Comparison of Emission Spectrum in Series and Parallel Configured Dielectric Barrier Discharge (DBD) Reactors and Its Application for Textile Wastewater Treatment

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Abstract – *Textile wastewater represents one of the world's largest aquatic pollutants due to industrial activities. Ozonation, an advanced oxidation process (AOP), serves as a cost-effective wastewater treatment method. This study compares emission spectra from series and parallel-configured dielectric barrier discharge (DBD) reactors and correlates them with ozone production for textile wastewater treatment. The discharge emission spectrum (OES) was analyzed to identify reactive species, while ozone concentration was quantified via titration. Ozonation was applied for 0–60 minutes, monitoring absorbance, dissolved oxygen (DO), total dissolved solids (TDS), total suspended solids (TSS), and conductivity. OES analysis revealed higher emission intensities of OH radicals and N_2 in the series configuration versus parallel, indicating enhanced plasma reactivity. Consequently, the series configuration yielded superior ozone production, achieving 53.14% degradation efficiency after 60 minutes. Significant reductions in absorbance, TDS, TSS, and conductivity occurred alongside increased DO. Longer treatment durations improved degradation efficiency.*

Keywords: *Dielectric barrier discharge; ozone; optical emission spectroscopy; emission spectrum; textile wastewater.*

1. Introduction

Due to the massive volumes of wastewater that are discharged into the environment, the textile industry plays a major role in the global water pollution problem. These pollutants include dyes, heavy metals, and organic compounds. Treatment procedures are significantly hampered by the complex makeup of textile wastewater, which frequently contains harmful, non-biodegradable materials [1–3].

Textile wastewater has long been treated using traditional biological treatment techniques like activated sludge processes. Nevertheless, these techniques frequently fail to completely degrade and cause secondary pollution when trying to remove stubborn dyes and other harmful organic compounds. These drawbacks emphasize the demand for more sophisticated and potent therapeutic approaches [4–6]. These limitations highlight the need for more advanced and effective treatment techniques.

Because of its potent oxidative properties, ozonation has become a highly effective treatment for textile wastewater, effectively breaking down the complex organic molecules that are present. Ozonation has the benefit of being able to function at room temperature and pressure, producing very little sludge, and reacting quickly enough to completely mineralize pollutants [7–9]. Moreover, ozonation can efficiently remove a variety of organic pollutants, lower chemical oxygen demand (COD), deteriorate color, eliminate bacteria, and achieve this without producing hazardous by-products [10–13]. Altering the configuration of two dielectric barrier discharge (DBD) reactors into a series arrangement, capable of generating more ozone than a single reactor or two reactors in parallel, serves as an additional approach to enhance ozone production [14].

Numerous approaches have been explored to improve DBD reactor efficiency for textile wastewater treatment. To enhance ozone production, these include optimizing reactor design parameters such as electrode material, gap distance, dielectric material, and configuration, where series arrangements demonstrate more stable emission spectra [15–17].

This study aims to investigate emission spectra from series and parallel-configured DBD reactors and their impact on ozone production. For each reactor configuration, optical emission spectroscopy (OES) quantified OH radical and N_2 intensities. The generated ozone was then applied to degrade batik wastewater, with degradation efficiency monitored through absorbance, TSS, TDS, DO, and electrical conductivity measurements.

2. Materials and Methods

2.1 Investigated wastewater

The sample used in this research was batik wastewater in the city of Solo. The waste used is waste from washing batik. Batik wastewater was collected in 2 liters and stored in Polyethylene Terephthalate containers. The parameters measured in this study consisted of absorbance, TSS, TDS, DO and electrical conductivity. Samples are processed 24 hours from collection to simulate the original state of batik wastewater when it is discharged into the sewer.

2.2 Set-up of ozone treatment

The DBD Plasma reactor uses iron and Cu Tape-Mesh as electrodes and Pyrex glass as a barrier. The experiment scheme is shown in Fig. 1**.** Ozone Production was measured with an indirect method using a titration technique [18]. OH radical and nitrogen were measured using the Ocean Optic Pro 200 spectrometer in each reactor and all circuits. Also, all the characteristics of their own instruments.

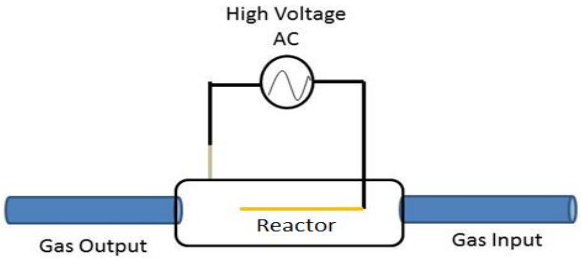

Figure 1. Experiment scheme.

2.3 Analysed parameters

In this research, the DBD reactors were arranged in series and parallel. The ozone production capacity was measured at voltage variations of 5, 7 and 9 kV. Emission spectrum measurements were also carried out for each variation of the reactor arrangement.

The batik waste is then treated with ozone for 60 minutes at a voltage of 9 kV with a series circuit variation as the best ozone producer. Every 10 minutes, a sample of 10 mL was taken and then characterized using UV-Vis spectroscopy to see degradation over time. Every 10 mL is also used to measure TSS, TDS, DO and electrical conductivity.

Wastewater degradation is carried out by channeling the output gas from the reactor into a container containing samples using a continuous system. The voltage used in waste treatment is 9 kV with variations in treatment time. Based on the data obtained, the reaction rate in waste degradation can also be analyzed using the general Eq. (1) [19].

$$Reaction\ rate = V = k[A][B] \quad (1)$$

In this equation, V denotes the reaction rate, expressed as the change in concentration of reactants over time. k is the rate constant, which depends on temperature and reaction conditions. [A] and [B] represent the concentrations of the reactants involved—ozone and the organic pollutants in batik wastewater, respectively.

Total Dissolved Solid is measured using a TDS meter by inserting the electrode into the sample solution for a few moments until it stabilizes. TDS measurements are carried out at each variation in treatment time to determine changes in TDS values over time. The ion content in the waste sample influences the value measured on the TDS meter.

TSS characterization in this study employed a gravimetric method, utilizing filtration and evaporation principles, in accordance with the Indonesian National Standard (SNI 06-6989.3-2004). The filter paper is oven at a temperature range of 103 ºC to 105 ºC for approximately 1 hour and cooled before weighing so that the temperature is stable. After weighing, filter paper is used again to filter the treated sample and then evaporated again at the same temperature and time. The filter paper is cooled after weighing. TSS can be calculated with Eq. (2).

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$$TSS = \frac{(W_1 - W_0)x\ 1000}{Volume} \quad (2)$$

W_1 = weight of filter paper + residue (mg), W_0 = weight of filter paper (mg), and V = sample volume (mL).

Dissolved oxygen is measured using a digital DO meter. Before taking measurements, the DO meter is first calibrated with the solution provided. The DO meter range value is 0-20 mg/L. DO measurements take a little longer after being dipped in the solution, so that the temperature does not affect the electrode. The DO value is measured at each variation in treatment time.

Electrical Conductivity is measured using a DHL meter or also known as a conductor meter. Measurements were carried out at each variation in treatment time to determine changes in DHL over time. The use of a conductimeter is very sensitive because it is on a micro scale, so measurements must be carried out carefully and when the instrument is stable, it must not be moved during the measurement process.

3. Results and Discussion

3.1 Ozone concentration

The research results indicate that the series configuration in the ozone reactor produces higher ozone output compared to the parallel configuration at all applied voltage variations, namely 5 , 7 , and 9 kV. The highest concentration value was observed at a voltage of 9 kV in the series configuration, reaching 576 ppm, whereas, at the same voltage, the parallel configuration only achieved 360 ppm as shown in Fig. 2. This difference can be explained by several factors affecting ozone generation efficiency in the two configurations.

In the series configuration, gas passes through more than one reaction zone before being released, thereby increasing the contact time between oxygen molecules and the electric field generated by the DBD. Longer contact time allows more oxygen molecules to be activated into ozone (O_3), resulting in a higher total ozone output. This finding aligns with previous studies showing that increasing the gas residence time in the reactor enhances ozone production efficiency [20].

Moreover, in the series configuration, each reactor stage can be optimized to improve the ozone formation process. This approach allows unconverted oxygen molecules from the previous stage to be activated, which does not occur in the parallel configuration, where each reactor operates independently. Consequently, the synergy between reactors in the series configuration cumulatively increases the oxygen-to-ozone conversion.

In contrast, the parallel configuration has drawbacks in terms of uneven gas flow distribution among independently operating reactors. Variations in gas flow rates across reactors may reduce overall ozone formation efficiency, as some reactors might not have sufficient contact time to optimize the oxygen-to-ozone conversion.

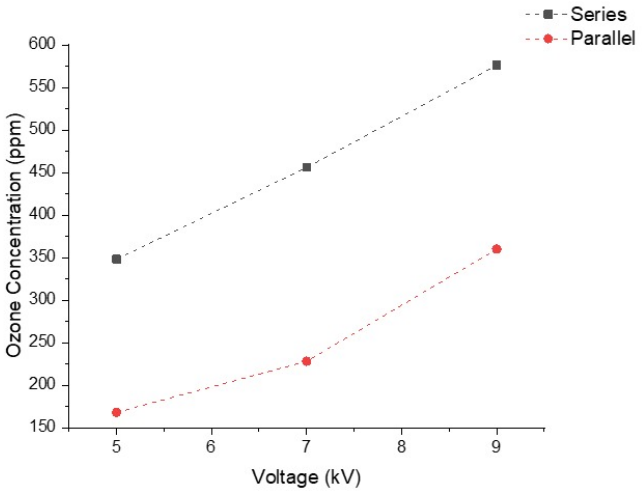
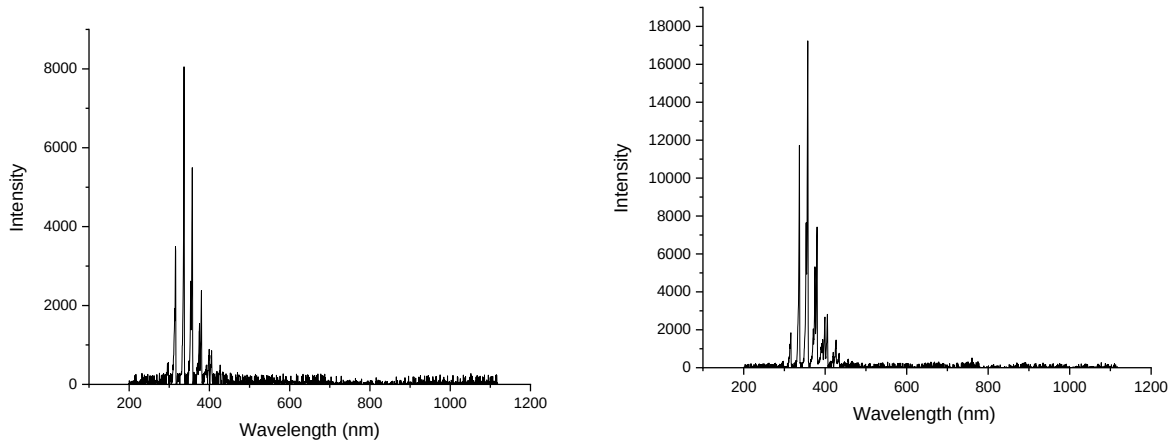


Figure 2. Ozone concentration produced at different applied voltages in series and parallel dielectric barrier discharge (DBD) reactor configurations, showing the effect of reactor arrangement on ozone generation efficiency.

3.2 Discharge emission

The emission spectrum graph illustrates the wavelengths and intensities of the discharge produced by the DBD plasma reactor. The intensity correlates directly with the concentration of reactive species generated. The OH (3-2) species is observed at 295 nm, O (4p-3s) at 725 nm, and O (3p-3s) at 777 nm [21]. In this study, the intensities of •OH and N_2 are analyzed as degradative agents.

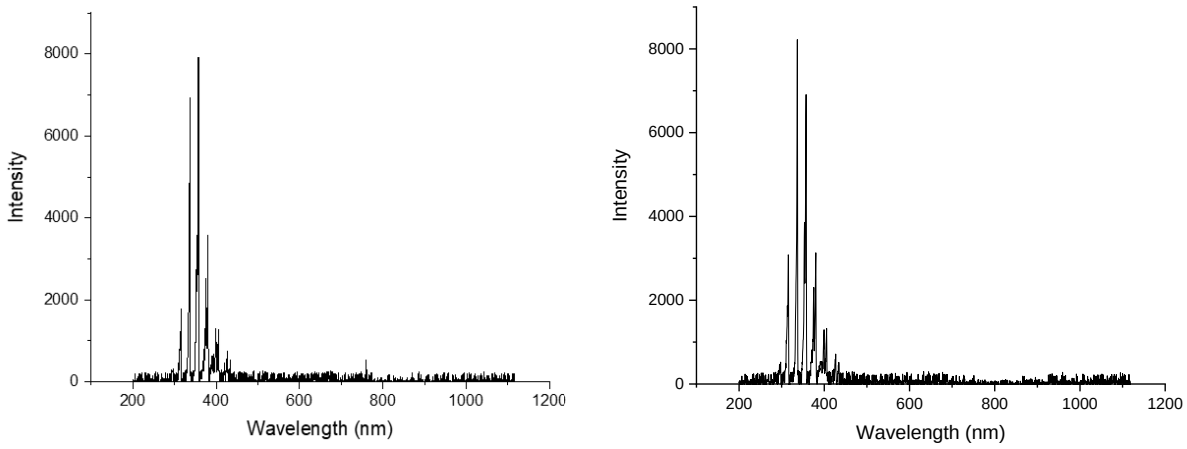
In a series reactor configuration, the reactors are connected directly, where the gas output from Reactor 1 is fed directly into Reactor 2. The graphical results indicate different maximum intensities, with Reactor 2 producing a higher •OH intensity, as shown in Fig. 3. In the parallel configuration, each reactor receives input gas directly from the gas source, and the output gases from both reactors are combined. The graphical results indicate that the OH intensity patterns in both reactors exhibit a similar trend, as shown in Fig. 4.



a) b)

Figure 3. Spectrum emission series circuit. a) First reactor and b) Second reactor.

In the series configuration graph, the second reactor demonstrates a higher OH and N_2 intensity among reactive ozone-producing species compared to the parallel configuration. This occurs because ozone that does not fully form in Reactor 1 completes formation in Reactor 2, resulting in greater ozone production. In contrast, in the parallel configuration, each reactor operates independently, producing less ozone overall. This conclusion aligns with previous calculations of ozone concentration for each configuration.



a) b)

Figure 4. Spectrum emission parallel circuit.

3.3 Other characterization (absorbance, total dissolved solids, total suspended solids, and conductivity)

The degradation of batik wastewater was carried out using the optimal ozone concentration setup, which employed a series configuration operating at the maximum voltage of 9 kV. The highest voltage produced the highest ozone concentration, which enhanced the degradation efficiency of the wastewater [22]. The research findings demonstrate that variations in ozone treatment duration significantly affect the reduction in absorbance peaks measured using a UV-Vis spectrophotometer. At the initial observation (0 minutes), the absorbance value was at its highest, reflecting the intact concentration of organic compounds in the wastewater. As the treatment time increased to 60 minutes, a gradual yet significant decrease in absorbance was observed, indicating that the organic compounds in the wastewater were degraded through oxidation by ozone generated from the DBD as shown as in Fig. 5. At 60 minutes, the absorbance reached its lowest point with degradation efficiency, suggesting that most of the color-causing compounds had been degraded as shown in Fig. 6 and 7.

Statistical analysis using ANOVA confirmed significant differences at each time interval ($p < 0.05$), indicating that variations in treatment duration significantly influence the degradation level of batik wastewater. This finding highlights the effectiveness of ozone in reducing the concentration of harmful organic compounds and suggests that extending the treatment duration can enhance the overall efficiency of wastewater degradation.

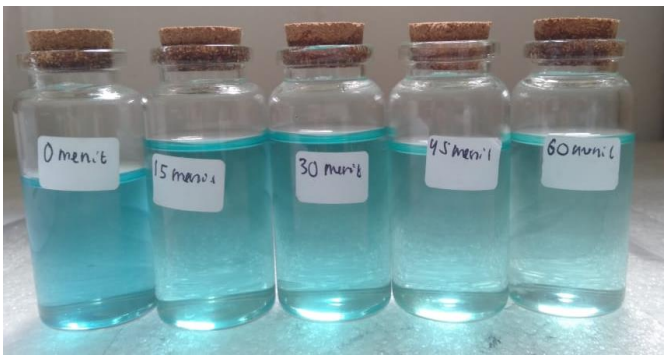


Figure 5. Visual comparison of batik wastewater samples treated with ozone over different exposure times.

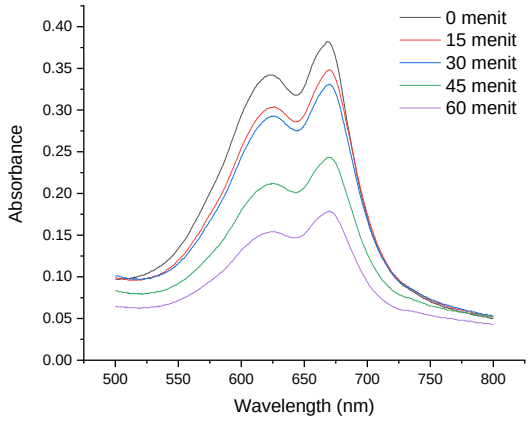


Figure 6. UV-Vis absorbance spectra of batik wastewater before and after ozone treatment, showing changes in absorbance at various wavelengths over the degradation process.

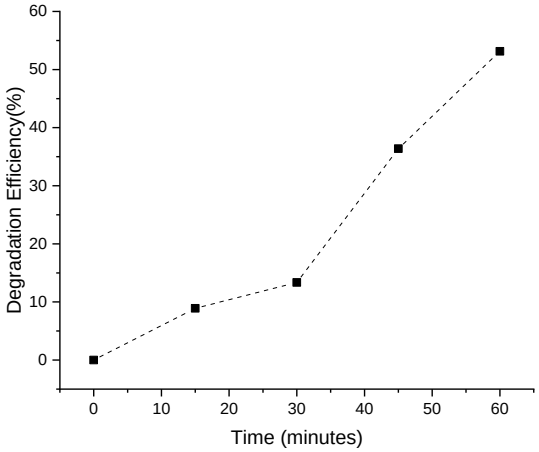


Figure 7. Degradation efficiency of batik wastewater at different ozone exposure times using a series DBD reactor configuration.

The measurement results showed that the Total Dissolved Solids (TDS) values in batik wastewater decreased with increasing ozone treatment duration. At the start of the treatment (0 minutes), the TDS value was at its highest, indicating a high concentration of dissolved substances in the wastewater. As the treatment duration extended to 60 minutes, the TDS values gradually decreased, becoming significant at 30–40 minutes, as shown in Fig. 8. This indicates that the organic and inorganic compounds in the wastewater were oxidized by ozone and broken down into lower molecular weight substances or fully decomposed.

The reduction in TDS values highlights the effectiveness of the ozonation process in reducing the total concentration of dissolved substances in the wastewater, resulting in cleaner water that meets better environmental standards. The decreasing TDS values over time also confirm that ozonation not only reduces the color of wastewater but also lowers the dissolved load, which is crucial for improving the quality of treated water [23].

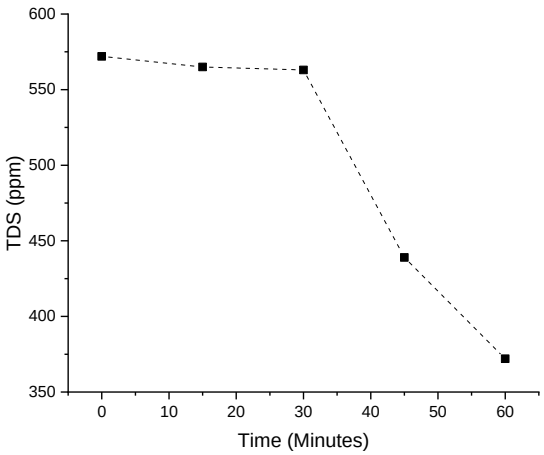


Figure 8. TDS treatment over time.

The analysis results show that the electrical conductivity (EC) or conductivity of batik wastewater tends to decrease with increasing ozone treatment duration. Initially, the EC value was relatively high, indicating a high concentration of dissolved ions in the wastewater, including ionic organic and inorganic compounds. As the treatment duration increased, ozone progressively oxidized these compounds, breaking some of them down into non-charged substances or simpler structures with reduced conductivity as shown as in Fig. 9.

This reduction in EC indicates that ozonation not only decreases the total dissolved substances but also affects the type and quantity of ions in the solution. Overall, the decreasing trend in EC demonstrates that the ozonation process effectively reduces the concentration of dissolved ionic substances in batik wastewater, improves the quality of treated water, and contributes to achieving better environmental water quality standards.

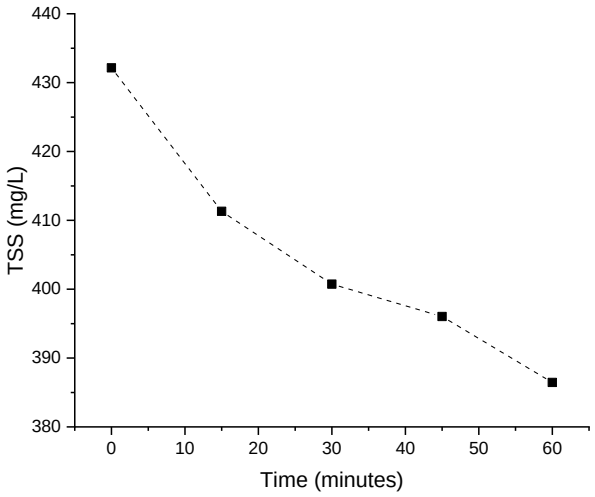


Figure 9. EC treatment over time.

The measurement results of Total Suspended Solids (TSS) in batik wastewater showed a consistent decrease with increasing ozone treatment duration, as shown in Fig. 10. At the start of the treatment (0 minutes), the TSS value was recorded at a high level, reflecting the large number of suspended particles in the batik wastewater. Over time, ozone generated by DBD effectively oxidized and broke down these suspended particles into smaller fragments or even dissolved them, thereby reducing the amount of suspended solids in the solution.

This reduction in TSS demonstrates that ozonation is effective in reducing suspended particulates that are difficult to decompose naturally, aiding in the clarification of wastewater. This trend also suggests that ozonation can enhance wastewater quality by reducing turbidity and suspended solid content.

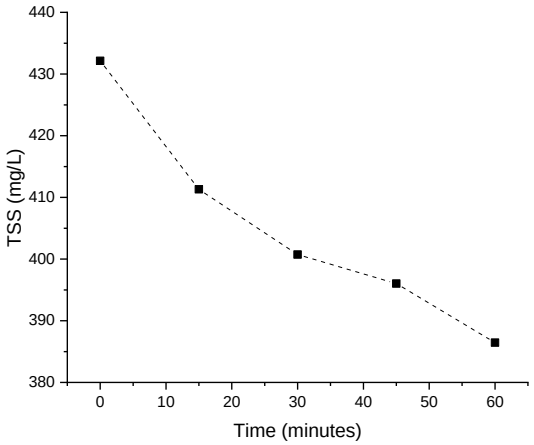


Figure 10. EC treatment over time.

The measurement results show that the dissolved oxygen (DO) levels in batik wastewater increased with prolonged ozone treatment duration. Initially, the DO values were relatively low, indicating limited dissolved oxygen availability due to the high concentration of organic compounds and pollutants that consume oxygen as shown as in Fig. 11. However, as the treatment progressed, the ozonation process contributed additional dissolved oxygen to the water through oxidation mechanisms, where ozone (O_3) decomposes into oxygen (O_2), which then dissolves in the solution.

This increase in DO indicates that ozonation not only reduces pollutant levels but also enriches the oxygen content in wastewater, which is essential for supporting aerobic conditions for decomposer microorganisms in advanced treatment systems. The rise in DO over time highlights the added benefit of ozonation in improving wastewater quality.

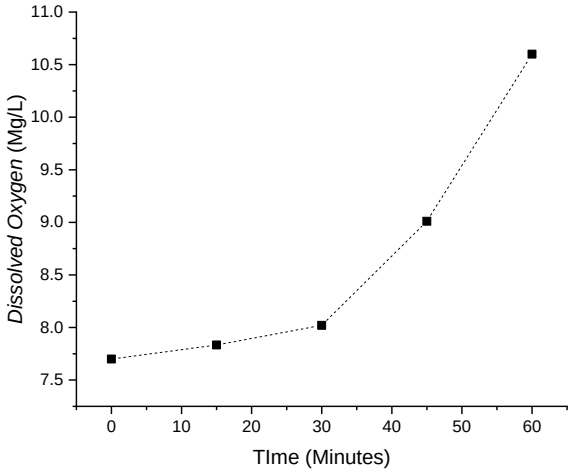


Figure 11. DO treatment over time.

4. Conclusion

This study demonstrates that dielectric DBD reactors in series configuration exhibit higher emission intensities of OH radicals and N_2 (via OES analysis) than parallel configurations, correlating with enhanced ozone production. Applied to batik wastewater treatment, this series configuration achieved 53.14% degradation efficiency within 60 minutes, reducing TSS, TDS, and conductivity, while increasing dissolved oxygen. These results confirm that series-configured DBD reactors are highly effective for treating textile wastewater, with emission spectra serving as a critical indicator of reactor performance.

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