Chapter

Application of Nonthermal Plasma System for Wastewater Treatment

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Abstract

Nonthermal atmospheric pressure plasma jets are becoming increasingly important in wastewater treatment applications. Especially, it is quite difficult to remove the color found in the wastewater of some industries such as textile and paint industries by traditional methods. Therefore, in the study, the color removal efficiency was investigated using atmospheric pressure plasma system. In the design of the system, an electric current is directed from a low pressure gas flow and an atmospheric plasma field is created. Treatment is achieved as a result of contact with the wastewater. In this study, the removal efficiencies of pomegranate wastewater and methyl orange (MO) as a model dye were investigated. Oxygen gas was studied as feed gas. Plasma discharge flow rate was applied as 12 mg/L, and plasma duration was 5 minutes. The results were evaluated for two different wastewaters. For an initial concentration of 20 mg/L, the COD removal efficiencies of methyl orange and pomegranate wastewater (PW) were found to be 83.7 and 98.4%, respectively. The highest color removal efficiency for methyl orange was calculated as 97%. In addition, *Lepidium sativum* toxicity test was used to determine whether there was any toxic effect due to radicals formed in the system. No toxic effects from the plasma system were observed. As a result, inspired by the studies conducted worldwide on the usability of plasma technology in water treatment, the usability of the atmospheric pressure plasma system, which is a new technology in the field of water treatment, was evaluated.

Keywords: atmospheric pressure plasma, methyl orange, pomegranate wastewater, *Lepidium sativum*, degradation

1. Introduction

Water pollution is a serious problem in modern society. Recently, there has been a dramatic increase in the amount of organic pollutants (volatile organic compounds, pharmaceuticals, organic dyes, and so on) detected in water resources, and this poses a serious concern for public health [1]. Colored wastewater is not just an inherent feature of textile and dye waste; it is produced in industries such as food companies, cosmetics industries, chemical and pharmaceutical companies, paper mills, and oil industries [2]. With the rapid development of the printing and dyeing industry, chemical industry, and oil industry, a large amount of low or nonbiodegradable organic dye wastewater is discharged, causing a serious environmental problem [3, 4]. In modern industrial society, large amounts of dyes and other organic pollutants are

emitted into the environment and the organic contamination degradation has become the focus of environmental remediation efforts.

The production amount of dye industries in our country is increasing day by day. Since the increase in production is parallel to the amount of wastewater generated by the facilities, the amount of wastewater generated in this area is also increasing. This type of wastewater is dark colored, has high pH, contains high organic matter, and has low biodegradability [5]. The main processes of pomegranate fruit-juice and other fruit-juice productions are usually in the packing operation where water is used for general washing and cleaning, the selection and cleaning operation where water is used mainly for washing, cleaning, and moving of the fresh fruit prior to the extraction process, juice extraction and treatment, peel treatment, and emulsion treatments. These processes require large quantities of fresh water and also produce plenty of wastewater. These wastewaters are characterized by high chemical oxygen demand (COD) contents of organic matter, a low pH, an imbalance of nutrients, color, dissolved solids, and suspended solids [6, 7]. Hence, the discharge of these types of wastewaters into urban wastewater treatment plants is not allowed, thus requiring a prior treatment. The hazard effluents produced from these industries have serious problems as they are low or nonbiodegradable. The prominent problems for dyeing wastewater treatment are color removal and degradation of organic compounds [3]. Thus, they must be treated to satisfy the water quality standards before discharging into the environment [6].

The development of a new and efficient treatment technique for the organic contaminants is necessary [8]. Various methods such as physical methods [9, 10], chemical methods [11, 12], biological methods [13], and combined methods [14–16] have been proposed. Physical methods such as adsorption [17] can be effectively separated the dye from effluents, but without complete degradation, so a secondary pollution may produce by converting dye from one phase to another. Therefore, physical and chemical methods transfer the pollutants to another phase, which usually induce by-products formation, so this methods are not effective. Biological methods are not effective for the highly colored and low degradable dyeing wastewater [18]. Therefore, the development of environmentally friendly and efficient methods for wastewater treatment receives great attention [19].

Plasma technologies: it is used as a technology that has become increasingly important in recent years in the treatment of persistent, recalcitrant, and difficult-to-remove pollutants in water, requiring less chemical use during treatment and having high removal efficiency in a short time. Plasma oxidation process, with high efficiency and without secondary pollution, is one of the most promising methods for colored wastewater treatment [19]. All plasma systems are classified into two main categories, thermal and nonthermal plasma [20]. In the thermal plasma (such as arc discharges or radio frequency (RF)), sufficient energy is inserted to make the plasma constituents in a thermal equilibrium. On the other hand, less power (such as corona discharge and dielectric barrier discharge) is used to obtain the nonthermal plasma. The nonthermal plasma produces energetic electrons that collide with another molecule such as O_2, N_2, and H_2O produces secondary species include radicals, ions, photons, and electrons [21, 22]. In the remediation of the wastewater, the organic contaminates may be dissociated by the action of the energetic electrons as well as the action of the active radicals and active molecules. Furthermore, the physical effects can also act on the organic pollutants in water. Thus, the remediation of water polluted with organic compounds may be effective and rapid owing to the high oxidative potential of active species as well as the actions of physical effects [6]. Nonthermal

plasma (NTP) is plasma characterized by nonequilibrium conditions: the temperature of the bulk gas, typically near room temperature, is much lower than that of the plasma reactive species, that is, free electrons and ions, atoms and radicals, and excited molecules [23]. Nowadays, NTP has many applications, ranging from microprocessors cooling [24], to surface modification, to living tissues treatments [25], to bio-decontamination [26], and to air [27] and wastewater treatments [26, 28]. In wastewater treatment, a high voltage electrical discharge is applied above the surface of the water inducing physical and chemical phenomena in the gaseous, liquid, and interfacial media. The chemical properties of such complex systems depend on the gas to which the discharge is applied. Oxidant species common to any gas are hydroxyl radicals (OH) and hydrogen peroxide (H_2O_2), formed by the interaction of water molecules with high-energy electrons [28, 29]. In particular, OH radicals are produced by the well-known water dissociation reaction, while H_2O_2 is generally formed by OH recombination [29].

In this paper, the usability of plasma technology, an innovative technology that has gained importance in recent years, in the field of water treatment has been evaluated. Within the scope of the study, an atmospheric pressure plasma system fed with oxygen gas was established to be in contact with liquid. First of all, the removal efficiency of the plasma system was investigated for the aqueous solution of methyl orange dye, which has a stable, molecular structure and is resistant to degradation. However, to test the atmospheric pressure plasma system on colored wastewater, a pomegranate wastewater sample obtained from a fruit processing plant was used. In addition, this experimental study aims to investigate plasma systems, which are an innovative technology, and contribute to the literature with future studies on environmental engineering such as water and wastewater treatment [30].

2. Material and methods

2.1 Material

2.1.1 Reagents

In this study, powdered methyl orange (ZAG Chemical) and powdered $FeSO_4$ (Carlo Erba) powder were purchased from a private medical company and used. Chemicals were used by turning them into synthetic solutions with pure water. 1 M NaOH and 2% HCl were used for pH adjustments.

2.1.2 Apparatus and measuring materials

2.1.2.1 Hydrogen peroxide (H_2O_2) test

Supelco brand MQuant hydrogen peroxide test strips, which can measure in the range of 0.5–25 mg/L (H_2O_2), were used for measurement.

2.1.2.2 pH and conductivity

The pH meter used in the study was obtained from Necmettin Erbakan University Scientific Technology and Research Center, and temperature measurement was also carried out with this device. The conductivity device was obtained from Konya

Technical University, Faculty of Engineering and Natural Sciences, Department of Environmental Engineering, Wastewater Treatment and Research Laboratory.

2.1.2.3 UV-Vis spectrophotometer

For absorbance measurement, SHIMADZU brand UV-3600 Plus model UV-VIS-NIR Spectrophotometer, located within Necmettin Erbakan University Scientific Technology and Research Center, was used.

2.1.2.4 Lepidium sativum toxicity test

For *Lepidium sativum* toxicity analyses; 9 cm diameter glass petri dishes, 90 mm diameter Whatman 1 brand filter paper, deionized water, and cress seeds were used.

2.1.2.5 Atmospheric pressure plasma system

In the study, the OptoSense brand mini atmospheric plasma system within the Necmettin Erbakan University Scientific Technology and Research Center was used. The device consists of Radiofrequency generator was shown in **Figure 1(a)**, flexible gas distribution pipe and probe. The device has a size of 380 × 280 × 280 mm

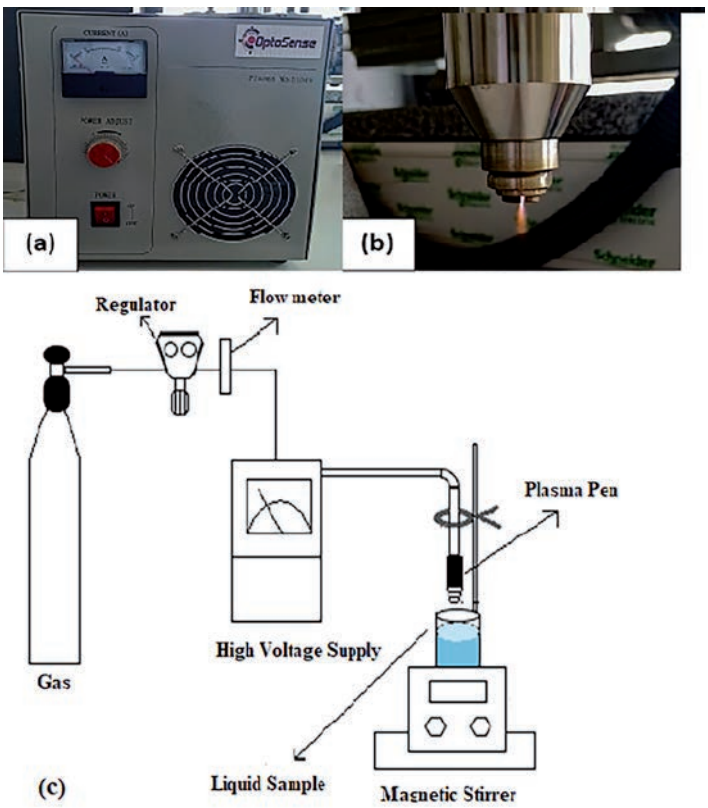


Figure 1.
(a) Plasma power supply, (b) Plasma beam, and (c) Experimental setup of atmospheric pressure plasma system [30].

UXHXW. The probe of the device has a 10–12 mm round head part and a 15–18 mm rectangular part on its body, as shown in **Figure 1(b)**. The device has 1000 VA expandable power and 220 (±5%) power. Inlet gas pressure is 2–2.5 kg 0.12 m^3/min. The device has been modified for use under laboratory conditions and made suitable for liquid sample processing. In order to increase the removal efficiency during the process, a magnetic stirrer was placed under the heat-resistant glass container containing the liquid sample. Since the device works with supply gas, it was connected to an oxygen cylinder. A flow meter was used to control the gas flow. A regulator was used to ensure pressure adjustment and gas flow. The experimental setup of the plasma system is given in **Figure 1(c)**.

For a better understanding of the work process, the workflow diagram is given in **Figure 2**.

2.2 Methods

2.2.1 Preparation of solutions

2.2.1.1 Preparation of methyl orange solution

To prepare 100 mg/L methyl orange stock solution, first 0.1 g of powdered methyl orange was taken into a 100 mL beaker and weighed on a precision balance. First, 80 mL of pure water was added to the beaker and mixed for 5 minutes in the mixer. The mixture was poured into a 1000 mL volumetric flask. By adding pure water to the

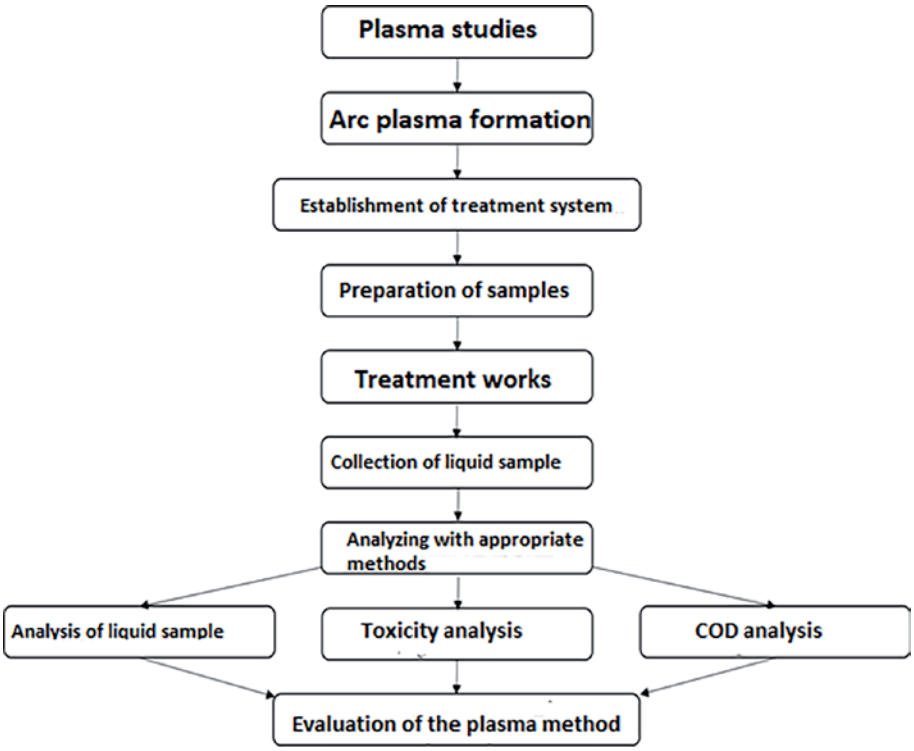


Figure 2.
Experimental flow diagram [30].

volumetric flask, it was filled to 1000 mL and shaken. 100 mg/L methyl orange stock solution was obtained. The following (Eq. (1)) was used to prepare dilute solutions at different concentrations:

$$M1 \times V1 = M2 \times V2 \quad (1)$$

$M1$ = Concentration to be prepared (mg/L); $V1$ = Volume to be prepared (mL); $M2$ = Stock solution concentration (mg/L); $V2$ = Volume to be ta ken from the stock solution (mL).

2.2.1.2 Preparation of iron 2 sulfate ($FeSO_4$) solution

To prepare a 1000 mg/L stock solution with powdered $FeSO_4$ with a molar mass of 278.05, 4.978 g of $FeSO_4$ powder was weighed and prepared according to the stock solution preparation procedure. In the study, iron II sulfate ($FeSO_4$) catalyst was used to investigate the effect of methyl orange on plasma removal efficiency.

2.2.2 Preparation of pomegranate wastewater sample

In the study, the efficiency of the atmospheric pressure plasma system was investigated in a colored wastewater sample. For this purpose, decolorization of a pomegranate wastewater sample obtained from a Fruit Processing Industry was tried with the plasma system. The supplied pomegranate wastewater sample was diluted at 100%, 25%, 10%, and 5% before the plasma study. These dilutions were taken into 50 mL sample containers for initial absorbance measurements.

2.2.3 Working principle of UV-Vis spectrophotometer

UV-Vis Spectrophotometer was used to determine color removal efficiency, and necessary calculations were made according to absorbance measurement results. For removal efficiency calculations, standard solutions of methyl orange samples were prepared at concentrations of 1, 3, 5, 7, and 10 mg/L and absorbance measurements were made. Calibration graphs were obtained with the absorbance values of the standard solutions for methyl orange at 465 nm [31]. From this calibration chart, the formula y = ax + b was obtained. When calculating the removal efficiency, the absorbance value (Co) of the initial sample was accepted as the y value in the formula. In the formula, the x value was accepted as the absorbance value (C) of the sample after plasma treatment. If dilution was made in the samples before absorbance measurement, the result was multiplied by the dilution ratio. After the C value was found, the % removal efficiency was calculated from the formula (Co-C)/Co*100 [32].

2.2.4 Lepidium sativum toxicity test procedure

Lepidium sativum acute toxicity test method was preferred for toxicity analyses. Toxicity testing was performed for the initial and post-plasma treatment samples of the methyl orange solution prepared under optimum conditions (20 mg/L concentration, 5 min. Plasma time, 5 min. Mixer time, 1.5 cm distance, 12 mg/L flow rate). *Lepidium sativum* toxicity test was performed with 6 controls and 3 methyl orange solutions prepared in dilutions of 3.125, 6.25, 12.5, 25, 50, and 100%. In the

experiment, two 90 mm diameter Whatman 1 brand filter papers were placed in 9 cm glass petri dishes. 5 mL of pure water was placed in the control petri dishes, and 5 mL of the prepared sample at different dilutions was placed in the sample petri dishes, and placed so that no air bubbles remained under the filter paper. 25 undamaged *Lepidium sativum* seeds of equal size were placed in each petri dish at equal intervals, and the sealed petri dishes were incubated in a dark environment at approximately 25°C for 72 hours. At the end of the test period, the root and stem lengths of the 20 best-developing *Lepidium sativum* seeds in each petri dish were measured. At the end of the test period, the average values of root and stem lengths observed in the *Lepidium sativum* seeds of the samples were compared with the average root and stem length values measured in the control petri dishes, and the % inhibition rate and EC_{50} value were determined. The studies were evaluated according to the toxicity classification by calculating the % inhibition values and Toxic Unit value for 3.125, 6.25, 12.5, 25, 50, and 100% dilutions.

2.2.5 COD measurement

Analysis was carried out with the SM 5220 C method. For this study, initial and post-plasma COD analyzes were performed on methyl orange solution and pomegranate sample prepared under optimum conditions. % removal efficiency was calculated from the analysis results.

2.2.6 Atmospheric pressure plasma system working principle

The atmospheric pressure plasma and magnetic stirrer devices were turned on and the distance between the probe, and the sample was adjusted to the desired size. 50 mL sample was taken into the beaker where the study would be performed and placed in the magnetic stirrer in the plasma device. The magnetic stirrer was added to the system to accelerate the reactions that occur during and after the plasma process. The sample continued to be mixed for the desired periods of time while the plasma was running and after the plasma was turned off. Oxygen gas was used as feed gas in the experiments. After the gas cylinder valve was opened, the flow meter and ampere levels were fixed and the gas pressure was brought to the desired level by turning the regulator valve. The removal process was carried out by initiating the interaction of the plasma beam and the sample.

3. Results

3.1 Effect of plasma on methyl orange color removal

In this study, 3 replicate studies were carried out under the same conditions with 50 mL of methyl orange solution at a concentration of 20 mg/L to test the effect of the Atmospheric Pressure Plasma System on methyl orange removal. Absorbance measurements were read at 465 nm on a UV-Vis Spectrophotometer. Optimum conditions were provided for the study, and the removal efficiency is given in **Table 1**, and the absorbent curve graph is given in **Figure 3**.

Jiang et al. [31] used an oxygen-fed atmospheric pressure plasma system in their study. 20 min after plasma treatment, they reached 92% removal efficiency of methyl orange solution with a concentration of 40 mg/L. The results obtained were found to

Concentration (mg/L)	Initial UV (abs)	Post UV plasma (abs)	Removal efficiency (%)
20	1586	0,05	97
20	1586	0,034	98
20	1586	0,049	97

Table 1.
Effect of plasma on methyl orange removal efficiency [30].

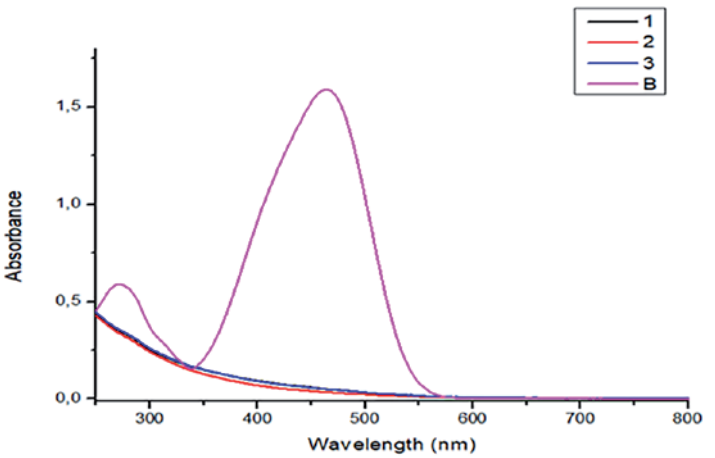


Figure 3.
Absorbance graph of methyl orange analyzes performed under the same conditions as plasma (B: Starting sample) [30].

be compatible with the literature. They stated that hydroxyl radicals and O_3, which have high oxidation potential, are effective for the degradation of pollutant color molecules, and based on the theory of bond dissociation energies, they gave suggested ways for the oxidation of MO with hydroxyl and ozone radicals in their research. Accordingly, the oxidation pathways of MO molecules and their intermediate products in the plasma treatment process were given in **Figure 4**.

In **Figure 5**, the increase-decrease slopes of pH (A) and conductivity (B) results of plasma studies performed with MO solutions were given, respectively. Accordingly, it was observed that the initial pH decreased after plasma. When the conductivity curve was examined, an increase in conductivity was observed after the plasma treatment.

3.2 Effect of catalyst

FeSO4 was preferred to examine the effect of catalyst addition on removal efficiency. For this purpose, catalyst was added at a fixed concentration of 20 mg/L to the methyl orange synthetic solution prepared at a concentration of 20 mg/L. Absorbance readings of the study were made at 465 nm for methyl orange. The removal effect of catalyst addition on methyl orange is given in **Table 2**. The absorbance curve graph is given in **Figure 6**. According to the analysis results obtained in the study, it was concluded that the reaction rate of the atmospheric pressure plasma system for methyl orange removal is high, but the addition of catalyst may not be necessary.

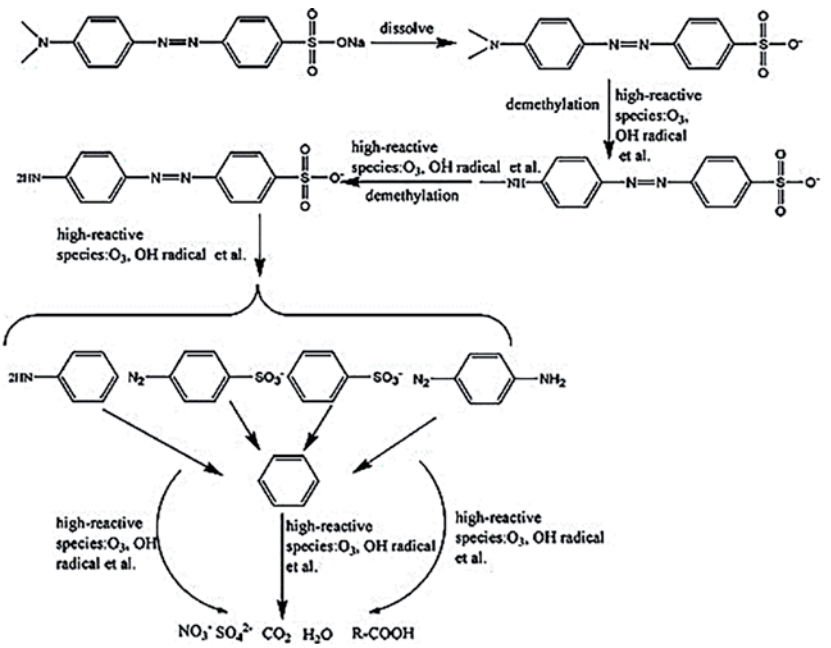


Figure 4.
Proposed pathways for mineralization of methyl orange molecules by atmospheric pressure plasma system [31].

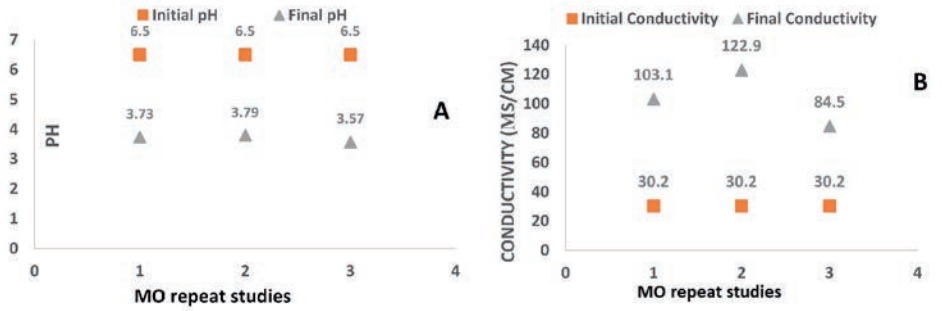


Figure 5.
Initial (before plasma) and final (after plasma) pH (A) and conductivity (B) values of 3 samples studied under the same conditions [30].

Concentration (mg/L)	Initial UV (abs)	Post UV plasma (abs)	Removal efficiency (%)
20	1582	0,142	91

Table 2.
Effect of $FeSO_4$ addition on MO removal efficiency [30].

Figure 7(A) and **(B)** shows the increase-decrease slopes of pH and conductivity results, respectively, of plasma studies conducted with catalyst-added MO solution. Studies have shown that initial pH decreases after plasma. When the conductivity curve was examined, an increase in conductivity was observed after the plasma treatment.

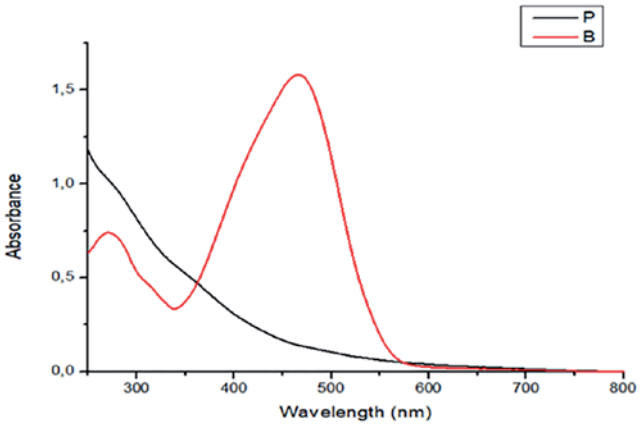


Figure 6.
Absorbance graph of samples before (B) and after (P) plasma treatment of MO solution with catalyst addition [30].

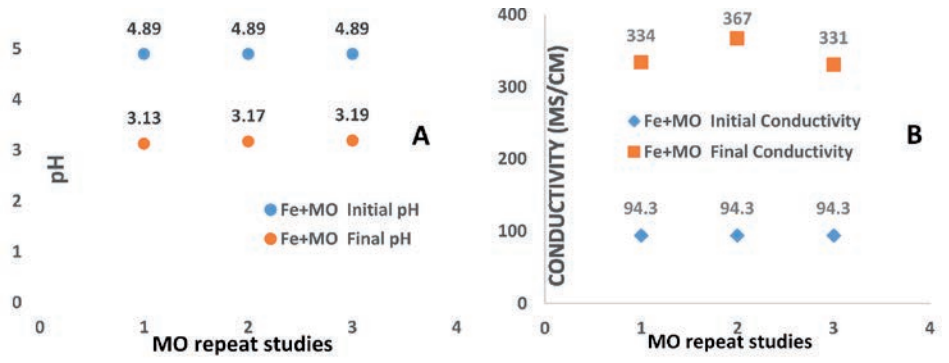


Figure 7.
Initial (pre-plasma) and final (post-plasma) pH (A) and conductivity (B) values of the catalyst-added MO sample [30].

3.3 Effect of plasma on colored wastewater sample

Oxygen gas-fed plasma study of the pomegranate wastewater sample obtained from a Fruit Processing Facility was carried out under optimum conditions. 660 nm of samples diluted in certain proportions. Absorbance values were also read. The absorbance curve graph is in **Figure 8**, and the pH and conductivity graphs are in **Figure 9(A)** and **(B)**. When looking at the absorbance values before and after plasma given in **Table 3**, a decrease in color removal was observed. According to the graphs of the increase-decrease slopes of pH and conductivity results, it was seen that the initial pH of the studies decreased after plasma. When the conductivity curve was examined, an increase in conductivity was observed after the plasma treatment.

Regarding pomegranate wastewater, reference [33] investigated the color removal of pomegranate juice with atmospheric pressure plasma in their literature study. They worked for 3, 5, 7 minutes for the plasma process and achieved color removal after the plasma process.

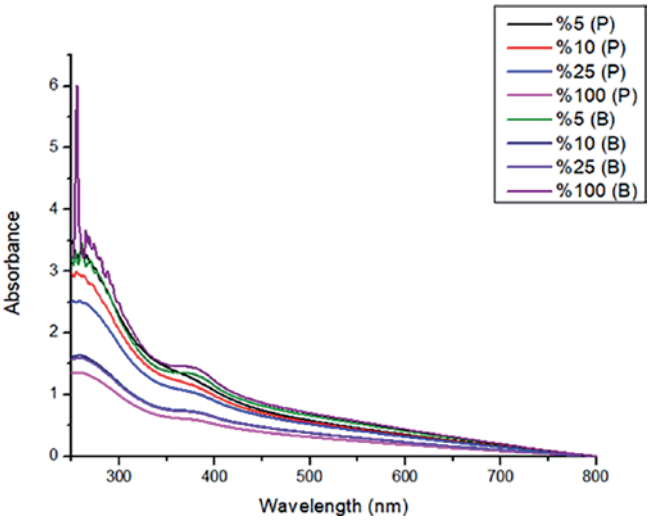


Figure 8.
Absorbance values of the pomegranate wastewater sample studied with different dilutions before (B) and after (P) plasma treatment [30].

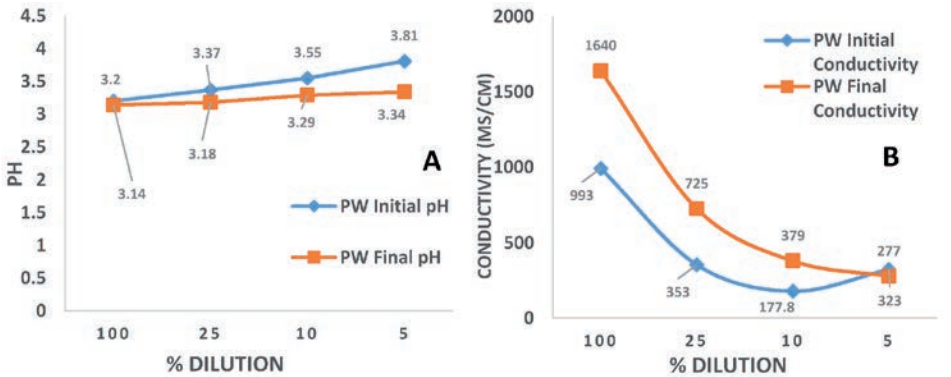


Figure 9.
Initial (before plasma) and final (after plasma) pH (A) and conductivity (B) values of the pomegranate wastewater sample studied with different % dilutions [30].

Dilution ratio (%)	Initial UV (abs)	Post UV plasma (abs)
100	0,395	0,916
25	0,284	0,299
10	0,271	0,332
5	0,152	0,238

Table 3.
Effect of plasma system on color removal of pomegranate wastewater sample [30].

3.4 COD effect of plasma

The COD pollution parameters of the methyl orange synthetic solution prepared under optimum conditions and the pomegranate wastewater sample taken from the fruit processing plant were examined before and after plasma treatment. The initial COD values, post-plasma COD values, and % removal values of the samples are given in **Table 4**, and the comparison of % removal efficiencies is given in **Figure 10**. In the literature, reference [31] used an Atmospheric pressure plasma system working with oxygen gas in their study and stated that plasma could efficiently reduce organic pollutants with a 67% COD removal efficiency as a result of a 20 minute plasma treatment for methyl orange removal.

3.5 *Lepidium sativum* toxicity test results

In the study, *Lepidium sativum* toxicity test results were determined for the methyl orange synthetic solution prepared under optimum conditions and kept in plasma discharge. In the study, dilution rates of 3.125%, 6.25%, 12.5%, 25%, 50%, and 100% were used. EC_{50} value and Toxic Unit (TU) value were calculated according to *Lepidium sativum* toxicity test results. In this study, the EC_{50} values and toxic unit classification calculated for the *Lepidium sativum* toxicity test are given in **Tables 5** and **6** for MO initial and post-plasma, respectively.

The result of the *Lepidium sativum* toxicity test was given for the initial and post-plasma solution sample according to toxic unit classification. According to the results of the study, the Toxic Unit values of the methyl orange solution were "Slightly Toxic" according to the root and hypocotyl values before and after plasma [34]. In their study, the toxic classification was found as "Toxic" according to the *Lepidium sativum*

Samples	Initial COD (mg/L)	Post plasma COD (mg/L)
PW	65,600	1024
MO	256	41,6

PW: pomegranate wastewater, MO: methyl orange.

Table 4.
COD removal efficiencies of pomegranate wastewater sample and MO solution [30].

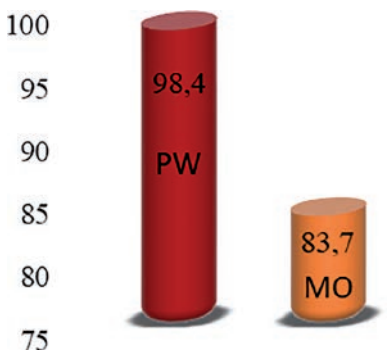


Figure 10.
COD % removal efficiency comparison [30].

Active ingredient	EC_{50}	TU	Classification
Root Length	440,084	0,227	Slightly Toxic
Hypocotyl Length	538,131	0,186	Slightly Toxic

Table 5.
Calculated EC_{50} and toxic unit value for methyl orange initial solution [30].

Active ingredient	EC_{50}	TU	Classification
Root length	450,802	0,222	Slightly toxic
Hypocotyl length	552,409	0,181	Slightly toxic

Table 6.
EC_{50} and toxic unit value calculated for methyl orange solution after plasma discharge [30].

toxicity test result for the real wastewater sample. In this study, although a synthetic solution was used, it should be considered that discharging a real textile wastewater without treatment may increase the toxic effect in wastewater treatment plants.

3.6 Effect of H_2O_2 (hydrogen peroxide) formation

Reference [35] stated in their study that H_2O_2 is one of the most important oxidants produced in the atmospheric pressure plasma system. Reference [36] mentioned in their study that long-lived reactive species such as hydroxyl radical and hydrogen peroxide are formed by plasma discharge. They mentioned that the resulting reagents play an important role in breaking down the contaminants in the liquid contacted in the plasma application and that these radicals can form at the liquid-gas interface or directly in the liquid. Reference [32] stated in oxygen gas fed plasma studies that hydrogen peroxide is an important oxidizing agent (1.78 V oxidation potential), has a longer lifespan than other radicals, and is therefore effective in pollutant removal. They also mentioned that in the aqueous phase, the transferred reactive species interact with the surrounding molecules for a long time; therefore, new reactive species are produced according to their properties, which enable them to participate in chemical reactions. In literature studies, it is mentioned that the most important of the reactive species formed by plasma contact is that hydrogen peroxide has a long life and that oxidation continues for a while after the discharge is stopped in plasma application, thus treatment continues. In this study, the amounts of hydrogen peroxide formed after plasma for MO and pomegranate wastewater sample and pure water for the highest removal efficiencies are given in **Table 7**.

Samples	H_2O_2 amount (mg/L)
MO	25
PW	25
DW	25

PW: pomegranate wastewater, MO: methyl orange, DW: deionized water.

Table 7.
Effect of plasma on H_2O_2 formation [30].

4. Discussion

Within the scope of the study, the atmospheric pressure plasma system, an innovative technology, was preferred for target pollutants. To investigate the color removal efficiency of atmospheric pressure plasma, two different samples, a dye (methyl orange) and a colored wastewater sample (pomegranate wastewater), were analyzed. Oxygen gas was used as feed gas in the study.

Methyl orange color removal study was carried out in three repetitions under optimum conditions (20 mg/L concentration, 5 minutes plasma contact time, 5 minutes mixer time, and 1.5 cm distance and 12 mg/L flow rate). The best color removal was achieved as 98% (other repeat studies were 97%).

$FeSO_4$ was used for catalyst addition. Catalyst studies were carried out under optimum conditions for methyl orange dyestuff. Accordingly, 91% color removal efficiency was achieved after plasma contact with the addition of catalyst. As a result of the study, it was concluded that plasma achieved color removal with high efficiency even without the addition of catalyst.

pH and conductivity measurements were made before and after plasma contact. For all measurements made, it was observed that the pH values after plasma decreased compared to the initial pH. According to the literature research, it can be said that it is important to monitor the pH change of the solution after plasma, as the density of the oxidant produced varies depending on the pH values and can therefore indicate the type of reactions going on during the experiments. For all measurements made in the study, post-plasma conductivity values reached higher values than the initial conductivity values. According to literature research, we can say that plasma discharge increases inorganic ions in water, and as a result, plasma increases the conductivity in water.

In this study, pomegranate wastewater sample was used for colored wastewater experiment. Pomegranate wastewater was prepared at 100%, 25%, 10%, and 5% dilutions, and absorbance was measured before and after plasma. The absorbance value of the raw sample (100%) pre-plasma was 660 nm. While the value of this was read 0.395, it was read 0.916 abs after plasma. Based on these data, it was concluded that plasma is also effective in removing the color of colored fruit wastewater.

The effect of plasma on COD removal for methyl orange solution and pomegranate wastewater was examined. COD removal efficiencies of 88.6% and 83.7% were obtained, respectively. Considering the efficiency, it was seen that plasma was very effective for COD removal, especially in fruit wastewater.

Literature studies indicate that hydrogen peroxide has a longer lifespan than other radicals formed by plasma discharge and plays an important role in oxidizing pollutants. Based on this, hydrogen peroxide formation was examined with kits in the study. In experiments conducted with plasma contact, the highest value on the scale, that is, 25 mg/L hydrogen peroxide formation, was observed for the best removal efficiency.

In addition to color purification using plasma technology, the toxicity of possible by-products was also determined in the study. Toxicity testing was performed for methyl orange. According to the test results, root and hypocotyl lengths were calculated as 0.227 and 0.186, respectively, for the methyl orange starting solution, while they were calculated as 0.222 and 0.181, respectively, for the post-plasma solution. According to the toxic unit classification, all results were evaluated as "Slightly Toxic".

Considering the results obtained, it was seen that plasma was successful in removing color and COD in liquids with its high reaction speed and energy efficiency.

5. Conclusion

In conclusion, effect of some chemical and physical factors on the process was studied. Response surface methodology was used to optimize the process. Based on the analytical techniques, a degradation pathway was proposed.

Today, the fact that plasmas produced at atmospheric pressure give effective results in applications and are easier and more economical to install than vacuum plasma systems, rapidly increases the interest in these systems. For this reason, by establishing an atmospheric plasma system, a system that can be easily implemented, allowing for minimum chemical use, contributing to green chemistry studies, and not creating waste sludge problems has been established.

This study will contribute to the applications in the field of green chemistry, which have been increasing day by day in recent years, in terms of reducing the chemicals used in advanced oxidation (AOP) processes and thus preventing sludge formation. For this reason in this study, plasma treatment was used as green technique in the water treatment. It is aimed to contribute to the literature with the future applicability of the plasma technology we have created on a laboratory scale in areas related to environmental engineering (cleaning of membrane filters, adsorption and desorption, and so on).

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References

[1] Kumar A et al. Cold atmospheric plasma technology for removal of organic micropollutants from wastewater—A review. The European Physical Journal D. 2021;**75**(11):283

[2] Collivignarelli MC et al. Treatments for color removal from wastewater: State of the art. Journal of Environmental Management. 2019;**236**:727-745

[3] Basha CA et al. Photoelectrocatalytic oxidation of textile dye effluent: Modeling using response surface methodology. Industrial & Engineering Chemistry Research. 2012;**51**(7):2846-2854

[4] Martínez-Huitle CA, Brillas E. Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review. Applied Catalysis B: Environmental. 2009;**87**(3):105-145

[5] Erkuş A et al. Boya Endüstrisi Atıksularının Karakterizasyonu. Yüzüncü Yıl Üniversitesi Fen Bilimleri Enstitüsü Dergisi. 2018;**23**(3):308-319

[6] Fahmy A et al. Modeling and optimizing acid orange 142 degradation in aqueous solution by non-thermal plasma. Chemosphere. 2018;**210**:102-109

[7] Can OT. COD removal from fruit-juice production wastewater by electrooxidation electrocoagulation and electro-Fenton processes. Desalination and Water Treatment. 2014;**52**(1):65-73

[8] Huang F et al. Degradation of methyl orange by atmospheric DBD plasma: Analysis of the degradation effects and degradation path. Journal of Electrostatics. 2012;**70**(1):43-47

[9] Ong YK et al. Nanofiltration hollow fiber membranes for textile wastewater treatment: Lab-scale and pilot-scale studies. Chemical Engineering Science. 2014;**114**:51-57

[10] Sojka-Ledakowicz J et al. Application of membrane processes in closing of water cycle in a textile dye-house. Desalination. 2010;**250**(2):634-638

[11] Liu Y et al. Carbamazepine removal from water by dielectric barrier discharge: Comparison of ex situ and in situ discharge on water. Chemical Engineering and Processing: Process Intensification. 2012;**56**:10-18

[12] Patil BN, Naik DB, Shrivastava VS. Photocatalytic degradation of hazardous Ponceau-S dye from industrial wastewater using nanosized niobium pentoxide with carbon. Desalination. 2011;**269**(1):276-283

[13] Işık M, Sponza DT. Biological treatment of acid dyeing wastewater using a sequential anaerobic/aerobic reactor system. Enzyme and Microbial Technology. 2006;**38**(7):887-892

[14] Ou W et al. Experimental study on coupling photocatalytic oxidation process and membrane separation for the reuse of dye wastewater. Journal of Water Process Engineering. 2015;**6**:120-128

[15] Qi L, Wang X, Xu Q. Coupling of biological methods with membrane filtration using ozone as pre-treatment for water reuse. Desalination. 2011;**270**(1):264-268

[16] Shin C-H, Bae J-S, Rudolph V. Co-treatment systems combined with unit processes for dye wastewater recycling. Journal of Industrial and Engineering Chemistry. 2014;**20**(2):710-716

[17] Khan TA, Dahiya S, Ali I. Use of kaolinite as adsorbent: Equilibrium, dynamics and thermodynamic studies on the adsorption of Rhodamine B from aqueous solution. Applied Clay Science. 2012;**69**:58-66

[18] Patel D et al. An overview of recent advances in treatment of complex dye-containing wastewater and its techno-economic assessment. Journal of Environmental Management. 2024;**370**:122804

[19] Tao X et al. A novel two-level dielectric barrier discharge reactor for methyl orange degradation. Journal of Environmental Management. 2016;**184**:480-486

[20] Bogaerts A et al. Gas discharge plasmas and their applications. Spectrochimica Acta Part B: Atomic Spectroscopy. 2002;**57**(4):609-658

[21] Fahmy A et al. Plasma polymerized allyl alcohol/O_2 thin films embedded with silver nanoparticles. Thin Solid Films. 2016;**616**:339-347

[22] Vandenbroucke AM et al. Non-thermal plasmas for non-catalytic and catalytic VOC abatement. Journal of Hazardous Materials. 2011;**195**:30-54

[23] Fridman A. Elementary Plasma-Chemical Reactions in Plasma Chemistry. Cambridge University Press; 2008. pp. 12-91

[24] Go DB et al. Ionic winds for locally enhanced cooling. Journal of Applied Physics. 2007;**102**(5):053302

[25] Park GY et al. Atmospheric-pressure plasma sources for biomedical applications. Plasma Sources Science and Technology. 2012;**21**(4):043001

[26] Pârvulescu VI, Magureanu M, Lukes P. Plasma Chemistry and Catalysis in Gases and Liquids. John Wiley & Sons; 2012

[27] Mizuno A. Generation of non-thermal plasma combined with catalysts and their application in environmental technology. Catalysis Today. 2013;**211**:2-8

[28] Samukawa S et al. The 2012 plasma roadmap. Journal of Physics D: Applied Physics. 2012;**45**(25):253001

[29] Locke B, Shih K-Y. Review of the methods to form hydrogen peroxide in electrical discharge plasma with liquid water. Plasma Sources Science and Technology. 2011;**20**:034006

[30] Zambak ŞB. Investigation of the Usage of Plasma Systems in the Field of Environmental Engineering [Thesis]. Turkey: Konya Technical University, Graduate Education Institute; 2023. p. 106

[31] Jiang B et al. Degradation of azo dye using non-thermal plasma advanced oxidation process in a circulatory airtight reactor system. Chemical Engineering Journal. 2012;**204-206**:32-39

[32] Yamada M et al. Nonthermal atmospheric pressure plasma for methylene blue dye decolorization by using slug flow reactor system. Plasma Chemistry and Plasma Processing. 2020;**40**(4):985-1000

[33] Bursać Kovačević D et al. Effects of cold atmospheric gas phase plasma on anthocyanins and color in pomegranate juice. Food Chemistry. 2016;**190**:317-323

[34] Tongur S, Atmaca H. A battery of simple bioassays for domestic and industrial wastewater treatment plants in Konya, Turkey. Sustainability. 2024;**16**(1):316

[35] Chandana L, Lakshminarayana B, Subrahmanyam C. Influence of hydrogen

peroxide on the simultaneous removal of Cr(VI) and methylene blue from aqueous medium under atmospheric pressure plasma jet. Journal of Environmental Chemical Engineering. 2015;**3**(4, Part A):2760-2767

[36] Sanito R, You S-J, Wang Y-F. Degradation of contaminants in plasma technology: An overview. Journal of Hazardous Materials. 2021;**424**:127390