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Design and Implementation of a Pulsed Plasma System Combined With Image Processing For Plant Processing

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ABSTRACT

Applying plasma food and plant products to improve their quality is a novel goal considering the importance of food security for human societies. The present study aims to design and implement a portable and cost-effective plasma generator system for use in plant environments. Different dielectric materials were evaluated. To evaluate the system, the plasma was applied on the leaves of different plants. Also, image processing technology was applied to investigate the effect of pulsed plasma on plants. The results indicated the suitability of glass rather than paper dielectric. Based on the related image processing findings of samples, the effect of plasma on the color indices, it can be concluded that pulsed plasma was successful in drying the samples. The values of changed color indexes (R, G, B, L*, a*, and b*) indicate the dryness of the samples affected by plasma. So, the plasma system can be used as an in plant environment.

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INTRODUCTION

Sustainable production requires new and beneficent technologies to increase technical performance (Kheiralipour, 2022). Biosystems engineering involves applying new technologies on agricultural, biological natural resources, and food (Kheiralipour, 2024). One of the interesting technology in biosystems engineering in plasma. Although the specific interaction of plasma with surfaces, tissues, and cells is not fully understood (Laroussi, 2009). It has been proposed as a novel method in plant, fruits and vegetables, and food products (Bourke et al., 2018; Sarangapani et al., 2017). It is a gas medium that contains active atoms and excited molecules, charged particles (ions, electrons), free radicals, and ultraviolet waves. It is electrically neutral; however, due to the presence of free charge carriers, it is a conductor of electric current, and its electrical conductivity can be even higher than that of metals such as gold and copper. In fact, as a highly ionized gas and a good electrical conductor, plasma exists in two forms: natural and artificial (laboratory-generated) (Fridman et al., 2008).

Plasma technology and various plasma devices including DBD, jet, and corona plasma, each with distinct characteristics, have been applied in research on plant products (Guragain et al., 2023). This is due to the absence of thermal damage to living materials, the lack of special facilities, and the low costs associated with ambient air use, and other available gases, and the lack of a vacuum (Pańka et al., 2022). Different researches showed the effect of plasma on seed germination (Dobrin et al., 2015), inactivation of pathogen (Lu et al., 2014), storage life (Ramazzina et al., 2015), and antioxidant activity and phenolic content of agricultural materials (Won et al., 2017). In point of drying, plasma has been used as a pretreatment in drying process of grain (Bai et al., 2025) and thin layered fruits (Subrahmanyam et al., 2024). However, the novelty of the present research is to apply plasma on plant leaves.

In other hand, image processing is a beneficial technology that has vast applications in different fields through processing the acquired images and analysis the obtained data. It has different advantages including high speed, high reliability, and low cost (Kheiralipour, 2024). This technology has been applied for plant medium (Kheiralipour, 2024). Image processing has been used to calculate color indexes of different image spaces. So, the goal of the present research is to design, implement, and evaluation of a portable and cost-effective plasma generator system for use in plant environments and using image processing technology to evaluate its effect on plant.

MATERIALS AND METHODS

Artificial plasma is further classified into equilibrium (hot) plasma and non-equilibrium (cold) plasma based on the temperature and thermal balance within it (Kong et al., 2009). Plasma production methods include electron beam irradiation, various electrical discharge techniques such as glow discharge, corona discharge, dielectric barrier discharge, radio frequency discharge, and floating electrical discharge. Common plasma generation methods include dielectric barrier discharge, jet discharge, corona discharge, and microwave discharge. Most plasma generation sources are based on dielectric barrier discharge (DBD), it is generated between two electrodes, each covered with a dielectric layer, often made of glass (Jayasena et al., 2015). In this method, the dielectric barrier limits the electric current, prevents the electric sparks and ohmic current, and only allows the generation of a displacement and convection current (Bárdos & Baránková, 2010). By adding a circuit that generates regular alternating pulses with desired and adjustable frequencies to the system, pulsed plasma is also created. Notably, pulsed electrical discharge includes both microsecond pulse discharge and nanosecond pulse discharge. The gas mass is at ambient temperature in the pulsed plasma in this method, but the electrons that are generated through plasma ionization have a high temperature and sufficient energy to drive a chemical reaction. By switching from continuous to pulsed electrical discharge mode, these electrons are still produced. However, because they must collide with reactant molecules shortly after being generated to initiate reactions, this process occurs within a very short time frame. If the source generates very short pulses in the nanosecond range, reaction disruption is minimized. Moreover, energy consumption is reduced, which significantly enhances the overall energy efficiency. In this type of plasma, the pulse frequency is a very important parameter that significantly affects the conversion rate, reaction progress, and the energy consumption efficiency. In the present research, an integrated LM555 bromine-based pulse generator circuit has been developed for plasma generation, as shown in Figure 1.

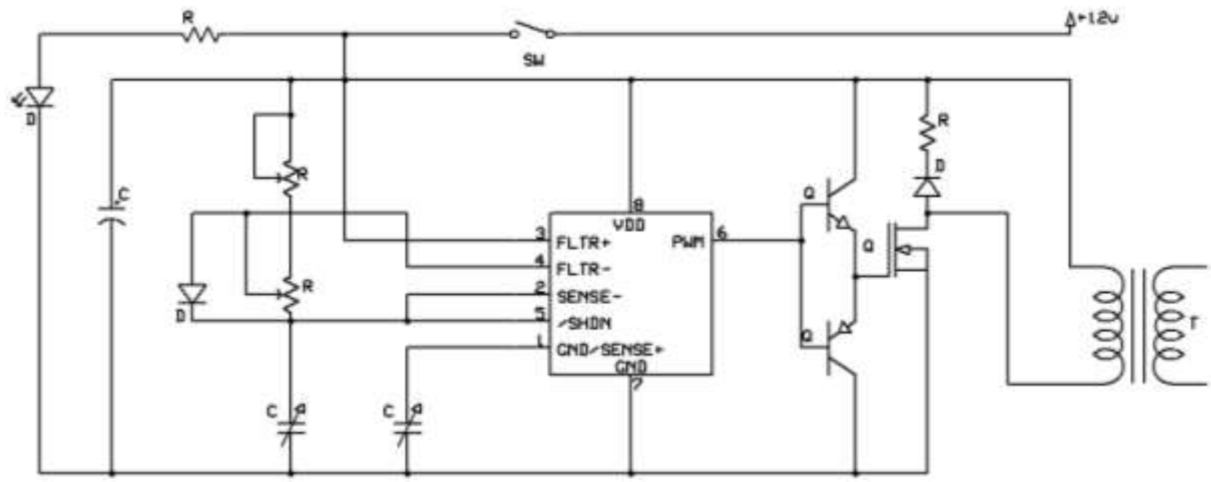

Figure 1. Proposed driver circuit for pulsed plasma generator.

In the proposed integrated circuit driver, a square wave is used to drive the power MOSFETs that switch a flyback transformer. The switching of the MOSFETs at a specific frequency is controlled by the duty cycle and frequency of the 555 timer, thereby generating the high voltage required to produce plasma at the output of the transformer. In the prototype built in this research, a potential difference between 0 and 30 kV was measured at the transformer. The LM555 timer generates a stable pulse, with its frequency and duty cycle controlled by potentiometers connected to the timer, and the output signal is used to drive the MOSFETs at a switching frequency between 10 and 40 kHz. Given the relatively high power of the MOSFETs, a heat sink is used and capacitors were used to control power dissipation. Following the initial simulation and signal verification, the printed circuit board for the desired circuit was fabricated, the electronic components were assembled on the board, and appropriate packaging was prepared, resulting in a laboratory-scale sample device ready for operation.

In the next step, to apply the designed system to a plant medium, a suitable reactor was designed and implemented according to the schematic shown in Figure2. The device initially subjected to numerous energy test as output energy is a critical factor in studies related on the plant medium. Finally, the main prototype was operational, as shown in Figure 3 and the initial tests regarding its effect on the plant medium were successfully reported in this research. As shown in Figure 2 and 3, the dielectric barrier corona discharge system consists of a flat plate electrode and a needle-shaped one placed at a specific distance, with a dielectric between them.

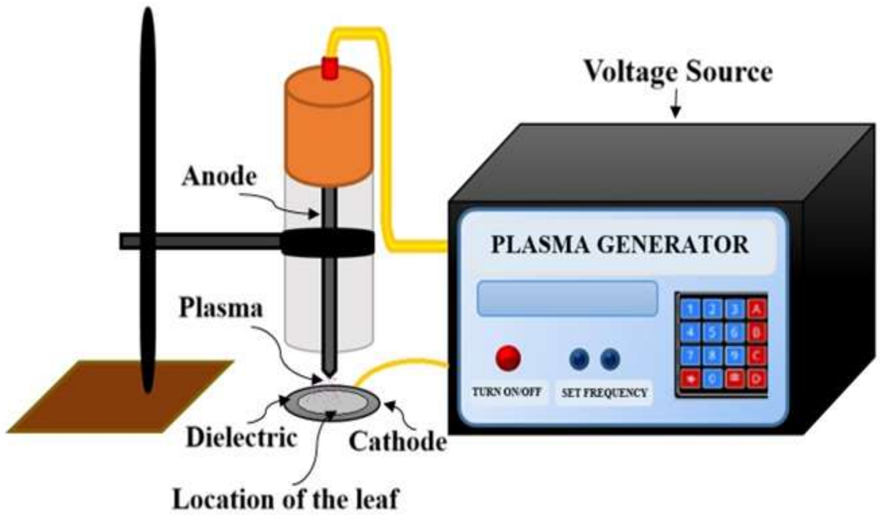

Figure 2. Schematic of the proposed electrical discharge reactor pulsed plasma system.

In other words, a flat lead plate with a 5.30 cm diameter served as the bottom electrode, while a copper needle electrode with a tip diameter equal to 1.38 mm was positioned 1.5 cm above it. The electrode assembly was placed inside a Pyrex cylinder with a length of 10.5 cm, and an inner diameter equal to 34 mm; its wall thickness is 2 mm, with a paper dielectric placed between the electrodes. The electrodes were connected to the pulsed plasma generator, as shown in the figure. The gas used in this experiment was air, which was supplied through the air gap between the bottom electrode and the quartz cylinder maintained by a support base. Atmospheric pressure air was chosen as the working gas due to its availability, reduced treatment costs, ease of development and commercialization, and its composition being over seventy percent nitrogen. Moreover, in addition to the above advantages, the presence of nitrogen, which is essential for chlorophyll production, was also considered. Since plasma technology is an efficient and environmentally friendly method of promoting plant growth that reducing the use of chemical fertilizers (Adhikari et al., 2020), it is also economically viable due to reduced energy consumption and cost. On the other hand, plant structures are mainly composed of lipids, and the energy required to excite lipids has been reported to be about 12-14 keV which is achievable using plasma technology. In this research, using the proposed circuit, a pulsed plasma device was successfully designed, and its laboratory prototype was implemented as shown in Figure 3 (top image). The generation of plasma and its initial effect on plants was demonstrated in Figure 3 (middle images show plasma generation and bottom images show the effect on the plant environment).

Figure 3. The fabricated laboratory prototype (top), the produced pulsed plasma (middle), plant sample before (bottom left), and plant after 10 min of plasma application (bottom right).

To evaluate the implemented plasma system, the leaves of mint plant were exposed to plasma at a voltage of 12.5 kV and a frequency of 625 Hz for 10 min. Also, the effect of plasma exposure duration in the experiment has been investigated. Also, the effect of dielectrics was examined. For that two types of paper and glass dielectrics were tested.

Then, image processing technology was employed to evaluate leaves of 25 different plant species, including leafy vegetables and tree leaves. The leaves were collected and stored in a cold box until the experiment to prevent wilting or possible changes. The leaves were exposed to plasma at a voltage of 12.5 kV and a frequency of 625 Hz for 10 min. The experiments were conducted in same condition in room temperature for all plants.

The image of the leaves was captured using a digital microscope before and after plasma application, in same condition for all plants' leaf. In image processing task, the images from RGB color space were transferred to L*a*b* and then different images channels were extracted including R, G, B, L*, a*, and b* channels (color indexes) (Kheiralipour, 2024). A box of the center part of each image was cropped and the values of all channels were calculated. The R channel shows the red color values, the G channel shows the green color values, and the B channel shows the blue color values of the images. The pixel value in each channel is from 0 to 256 that were normalized to be between 0 and 1, in the present research. The L* channel represents the brightness of the image from black (0) to white (100), while the a* and b* channels represent the color value of the images from -150 to +150, meaning that a negative value of the a* channel corresponds to green, a positive a* to red, a negative b* to blue, and a positive b* to yellow. For the images before and after applying plasma to each of the leaves, the values of the indexes were obtained by writing a codes in MATLAB software. The obtained data was prepared as an Excel output. Following plotting the color indexes of all leaves before and after plasma application, the change of each index was calculated using Eq. 1.

$$\Delta \mathrm{I} = \frac{\mathrm{I}_2 - \mathrm{I}_1}{\mathrm{I}_1} \times 100 \qquad (1)$$

Where I1 and I2 represent the value of the specific indexes (R, G, B, L* a*, and b*) before and after plasma application and ΔI show the change in the value of the indexes in percentage.

RESULTS AND DISCUSSION

Dielectric Effect

Figure 4 shows the effect of different dielectrics on plant during plasma application. The use of quartz dielectrics leads to the vegetables remaining healthy for a certain period of plasma application. Under the same conditions in terms of system type and equal frequency, with the use of paper dielectrics, the electrical discharge as shown in the figure causes leaves and even dielectrics to burn for some plants, which indicates the effect of the dielectric in the characteristics of the plasma system.

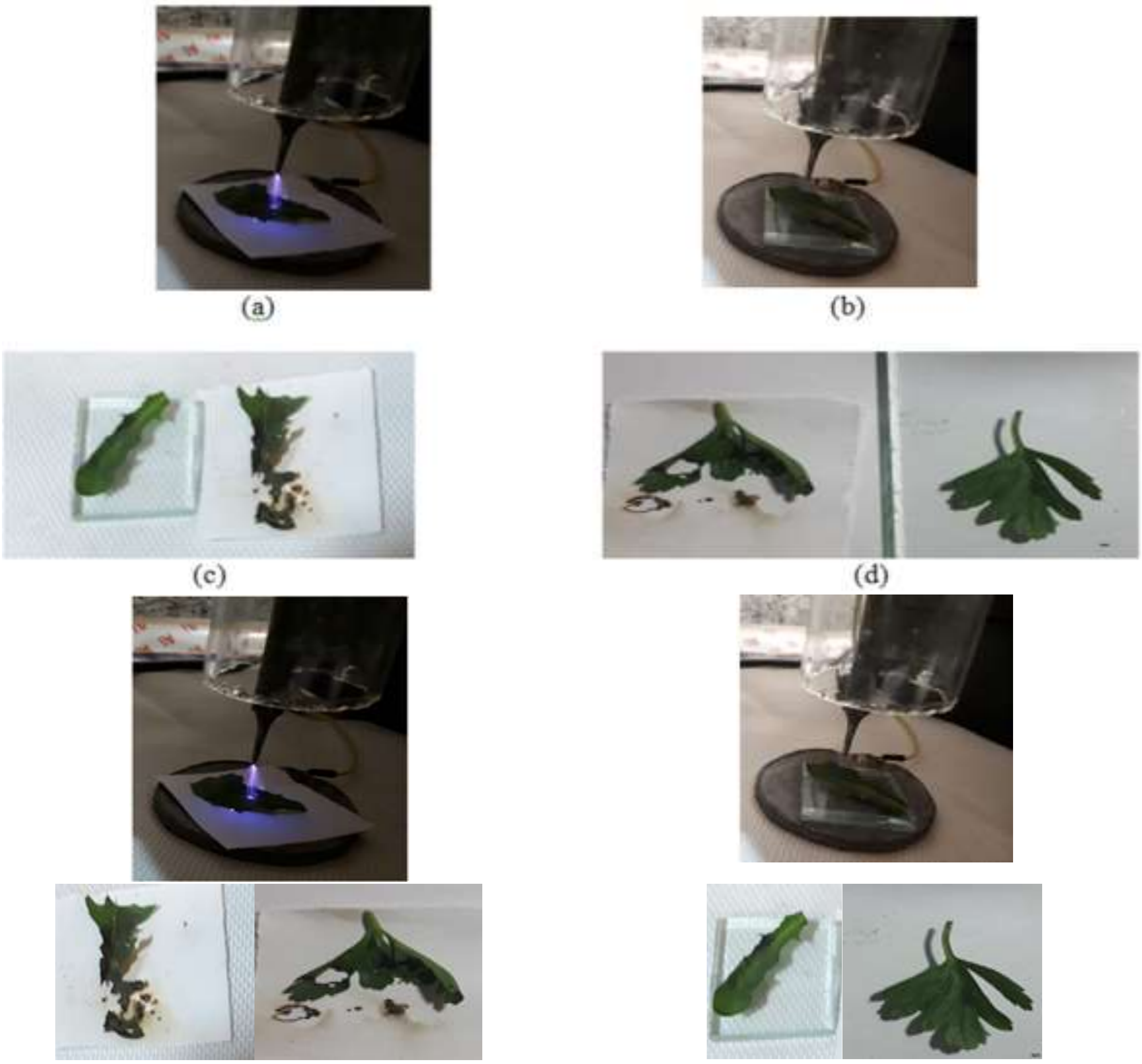

Figure 4. Different types of dielectric, paper (Left) and glass (Right) in the plasma system structure for different plant leaves.

Mint Drying

Table 2 listed the mas of mint leaves after plasma application for 1 t0 3 min. The longer plasma exposure time resulted in greater weight reduction, which can be attributed to increased water loss, and consequently increase in drying.

Table 2. The mass reduction of mint leaves by applying plasma.

Plasma application time (min)	1	2	3
Primary mass of leaves (g)	0.136	0.126	0.131
Secondary mass of leaves (g)	0.096	0.056	0.014
Mass changes (g)	0.040	0.070	0.117

Color Changes

The color indexes of 25 leaves before and after plasma application for 10 min have been plotted in Figure 5. The values of some plants were decreased after plasma application and for others were increased. Then, the changes of the indexes were calculated and listed in Table 2.

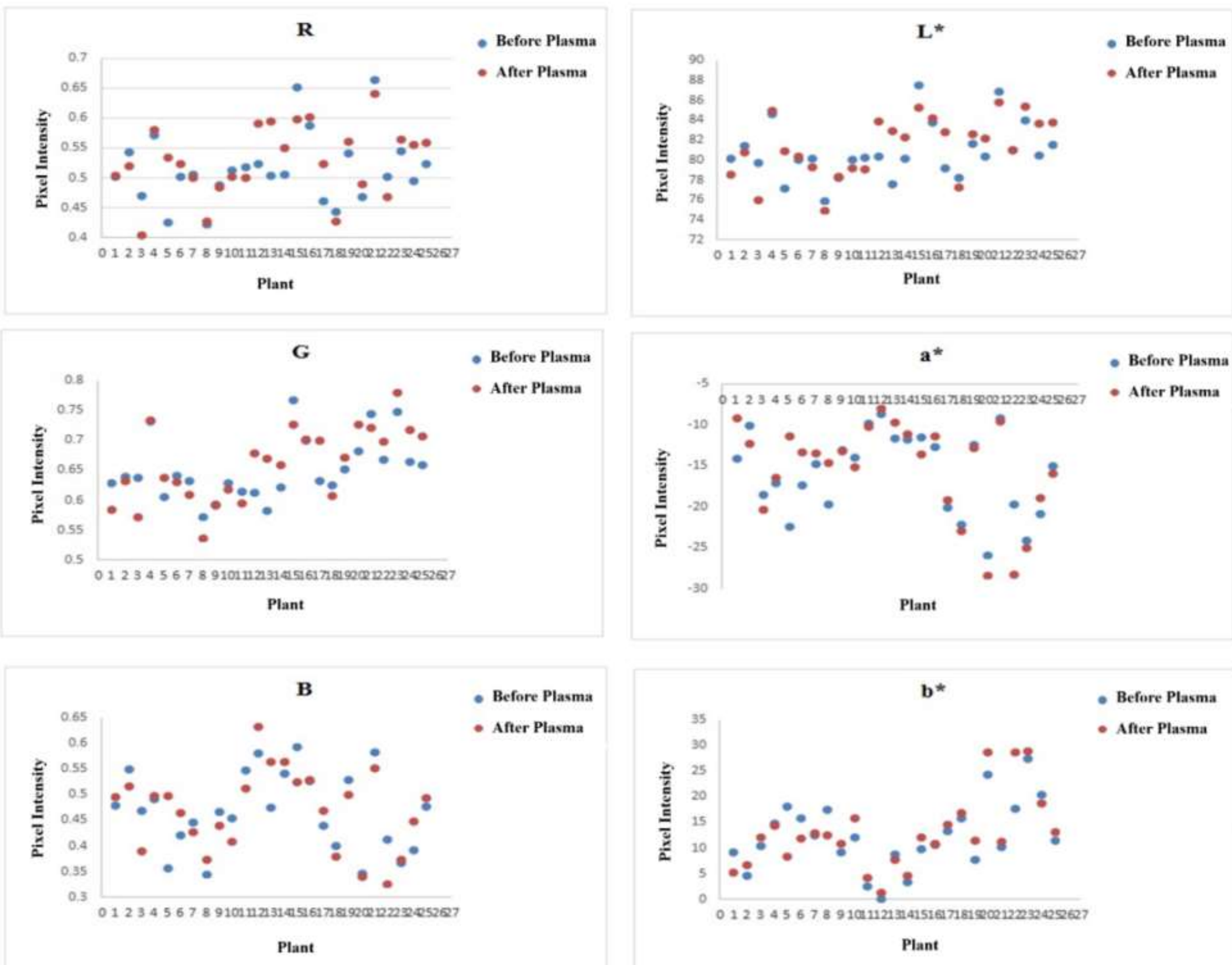

Figure 5. The plotted color indexes of different leaves

Table 2. The values of color change (%) of different leaves.

Plant number (type)	ΔR	ΔG	ΔB	ΔL*	Δa*	Δb*
1 (Mint)	-41.98	-34.59	-2.02	3.40	-6.85	0.35
2 (Chives)	45.22	22.90	-0.98	-6.26	-1.06	-4.37
3 (Badagh)	16.08	10.36	-4.78	-16.91	-10.00	-14.18
4 (Alfalfa)	-2.09	-3.60	0.27	1.26	0.34	1.35
5 (Bidvet)	-53.07	-49.13	4.82	39.46	5.39	25.89
6 (Yas)	-25.12	-22.49	0.36	10.08	-1.36	4.33
7 (Cheese plant)	3.18	-8.12	-1.06	-4.16	-3.25	-1.03
8 (Candlestick)	-28.90	-25.52	-1.33	8.52	-5.94	1.19
9 (Seal)	18.37	2.47	0.01	-5.57	-0.05	-0.67
10 (Ivy)	31.04	9.27	-1.07	-9.93	-1.54	-2.06
11 (Gift)	55.14	5.02	-1.42	-6.42	-3.13	-3.51
12 (Fig)	405.42	-6.44	4.41	8.90	10.71	13.06
13 (Persimmon)	-13.44	-15.41	6.80	18.71	15.40	18.28
14 (Plum)	40.75	-5.01	2.66	4.15	6.32	8.78
15 (Parsley)	22.66	18.43	-2.63	-11.22	-5.14	-8.22
16 (Tarragon)	1.82	-9.44	0.50	0.47	0.28	2.46
17 (Spinach)	8.75	-3.93	4.47	6.54	10.67	13.47
18 (Fenugreek)	6.66	4.07	-1.32	-5.29	-2.53	-3.87
19 (Mulberry)	47.50	4.34	1.08	-5.68	3.01	3.54
20 (Apple)	18.36	9.97	2.12	-1.89	6.65	4.91
21 (Sour cherry)	9.66	4.56	-1.34	-5.54	-3.01	-3.46
22 (Plum)	60.74	44.41	-0.06	-21.02	4.67	-6.64
23 (Grape)	5.22	4.53	1.56	1.67	4.38	3.64
24 (Cherry)	-8.28	-9.05	3.89	13.72	8.38	11.95
25 (Apricot)	14.44	6.65	2.71	3.56	7.34	6.63

In table 2, the changes in the aforementioned values were calculated according to Eq. 1 for 25 samples (%). As is clear from Table 2, the changes in color indices of most samples were from -53 to 405%. The maximum positive changes in the R, G, B, * L, a*, and b* indices were 25.39, 15.40, 39.46, 6.80, 44.41, and 405.41%, respectively, and their maximum negative changes were -14.18, -10.00, -21.02, -4.78, -49.13, and -53.07%, respectively. The values of red (R), blue (B), and green (G) indices increased in 60, 50, and 52% of the samples, respectively. Also, the values of L*, a*, and b* indices increased in 50, 60, and 70% of the samples, respectively. It is worth noting that the value of the L* index (brightness) of the samples was positive before plasma application and became more positive (whiter) in 50% of the samples. The value of a* before and after plasma was negative (towards green). The value of this index became more positive in 60% of the samples after plasma, i.e., it changed color from green to red. The value of b* related to the tested samples was positive (yellow) and decreased after plasma, i.e., it tended towards blue. The changes of the values of the calculated indexes can be related to water reduction of the samples (Alibas et al., 2019; Klement et al., 2021). In other words, the changes in the color indices of the samples indicate the effect of plasma on drying process of them.

CONCLUSIONS

In this research, a circuit of the pulsed plasma generator was proposed and after receiving suitable results of the generated energy for use in the plant medium, a prototype of the proposed design was built. In order to test its effect on the plant, different leaves were exposed to the plasma. There was observed that glass was better than paper in applying plasma on leaves. The values of the color indexes including R, G, B, and L*, a*, and b* were considered, indicating leaves drying. In Future, plasm drying can be compared with other drying method such as hot-air drying, freeze drying, and microwave drying, and assessed the advantages and limitations of plasma drying in terms of energy consumption, quality preservation, and cost. In future research, the effect of the implemented system on preventing the reduction of effective substances in the samples, the destruction of pests and diseases, the prevention of undesirable changes in color and texture, and ultimately increasing the quality of the samples can be investigated.

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