces surface drying of the apple slices, resulting in a firmer texture (Du et al., 2022).

Based on Tables 2, 3, and 5), it is evident that there are no significant differences among the various treatments, and there is an overlap between them when the statistical significance is $p < 0.05$. However, there were notable differences in the carbohydrate content of apple slices according to the treatments (Table 4).

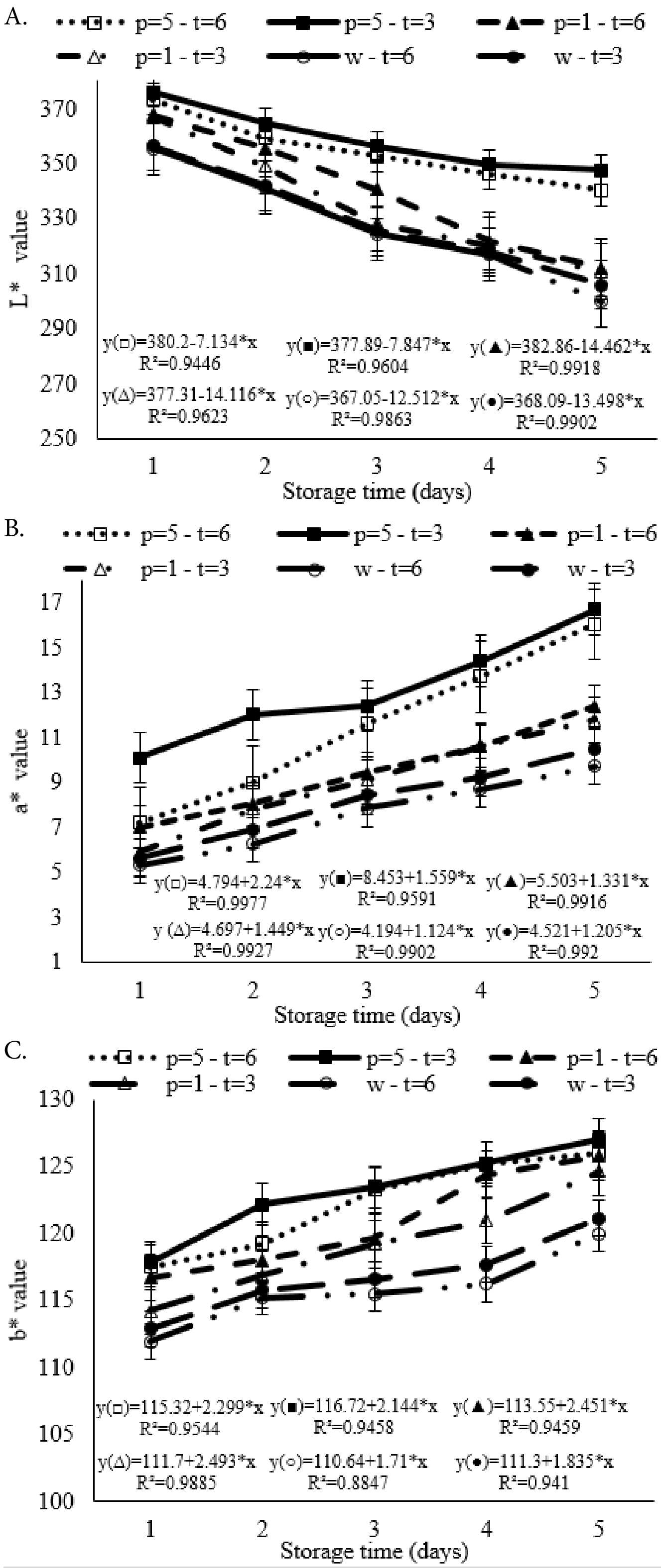
The storage period of apple slices impacts their color, often resulting in browning during storage. Figures 3A, 3B, and 3C depict the relationship between the distinct coefficients of apple slices and their corresponding L*a*b* values.

Figure 3 shows an inverse correlation between the L* value (reflected light intensity) and the storage time. Conversely, a direct relationship is observed between the a* values (indicating the red-to-green color) and b* values (representing the blue-to-yellow color) concerning the storage time.

Browning occurs due to fruit enzymes reacting with airborne oxygen, generating compounds like melanin and polyphenols, which darken the fruit's color (Singh et al., 2018). The color of the fruit affects the degree of color absorption (Al-Sammarraie et al., 2023).

Among the treatments, cold plasma treatment at 5 atm pressure with an immersion time of 3 minutes showed the most favorable L*a*b* values. Conversely, filtered water treatment at immersion times of 3 and 6 minutes yielded the lowest L*a*b* values. This result is attributed to cold plasma's ability to suppress ripening and browning enzymes while increasing the activity of antioxidant enzymes (Punia Bangar et al., 2022; Tappi et al., 2019). Studies indicate that cold plasma treatment can enhance color preservation and reduce darkening during storage (Pankaj et al., 2018).

Regarding the results observed, the superiority of cold plasma treatment at 5 atm pressure compared to 1 atm pressure can be attributed to high-pressure cold plasma generating a denser and more uniform plasma layer on the surface (Mandolfino et al., 2014; Turkoglu Sasmazel et al., 2021; Jihad, 2021). Concerning immersion time, excessive processing or



p = cold plasma treatment; t = immersion time; w = filtered water

Figure 3. A. L*, B. a*, and C. b* coefficients according to the storage time (days)

high plasma density can potentially harm fruit tissues and diminish overall fruit quality (Chen et al., 2020; Ketan & Aadim, 2023). Thus, the results underscore the effectiveness of cold plasma 5 atm pressure with a 3-minute immersion time compared to the 6-minute immersion time. Similarly, cold plasma treatment at 3 atm pressure with a 6-minute immersion time yielded better results.

Conclusions

1. The apple slices immersed in the cold plasma treatment at the pressure of 5 atm and 3-minute immersion time gave a sugar content of 17.5 °Brix, a carbohydrate content of 18, a degree of hardness of 3.67 kgf cm^{-2}, and a better color quality. The treatment with filtered water at a 6-minute immersion time gave the highest value for the moisture content of apple slices.

2. A positive relationship exists between storage time and a* and b* values. On the other hand, there is an inverse relationship between the L* value and storage time.

3. Cold plasma technology is efficient in the treatment of apple slices to maintain the quality of their internal and external characteristics, extend the storage period, and preserve the nutritional value.

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