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Degradation of Batik Waste Using Multibubble-Ozone Technology Generated by Corona Plasma Discharge

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ABSTRACT

Batik industrial wastewater contains synthetic dyes and dissolved pollutants that can negatively affect water quality. This study investigates the treatment of batik wastewater using ozone generated by corona plasma and dispersed through a mixed-size microbubble diffuser. The treatment was conducted for 60 minutes using a mixture of 500 mL batik wastewater and 500 mL distilled water, with water-quality changes evaluated through UV-Vis absorbance, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), and temperature. The maximum absorption wavelength was identified at 519 nm. The absorbance decreased from 0.13324 before treatment to 0.01534 after 60 minutes, corresponding to a degradation efficiency of 88.49%. TDS decreased from 1089 to 611 mg/L, EC decreased from 1425 to 908 µS/cm, and DO increased from 4.48 to 5.90 mg/L, while temperature changed from 23.4 to 22.6 °C. These results indicate that corona-plasma ozone treatment using mixed-size microbubbles was accompanied by changes in the optical and physicochemical characteristics of batik wastewater. The results provide a basis for discussing the role of gas–liquid contact and bubble characteristics in ozone-based wastewater treatment.

Keywords: Batik wastewater, corona plasma, multibubble-ozone, water quality

Degradasi Limbah Batik dengan Teknologi Multibubble-Ozone yang Dihasilkan Lucutan Plasma Corona

ABSTRAK

Limbah cair industri batik mengandung zat warna sintetis dan berbagai zat terlarut yang dapat menurunkan kualitas air. Penelitian ini mengkaji pengolahan limbah cair batik menggunakan ozon yang dihasilkan oleh plasma corona dan didispersikan melalui diffuser mikrogelembung berukuran campuran. Perlakuan dilakukan selama 60 menit menggunakan campuran 500 mL limbah cair batik dan 500 mL aquades, dengan perubahan kualitas air dievaluasi melalui

absorbansi UV-Vis, oksigen terlarut (DO), total padatan terlarut (TDS), daya hantar listrik (DHL), dan suhu. Panjang gelombang maksimum diperoleh pada 519 nm. Absorbansi menurun dari 0,13324 sebelum perlakuan menjadi 0,01534 setelah 60 menit, dengan efisiensi degradasi sebesar 88,49%. Nilai TDS menurun dari 1089 menjadi 611 mg/L, EC dari 1425 menjadi 908 µS/cm, dan DO meningkat dari 4,48 menjadi 5,90 mg/L, sedangkan suhu berubah dari 23,4 menjadi 22,6 °C. Hasil menunjukkan bahwa perlakuan ozon plasma corona menggunakan mikrogelembung berukuran campuran disertai perubahan pada karakteristik optik dan fisikokimia limbah cair batik. Hasil ini memberikan dasar untuk membahas peran kontak gas–cair dan karakteristik gelembung dalam pengolahan limbah berbasis ozon.

***Kata kunci**: Limbah Batik, Plasma Corona, Multibubble-ozon, Kualitas Air*

INTRODUCTION

Batik is one of the important textile products in Indonesia and its production requires a considerable amount of water. According to the Ministry of Industry in 2017, batik production in Indonesia reached an average of around 500 million meters of fabric per year. This production volume is estimated to require about 25 million m^3 of water. Approximately 85% of this water usage becomes batik wastewater, which is large in volume, dark in color, and has a pungent odor (Indrayani, 2018). Liquid waste is the most dominant type compared to other waste types (Martini et al., 2020). Batik wastewater is generally alkaline, dark-colored, and contains relatively high concentrations of COD and BOD. It may contain synthetic dyes, heavy metals, phenols, surfactants, and other compounds that are difficult to degrade (Adirajasa et al., 2022). High concentrations of COD and TSS can negatively affect aquatic ecosystems, cause odor and turbidity, and potentially pose risks to human health (Hannan et al., 2024). This pollution is associated with the use of chemicals during the batik production process, including NaOH, Na_2CO_3, H_2SO_4, dyes, and fixatives containing metal compounds (Indrayani, 2018). Therefore, effective and sustainable treatment technologies are required before batik wastewater is discharged into the environment.

Plasma is an ionized gas containing free electrons and ions and is commonly referred to as the fourth state of matter (Putra & Susanto, 2021). Corona plasma is a type of non-thermal plasma that can generate energetic electrons, ions, and reactive species. It has been applied in various technological processes, including ozone generation (Khamdi & Aminah, 2012). In a corona plasma system, the discharge generated between the electrodes produces high-energy electrons that interact with oxygen molecules in the reactor. These interactions involve ionization and dissociation processes that contribute to ozone formation. Ozone production in this system is influenced by several parameters, including applied voltage, electrode type and material, reactor design and configuration, gas-flow rate, and the type of gas used as the source (Kinandana et al., 2019).

Ozone is a strong oxidant widely used to inactivate microorganisms, decompose organic compounds, remove odors, and support water and wastewater treatment processes. The amount of ozone generated depends on the characteristics and operating conditions of the plasma reactor. Several factors can influence ozone production, including applied voltage, electrode type, reactor geometry and configuration, gas-flow rate, and gas source (Abdurrahman et al., 2022). Owing to its strong oxidation and disinfection properties, ozone has been widely applied in water and

wastewater treatment. In wastewater treatment, the effectiveness of ozone is also related to the transfer of ozone from the gas phase into the liquid phase. Therefore, efficient gas–liquid contact is an important consideration when applying ozone to wastewater treatment.

Microbubbles are small gas bubbles that provide a relatively large gas–liquid interfacial area compared with larger bubbles. Microbubbles with diameters in the micrometre range exhibit characteristics such as slower rising velocity, larger interfacial surface area, and higher internal pressure, which can influence their behavior and residence time in water (Athikoh et al., 2021). These characteristics make microbubbles potentially useful for wastewater treatment because they can increase gas–liquid contact and provide greater opportunity for gas transfer into the liquid phase. In ozone-based treatment, the use of microbubbles may facilitate the dispersion of ozone in wastewater and potentially improve ozone transfer from the gas phase to the liquid phase (Nur et al., 2023). Bubble size can also influence the hydrodynamic behavior of the treatment system. Smaller bubbles generally provide a larger interfacial area and longer residence time, whereas relatively larger bubbles can contribute to liquid circulation and mixing. Therefore, combining bubbles of different sizes may provide both gas–liquid contact and liquid mixing within the reactor. In the present study, the diffuser produces bubbles with approximate diameters of 5 μm and 10 μm. Both sizes are treated as microbubbles in this study and are referred to as smaller microbubbles (approximately 5 μm) and larger microbubbles (approximately 10 μm). Their combined use is referred to as a mixed-size microbubble configuration. However, because the individual contributions of each bubble size were not independently evaluated, their respective effects on ozone transfer and wastewater treatment performance cannot be determined separately from the present experiment.

Previous research by Kusumandari et al. (2022) investigated the degradation of batik dyes using atmospheric-air corona discharge plasma without requiring a vacuum system or an additional gas source. The results showed a decrease in absorbance with increasing treatment time and applied voltage, which was associated with the formation of reactive species, including hydroxyl radicals and ozone. The study demonstrated the potential of atmospheric-air corona plasma for batik dye degradation. However, the evaluation was primarily focused on color degradation and did not include other water-quality parameters or energy consumption, indicating the need for further studies with broader treatment evaluation. Putra & Susanto (2021) investigated the application of plasma, electrocoagulation, and their combination for reducing COD in batik wastewater with an initial concentration of 435 ± 10 mg O_2/L. Plasma and electrocoagulation treatments alone reduced COD by 8.1% and 12.6%, respectively, while the combined plasma–electrocoagulation treatment achieved a higher reduction efficiency of up to 44.8%. However, the study primarily evaluated COD and did not simultaneously examine other water-quality parameters or energy consumption. In addition, (Abdurrahman et al., 2025) compared different DBD plasma reactor configurations and reported differences in the production of reactive species and ozone between reactor configurations. The series configuration showed better performance under their experimental conditions and achieved a reported batik wastewater degradation efficiency of 53.14% after 60 minutes of treatment. These findings indicate that plasma reactor configuration can influence treatment performance. However, the DBD configuration investigated in that study differs from the corona-plasma ozone system and mixed-size microbubble diffuser used in the present study.

Based on these previous studies, plasma-based treatment has demonstrated potential for reducing pollutants in batik wastewater, particularly in terms of dye degradation and COD reduction. However, previous studies have generally focused on individual treatment indicators, such as absorbance or COD, while the simultaneous changes in optical and physicochemical water-quality parameters during corona-plasma ozone treatment using a mixed-size microbubble diffuser remain less explored. Therefore, this study evaluates the treatment response through UV-Vis absorbance, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), and temperature.

The novelty of this study lies in the integration of corona-plasma ozone generation with a mixed-size microbubble diffuser and the simultaneous evaluation of the treatment response through UV-Vis absorbance, DO, TDS, EC, and temperature. Unlike previous studies that mainly evaluated dye degradation or COD reduction, this study provides a broader description of the optical and physicochemical changes occurring during treatment. The mixed-size microbubble configuration is considered from the perspective of gas–liquid contact and bubble behavior. However, the individual contributions of the 5 μm and 10 μm bubbles and the dissolved ozone concentration were not independently measured in this study. Therefore, this study does not claim a direct causal relationship between individual bubble size, ozone dissolution, and pollutant degradation. The role of bubble characteristics is instead discussed as a possible physical factor associated with the observed treatment response.

From the perspective of physics education, the experimental system provides a practical context for applying concepts related to plasma discharge, electric fields, ozone generation, bubble dynamics, gas–liquid interaction, mass transfer, and measurement of physical quantities. The experimental observations can therefore be used to connect theoretical concepts in physics with an environmental application, particularly in the context of experimental physics and applied physics learning. This connection provides an opportunity to demonstrate how physical principles can be applied to address environmental problems, including wastewater treatment. Therefore, this study aims to (1) investigate the working principle of corona-plasma ozone treatment for batik wastewater using a mixed-size microbubble diffuser, (2) evaluate changes in wastewater characteristics based on UV-Vis absorbance, DO, TDS, EC, and temperature, and (3) discuss the observed changes from the perspective of gas–liquid contact and bubble characteristics. The results are expected to contribute to the development of plasma- and ozone-based wastewater treatment while providing an experimental context for the application of physics concepts to environmental problems.

METHOD

Research Design

This study employed an experimental method to investigate the degradation of batik wastewater using a multibubble-ozone system generated by corona plasma discharge. The experimental system consisted of a high-voltage power supply, a high-voltage coil, a corona plasma reactor, an air pump, and a multibubble generator. The generated ozone was introduced into the wastewater through the multibubble generator. The treated wastewater was subsequently analyzed using a UV-Vis spectrophotometer and a portable multiparameter water quality meter. The overall experimental setup and measurement instruments are presented in Figure 1.

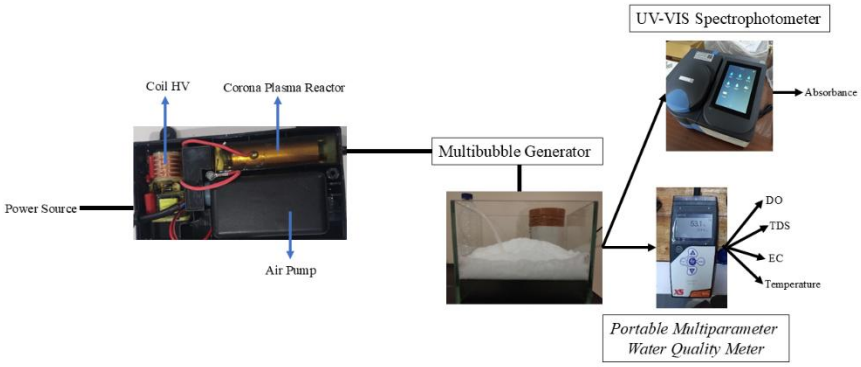


Figure 1. the experimental setup of the corona plasma–multibubble ozone treatment system and the water quality analysis instruments used.

The corona plasma reactor was used to generate ozone from atmospheric air. The operation began by connecting the power supply to the plasma generator, with the switch initially turned off. The voltage was then gradually increased until a stable plasma discharge was formed. Atmospheric air was supplied to the reactor using an air pump. During the plasma discharge process, the supplied air was used as the source for ozone generation, and the resulting ozone was subsequently directed toward the multibubble generator.

The multibubble generator was used to disperse the generated ozone into the wastewater. The system consisted of a combination of microbubbles with an approximate diameter of 5 μm and macrobubbles with an approximate diameter of 10 μm. The microbubbles provided a larger gas–liquid interfacial area and longer residence time, which supported ozone dissolution in the wastewater. Meanwhile, the larger bubbles contributed to gas distribution and mixing within the reactor. The wastewater samples were collected from the dyeing process of a batik industry in Sukoharjo, Central Java. The samples were stored in clean, airtight containers before treatment to minimize contamination and changes in their physicochemical characteristics. Prior to treatment, the wastewater was homogenized and its initial physicochemical parameters were measured as baseline values. Each experimental sample consisted of 500 mL of batik wastewater and 500 mL of distilled water, resulting in a total volume of 1,000 mL, and was placed in a 1-L glass reactor.

The degradation treatment was conducted for 60 minutes. Sampling was performed at 10-minute intervals, namely at 0, 10, 20, 30, 40, 50, and 60 minutes. The sample collected at 0 minutes represented the initial condition before treatment, while the subsequent samples were collected during the ozone treatment process. At each interval, the treated samples were analyzed to evaluate changes in absorbance, total dissolved solids (TDS), dissolved oxygen (DO), electrical conductivity (EC), and temperature.

Water Quality Analysis

Water quality analysis was performed to evaluate changes in the characteristics of batik wastewater during the corona plasma–multibubble-ozone treatment. The parameters analyzed were absorbance, TDS, DO, EC, and temperature. Absorbance was measured using a UV-Vis spectrophotometer, while TDS, DO, EC, and temperature were measured using a portable multiparameter water quality meter.

1. Absorbance

Absorbance measurements were performed using a UV-Vis spectrophotometer for samples collected at 0, 10, 20, 30, 40, 50, and 60 minutes. Before measurement, the spectrophotometer was turned on and allowed to warm up according to the operating procedure. Distilled water was used as the blank solution for baseline calibration using a clean cuvette. A wavelength scan was performed in the range of 325–1100 nm to determine the maximum absorption wavelength (λmax) of the batik wastewater. The maximum absorption wavelength was obtained at 519 nm. Therefore, subsequent quantitative absorbance measurements were performed at 519 nm to evaluate the reduction in absorbance during the treatment process. The degradation efficiency was calculated using:

$$\eta = \frac{A_0 - A_t}{A_0}\ x\ 100\%$$

where η is the degradation efficiency (%), A0 is the initial absorbance, and At is the absorbance at treatment time t.

2. TDS, DO, EC, and Temperature

TDS, DO, EC, and temperature were measured using a portable multiparameter water quality meter. Measurements were performed for samples collected at each treatment interval. The obtained values were recorded and compared with the initial values to evaluate changes in the physicochemical characteristics of the wastewater during the treatment process.

Data Analysis

The experimental data were analyzed by evaluating the changes in absorbance, TDS, DO, EC, and temperature as a function of treatment time. The absorbance degradation efficiency was calculated using the equation above. Changes in TDS, DO, EC, and temperature were evaluated by comparing the values obtained at each treatment interval with the initial condition. The decrease in absorbance over treatment time was used as an indicator of the degradation of colored compounds in the batik wastewater. The changes in the other water-quality parameters were used to describe the physicochemical changes occurring during the corona plasma–multibubble-ozone treatment.

RESULT AND CONCLUSION

Degradation Treatment of Batik Wastewater Using Corona Plasma with Multibubble-Ozone Variation

In this study, batik wastewater degradation was performed using a corona plasma system modified with multibubble-ozone technology, consisting of a combination of macrobubbles (10 μm) and microbubbles (5 μm). The operation of the system began by connecting the power supply to the plasma generator with the switch initially turned off. The voltage was then gradually increased until a stable plasma discharge was formed. Air was supplied as the source gas for ozone generation, where oxygen molecules were ionized to produce ozone, which was subsequently introduced into the reactor through a multibubble system.

The multibubble system plays a crucial role in enhancing ozone mass transfer efficiency into the liquid phase. Microbubbles, due to their smaller size, provide a larger surface area and longer residence time, thereby increasing ozone dissolution in the liquid. Meanwhile,

macrobubbles contribute to improved mixing and more uniform gas distribution within the reactor. The combination of both bubble sizes results in a more effective degradation process compared to the use of a single bubble size system. Previous research by Fitryan et al (2025) confirmed that smaller bubble diffusers (approximately 3.37 μm) significantly increase specific surface area, thereby enhancing ozone mass transfer efficiency in wastewater treatment processes.

The degradation process was conducted in an aquarium containing a mixture of batik wastewater and distilled water. Samples were collected at 0 minutes as the initial condition before treatment, followed by sampling at 10, 20, 30, 40, 50, and 60 minutes during the ozonation process. At each time interval, ozone generated from the corona plasma was dispersed through the multibubble system. Microbubbles enhanced ozone dissolution and reaction contact area, while macrobubbles supported gas distribution and mixing within the reactor. Each collected sample was analyzed to determine changes in absorbance, total dissolved solids (TDS), dissolved oxygen (DO), electrical conductivity (EC), and temperature, in order to evaluate the progression of the degradation process.

Water Quality Parameter Analysis of Batik Wastewater

Water quality analysis was conducted to evaluate the changes in the physicochemical characteristics of batik wastewater during the corona plasma–multibubble ozone treatment. The parameters analyzed included absorbance, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), and temperature. These parameters provide complementary information regarding changes in the optical characteristics, oxygen availability, dissolved substances, ionic properties, and thermal condition of the wastewater during treatment.

The treatment process combines corona plasma ozone generation with multibubble gas–liquid contact. Ozone is a strong oxidizing agent that can react with various organic compounds in wastewater, while the efficiency of ozone treatment is strongly influenced by the transfer of ozone from the gas phase into the liquid phase. The relatively low solubility and rapid decomposition of ozone in water can limit the efficiency of conventional ozonation; therefore, microbubble technology has been investigated as a means of improving ozone transfer and maintaining ozone availability in the aqueous phase (Lee et al., 2019; Xia dan Hu, 2018).

Microbubble systems provide favorable gas–liquid contact conditions because the presence of numerous small bubbles increases the available gas–liquid interface. Experimental studies have demonstrated that ozone microbubbles can enhance ozone mass transfer and improve the treatment of printing and dyeing wastewater (Wu et al., 2022). Similar observations have been reported in larger-scale ozone/micro-nanobubble systems, where gas–liquid mass transfer was identified as an important factor controlling ozone treatment performance (Robles et al., 2023).

The present study used a combined multibubble configuration consisting of approximately 5 μm and 10 μm bubbles. The results therefore represent the overall response of the combined configuration rather than the independent effect of each bubble size. Although smaller bubbles are generally associated with more favorable gas–liquid contact and ozone transfer characteristics, the present experiment did not separately compare the 5 μm and 10 μm configurations. Therefore, the available data cannot quantitatively establish the individual contribution of each bubble size or demonstrate a statistically proven synergistic effect.

This limitation is important when interpreting the following results. The observed changes demonstrate the response of the complete corona plasma–multibubble ozone system, while the detailed contribution of bubble size remains an important topic for further investigation.

1. Absorbance

UV-Vis measurements were performed to evaluate changes in the optical characteristics of the batik wastewater during treatment. The maximum absorption wavelength was identified at 519 nm, which was subsequently used as the reference wavelength for evaluating the changes in absorbance.

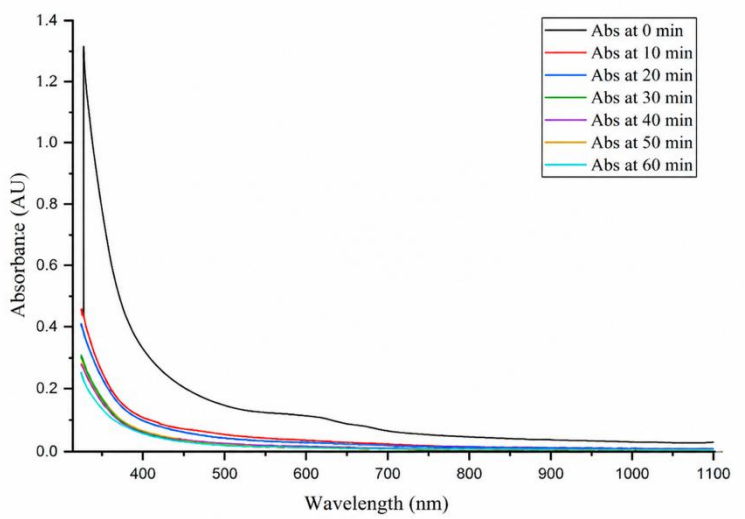


Figure 2. Relationship between Wavelength and Absorbance

The absorbance at 519 nm decreased from 0.13324 at 0 min to 0.04739 at 10 min, 0.03761 at 20 min, and 0.01893 at 30 min. A temporary increase to 0.02290 was observed at 40 min, followed by a decrease to 0.01785 at 50 min and 0.01534 at 60 min. Overall, the absorbance decreased by approximately 88.5% between the initial and final measurements. The most pronounced reduction occurred during the first 30 min, when the absorbance decreased by approximately 85.8% from its initial value. After 30 min, the changes were smaller, although the final absorbance remained substantially lower than the initial value. This temporal pattern indicates that the treatment produced its strongest optical response during the early stage of the process.

The decrease in absorbance can be associated with the oxidation of chromophoric compounds by ozone and reactive species generated during the plasma-assisted treatment. Ozone is widely applied for the removal of color and organic contaminants because of its strong oxidation capability. In batik wastewater containing azo dyes, ozonation has been reported to produce rapid decolorization, demonstrating the susceptibility of chromophoric structures to ozone oxidation(Pramugani et al., 2022).

The multibubble configuration can further support this process by facilitating contact between the ozone-containing gas and the wastewater. Microbubble ozonation has been shown to

enhance ozone transfer into water and improve treatment performance compared with less efficient gas–liquid contact conditions(Wu et al., 2022; Xia and Hu, 2018).

The temporary increase in absorbance from 0.01893 at 30 min to 0.02290 at 40 min requires cautious interpretation. The available data do not include chemical characterization of the wastewater that could confirm the formation of particular intermediate compounds or precipitation. Therefore, this fluctuation should be described only as a temporary variation in measured absorbance rather than being attributed to a specific chemical mechanism. The subsequent decrease to 0.01785 at 50 min and 0.01534 at 60 min indicates that the overall treatment trend remained toward lower absorbance. This supports the conclusion that the corona plasma–multibubble ozone treatment was effective in reducing the optical response associated with colored compounds in the wastewater.

However, absorbance reduction should not be interpreted as direct evidence of complete mineralization. Ozonation can transform dye molecules into smaller compounds without necessarily converting all organic matter into carbon dioxide and water. Research on batik wastewater has shown that ozonation can achieve substantial decolorization while chemical oxygen demand and degradation products require separate evaluation (Pramugani et al., 2022). Therefore, the present result is most appropriately interpreted as evidence of substantial decolorization or reduction in optical absorbance, rather than complete degradation of all organic pollutants.

2. *Dissolved Oxygen (DO)*

Dissolved oxygen measurements were performed at 0, 30, and 60 min to evaluate changes in the oxygenation condition of the wastewater during treatment.

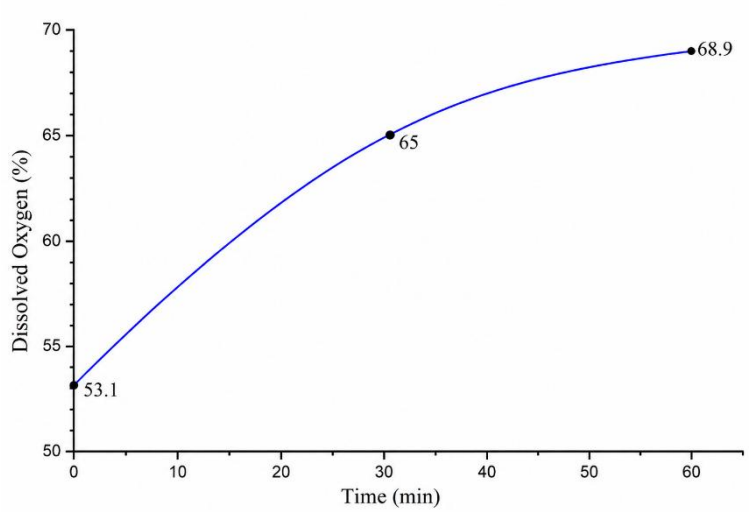


Figure 3. Relationship between Ozonation Time and Dissolved Oxygen Concentration

The DO concentration increased from 4.48 mg/L at 0 min to 5.54 mg/L at 30 min and 5.90 mg/L at 60 min. The total increase from the initial to the final condition was approximately 31.7%.

The increase during the first 30 min was 1.06 mg/L, whereas the increase between 30 and 60 min was only 0.36 mg/L. Therefore, the increase in DO was more pronounced during the first half of the treatment period.

The increase in DO is consistent with the introduction of oxygen-containing gas into the wastewater through the multibubble diffuser. The gas–liquid contact provided by the bubbles facilitates the transfer of gaseous species into the liquid phase. Microbubble ozonation studies have demonstrated that bubble-based gas dispersion can substantially improve gas–liquid mass transfer and increase the concentration of dissolved ozone in water (Wu et al., 2022; Xia and Hu, 2018). The increase in DO should nevertheless not be interpreted as a direct measurement of dissolved ozone concentration. Oxygen and ozone are different dissolved species, and the present experiment did not directly measure dissolved ozone. Thus, the DO results provide supporting evidence for enhanced gas–liquid interaction rather than a quantitative measurement of ozone dissolution.

The smaller increase in DO after 30 min may indicate that the dissolved oxygen concentration approached a relatively stable condition under the experimental operating conditions. This observation is also consistent with the general trend of several parameters showing larger changes during the initial treatment period. The DO results therefore strengthen the physical interpretation that gas–liquid interaction occurred during the treatment, while direct determination of ozone mass-transfer efficiency would require additional measurements such as dissolved ozone concentration, ozone feed rate, or mass-transfer parameters.

3. Total Dissolved Solids (TDS)

TDS measurements were performed to evaluate changes in the concentration of dissolved substances during the treatment process.

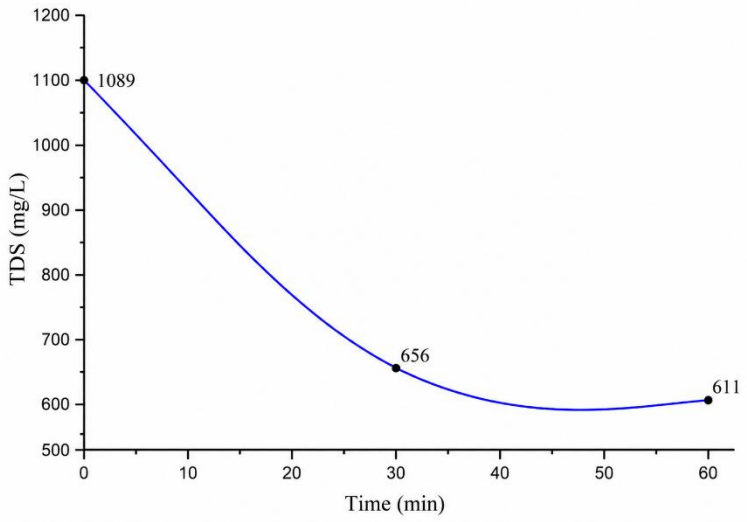


Figure 4. Relationship between Ozonation Time and TDS

The TDS concentration decreased from 1089 mg/L at 0 min to 656 mg/L at 30 min and 611 mg/L at 60 min. The overall decrease from the initial to the final measurement was 478 mg/L, corresponding to approximately 43.9% reduction. The majority of the observed decrease occurred during the first 30 min. TDS decreased by 433 mg/L during this period, whereas the decrease

between 30 and 60 min was only 45 mg/L. Thus, the treatment produced a substantially greater change in TDS during the initial stage. This behavior indicates that the treatment conditions had a stronger effect on the dissolved characteristics of the wastewater during the first 30 min. The smaller change after 30 min suggests that the response of the measured dissolved solids became less pronounced during the later treatment period. However, TDS is a bulk water-quality parameter and does not identify individual dissolved compounds. Consequently, the observed reduction cannot be directly assigned to the removal of specific pollutants, ions, or organic compounds.

The reduction in TDS should also not be interpreted as direct evidence of complete mineralization. Ozone oxidation can transform organic compounds into different chemical species, and the resulting compounds may remain dissolved in the wastewater. Additional chemical analysis would therefore be required to determine the specific processes responsible for the TDS reduction. The result is consequently best reported as an observed 43.9% reduction in TDS after 60 min, with the largest reduction occurring during the first 30 min.

4. Electrical Conductivity (EC)

Electrical conductivity was measured to evaluate changes in the electrical properties of the wastewater during treatment. EC is influenced by the concentration and mobility of dissolved ionic species.

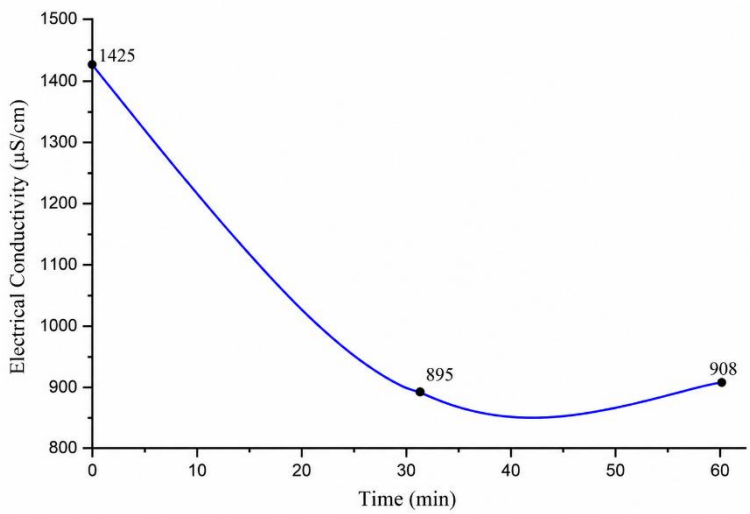


Figure 5. Relationship between Ozonation Time and Electrical Conductivity

The EC value decreased from 1425 µS/cm at 0 min to 895 µS/cm at 30 min, followed by a slight increase to 908 µS/cm at 60 min. Overall, EC remained approximately 36.3% below its initial value at the end of treatment. The most substantial change occurred during the first 30 min, when EC decreased by approximately 37.2%. Between 30 and 60 min, EC changed by only 13 µS/cm, indicating that the parameter remained relatively stable during the later treatment period. The decrease in EC indicates a change in the ionic characteristics of the wastewater during treatment. However, because EC does not identify individual ionic species, the present results cannot establish which specific ions were responsible for the observed reduction. The small increase from 895 to 908 µS/cm at 60 min should also be interpreted cautiously. As with the

absorbance fluctuation, there is insufficient chemical evidence to attribute this change to the formation of a particular intermediate product or precipitation. It is therefore more scientifically appropriate to describe this behavior as a minor fluctuation in EC.

The similar temporal patterns of TDS and EC are nevertheless noteworthy. Both parameters showed their largest changes during the first 30 min and relatively small changes thereafter. This suggests that the early stage of treatment was associated with the greatest change in the dissolved characteristics of the wastewater. However, TDS and EC should not be considered equivalent parameters. TDS represents the overall concentration of dissolved material, whereas EC is primarily related to the ability of dissolved ionic species to conduct electrical current. Therefore, the similar trends provide complementary evidence but do not establish a specific chemical mechanism

5. Temperature

Temperature was monitored to determine whether the corona plasma–multibubble ozone treatment caused substantial changes in the bulk thermal condition of the wastewater.

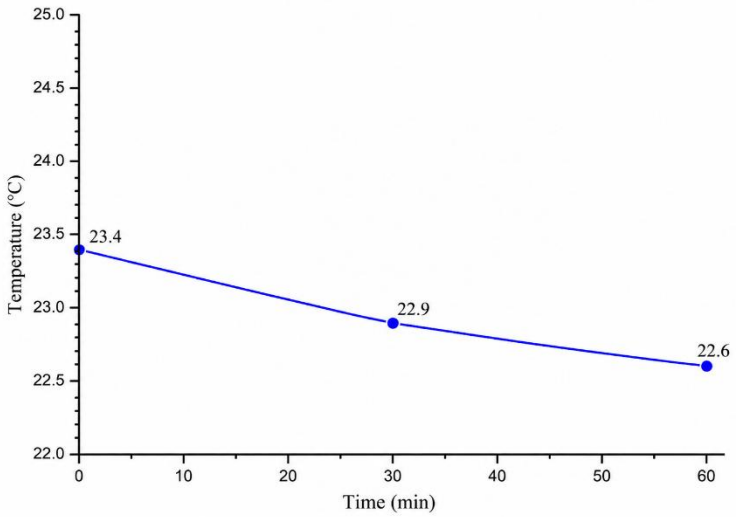


Figure 6. Relationship between Ozonation Time and Temperature

The wastewater temperature decreased from 23.4 °C at 0 min to 22.9 °C at 30 min and 22.6 °C at 60 min. The total decrease was only 0.8 °C, corresponding to approximately 3.4% relative to the initial temperature. Compared with the changes observed for absorbance, DO, TDS, and EC, the temperature variation was relatively small. This indicates that the bulk wastewater temperature remained comparatively stable during the 60-min treatment. Temperature is relevant to ozone treatment because it influences ozone solubility and reaction behavior. Lower temperatures generally favor gas solubility, whereas higher temperatures can accelerate certain reaction processes while reducing gas solubility. Previous research has therefore identified temperature as an important parameter in microbubble ozonation processes (Lee et al., 2019).

In the present experiment, however, the temperature changed only slightly. Therefore, the measured temperature variation is unlikely to represent a major change in the bulk thermal condition of the wastewater during treatment. It should also be emphasized that the measured temperature represents the wastewater temperature and does not directly characterize the local

temperature within the corona plasma region. Therefore, no conclusion regarding the thermal characteristics of the plasma should be made from these measurements alone. The combined results demonstrate that the corona plasma–multibubble ozone treatment produced measurable changes in the physicochemical characteristics of batik wastewater. The largest observed change occurred in absorbance, which decreased from 0.13324 to 0.01534, corresponding to approximately 88.5% reduction. TDS decreased from 1089 to 611 mg/L, corresponding to approximately 43.9% reduction, while EC decreased from 1425 to 908 µS/cm, corresponding to approximately 36.3% reduction. In contrast, DO increased from 4.48 to 5.90 mg/L, corresponding to approximately 31.7% increase, while temperature decreased only slightly from 23.4 to 22.6 °C.

An important feature of the results is that the largest changes in several parameters occurred during the first 30 min. The absorbance had already decreased by approximately 85.8% at 30 min, while approximately 90.6% of the total TDS reduction occurred during the same period. EC also exhibited its largest reduction during the first 30 min. This indicates that the early treatment stage was the most active period based on the measured water-quality parameters. The observed behavior can be explained by the interaction between corona plasma, ozone generation, gas–liquid transfer, and oxidation reactions. Corona discharge provides the energetic environment required for ozone generation, while the multibubble diffuser facilitates contact between the ozone-containing gas and the wastewater. Ozone microbubble studies have shown that gas–liquid mass transfer is a critical factor in determining ozone treatment performance (Wu et al., 2022; Xia & Hu, 2018). The physical importance of bubble size is also relevant. Smaller bubbles generally provide more extensive gas–liquid contact and longer interaction with the liquid compared with larger bubbles. Recent reviews have emphasized that bubble size, residence behavior, and interfacial characteristics are important factors affecting ozone transfer and treatment efficiency (Liu et al., 2026).

Nevertheless, the present experiment used the combined 5 µm and 10 µm bubble configuration and did not separately test the two bubble sizes. Consequently, the present results cannot establish whether the two sizes produce a true synergistic effect. Future experiments should include at least three configurations: 5 µm only, 10 µm only, and combined 5 + 10 µm bubbles. Replicated measurements would then allow statistical comparison of the configurations. Another limitation is the absence of sufficient replicate measurements. Because the available dataset does not contain independent repeated measurements for each treatment time, standard deviations and statistical significance cannot be reliably calculated. The percentage changes presented in this study should therefore be regarded as observed changes in the experimental dataset, rather than statistically validated treatment effects.

The absence of direct ozone measurements is another limitation. The present study does not provide sufficient data to determine dissolved ozone concentration, ozone utilization, or ozone mass-transfer efficiency. Therefore, the discussion of ozone transfer is based on the physical operating principle of the multibubble system and previous literature rather than direct measurement of these parameters. The absorbance result is particularly important because it demonstrates a substantial reduction in the optical response of the batik wastewater. Similar ozonation studies on batik wastewater have reported rapid decolorization of azo dyes, supporting the interpretation that ozone is effective for attacking chromophoric structures (Pramugani et al., 2022).

However, decolorization should not be equated with complete mineralization. Ozonation can break down dye molecules and generate transformation products, while the total organic load may require additional treatment or further oxidation. Therefore, future research should include COD, TOC, and chemical characterization to determine whether the observed color reduction is accompanied by substantial organic mineralization. From the perspective of physics education, this experimental system provides an opportunity to connect several physics concepts with an environmental application. Corona plasma introduces concepts related to electrical discharge, electric fields, energetic electrons, and plasma-assisted chemical processes. The multibubble diffuser introduces concepts related to bubble dynamics, gas–liquid interaction, mass transfer, and the influence of bubble size on contact conditions. UV-Vis analysis further provides an application of optical measurement and quantitative data analysis.

The system can therefore be developed as an applied physics laboratory activity. Students could investigate how treatment time and bubble characteristics affect the optical properties and other measurable parameters of wastewater. Such an approach would allow students to connect plasma physics, fluid phenomena, measurement systems, and environmental technology within one experimental framework. For practical application, the observed reduction in absorbance demonstrates the potential of the corona plasma–multibubble ozone system for batik wastewater decolorization. However, the present results alone are not sufficient to establish large-scale applicability, energy efficiency, or complete pollutant removal. Further optimization should therefore include direct measurement of ozone production, electrical power consumption, gas flow rate, bubble-size distribution, and chemical indicators such as COD and TOC.

CONCLUSION

The corona-plasma-generated ozone combined with mixed-size microbubbles showed potential for treating batik wastewater, particularly in reducing absorbance. After 60 minutes, the absorbance decreased by 88.49%, accompanied by reductions in TDS and electrical conductivity and an increase in dissolved oxygen. These changes indicate the potential role of ozone and gas–liquid contact in the treatment process. However, the individual contributions of the 5 μm and 10 μm bubbles and their synergistic effect could not be quantitatively confirmed because they were not separately evaluated. Future studies should include repeated experiments, direct ozone measurements, and separate evaluation of bubble-size configurations. The system also has potential as an applied physics laboratory platform for learning plasma physics, bubble dynamics, and gas–liquid mass transfer.

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