

Textile Wastewater Treatment via Membrane Photocatalytic Reactor (MPR) Incorporated ZnO-Kaolin

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DOI: <https://doi.org/10.30880/jamea.2024.05.02.003>

Article Info

Received: 24 January 2024
Accepted: 27 November 2024
Available online: 16 December 2024

Keywords

Textile wastewater treatment, membrane, photocatalytic, photocatalyst, ZnO-kaolin

Abstract

Improperly treated or discharged textile wastewater can have negative impacts on the environment, leading to the pollution of water bodies, disruption of ecosystems, and a reduction in biodiversity. This study investigated the effectiveness of MPR, which incorporates ZnO-kaolin, in treating textile wastewater. ZnO-kaolin photocatalyst was successfully produced and comprises selective elements using the precipitation method, and the physico-chemical properties were characterized by using Fourier transform infrared (FTIR) and x-ray diffractometers (XRD). This study involved parameters such as initial pH (pH 6, 7, 8), ZnO-kaolin dosage (0.05, 0.1, 0.15, and 0.2 g/L), and initial concentration (90, 95, and 100%). The study suggests that the initial pH level has a significant impact on the efficiency of ZnO-kaolin in treating wastewater. The optimal pH for the removal of pollutants was determined to be 8 based on the presented data. The best amount of ZnO-Kaolin to use for effectively lowering pollutants in wastewater is 0.1 g/L, as shown by the higher percentages of color, turbidity, TDS, conductivity, and COD. The results highlight the importance of the photocatalyst dosage in the effectiveness of the treatment process. The study suggests that the initial concentration of ZnO-Kaolin plays a crucial role in the effectiveness of the wastewater treatment process. The results highlight optimal concentrations of 95% for achieving desired reductions in color, turbidity, TDS, conductivity, and COD. This study presents significant potential for the textile industry to reduce environmental issues and move toward sustainability.

1. Introduction

The textile industry is a longstanding and important sector in global industrialization, employing over 35 million individuals and playing a crucial role in the economic development of numerous nations [1]. The textile industry utilizes a range of raw materials such as dyes, cotton, and chemicals for its various operations. Javed [2] found that the production of effluent from this source contains various pollutants, such as organic matter, colors, nitrogen, phosphorus, and others. Wet textile processing utilizes water as the main medium to eliminate impurities from fibers and facilitate dyeing, printing, and other finishing procedures. The excessive use of chemicals, specifically dyestuffs, in the textile industry is a significant concern. The effluent from the textile industry contains various chemicals, such as biocides, stain repellents, sequestering agents, anti-creasing agents, sizing agents, softening agents, and wetting agents. Textile wastewater discharge contaminates both surface water and groundwater sources in the vicinity [3]. The exceptional efficacy of ZnO nanoparticles in membrane photocatalytic reactors (MPR) for wastewater treatment has been recently confirmed [4]. The efficacy of ZnO-kaolin nanoparticles in MPR has not yet been established. Investigating ZnO-kaolin effects on the photocatalytic degradation of textile effluent is crucial to improving MPR performance. Novel and efficient approaches are necessary to address the challenges associated with treating textile wastewater, with a specific emphasis on textile wastewater itself. The study's goal is to make a ZnO-kaolin photocatalyst and see how well it works at treating textile wastewater using MPR. It focuses on the synthesis of ZnO-kaolin photocatalysts using the precipitation method. The physical and chemical properties of the ZnO-kaolin photocatalyst are characterized by using Fourier Transform Infrared (FTIR) and X-ray diffractometer (XRD) techniques. This research evaluates the performance of MPR for treating textile wastewater. The evaluation is conducted under various conditions, including different initial pH levels (6, 7, 8), dosing of ZnO-kaolin photocatalyst (0.05 g/L, 0.1 g/L, 0.15 g/L, 0.2 g/L), different initial concentrations (90%, 95%, 100%), and using a hollow fiber membrane configuration. This investigation examines various parameters of treated water, including color, turbidity, conductivity, total dissolved solids (TDS), pH, and chemical oxygen demand (COD).

2. Material and Methods

Oxalic acid (R&M Marketing, UK), zinc acetate (R&M Marketing, UK), kaolin (Sigma Aldrich, US), and zinc oxide (Sigma Aldrich, US) were utilized as materials. All compounds were utilized in their original state without any purification.

2.1 Preparation of ZnO-Kaolin

The synthesis of ZnO-kaolin was conducted via the precipitation process, incorporating zinc oxide (ZnO) nanoparticles into kaolin. Mix the oxalic acid solution with the zinc acetate solution and stir the mixture for five minutes at the room temperature. Add powdered kaolin into the mixture and allow it to rest at room temperature for an entire day, stirring periodically. This resulted in the formation of a ZnO-kaolin precipitate. Subsequently, place the dry ZnO-kaolin precipitates in an oven and heat them for one hour at 100°C. Finally, calcine the ZnO-kaolin powder and place it in the furnace.

2.2 Characterization

The synthesized ZnO-Kaolin was characterized for its composition and quality using a Cary 600 series Fourier transform infrared (FTIR) spectrometer at room temperature. The analysis was conducted with a spectral resolution of 8 cm⁻¹ and involved 16 scans in an open-beam air background within the mid-infrared range of 400–4000 cm⁻¹. The synthesized ZnO-Kaolin was characterized in terms of its composition and quality. The crystallinity of ZnO-Kaolin will be assessed using an X-ray diffractometer (XRD) (model Bruker AXS GmbH). The XRD utilized Cu-K α radiation at 1.54 Å, with a 2 θ angle spanning from 20° to 80° [4].

2.3 Textile Wastewater Treatment via MPR

The membrane sample was wetted using distilled water flowing in the MPR at 3 bar for 30 minutes prior to the experiment. This procedure is employed to avoid membrane compaction during permeation or separation trials. The photocatalyst will be activated by placing a UV light inside the reactor. Textile wastewater treatment will occur in a 2L reactor. The pH of the textile wastewater solution was modified using sodium hydroxide (NaOH) and hydrochloric acid (HCl) solutions. ZnO-kaolin nanoparticles were introduced into the mixture, which will then be subjected to air blasting throughout the trials. In addition, a water chiller was employed to circulate cooling water and regulate the temperature to approximately 25°C. After the photocatalysis process, a Masterflex peristaltic pump will deliver the treated water to the membrane module at a pressure of 6 bar. The experiment was repeated with variations in the initial pH levels (6, 7, 8), dosing of photocatalyst (0.05, 0.1, 0.15, 0.2 g/L), initial concentration of the solution (90%, 95%, 100%), and the use of a hollow fiber membrane configuration. The permeate volume was measured using an electronic balance. The color intensity, turbidity, conductivity, total

dissolved solids (TDS), pH, and chemical oxygen demand (COD) of the permeate will be measured and analyzed to determine its quality. All the parameters were calculated for reduction using equation (1). Fig. 1 shows the experimental process of quality textile wastewater analyses.

$$\text{Reduction \%} = \frac{P_i - P_f}{P_i} \times 100\% \quad (1)$$

where, P_i is the initial parameter and P_f is the final parameter.

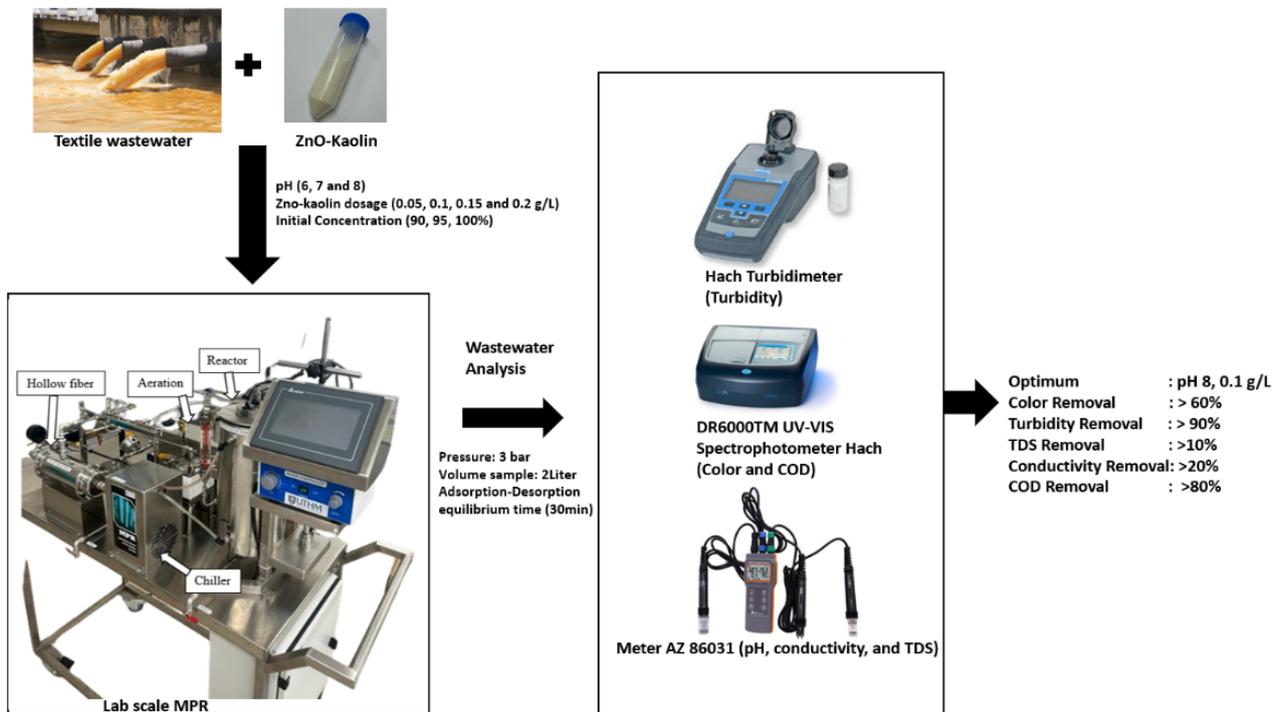


Fig. 1 Experimental process of quality textile wastewater analyses

3. Results and Discussion

3.1 Characterization of ZnO-Kaolin

The composition of ZnO, kaolin, and synthesized ZnO-kaolin, prepared via the precipitation method, was analyzed using Fourier Transform Infrared (FTIR) [5, 6]. Figure 2 presents the FTIR spectra of ZnO, kaolin, and the ZnO-kaolin composite within the range of 500-4000 cm^{-1} . The spectrum of kaolin exhibits absorption bands at approximately 3698-3625 cm^{-1} (OH vibration), 796 and 750 cm^{-1} (Si-O), and 560 and 533 cm^{-1} (Si-O-Al). The identification peaks of ZnO were noted at 513 cm^{-1} . The spectra's absorption peaks validated the incorporation of ZnO-kaolin. The ZnO-kaolin exhibits peaks corresponding to both ZnO and kaolin; however, the kaolin peak at 533 cm^{-1} (Si-O-Al) obscures the ZnO peak at 513 cm^{-1} .

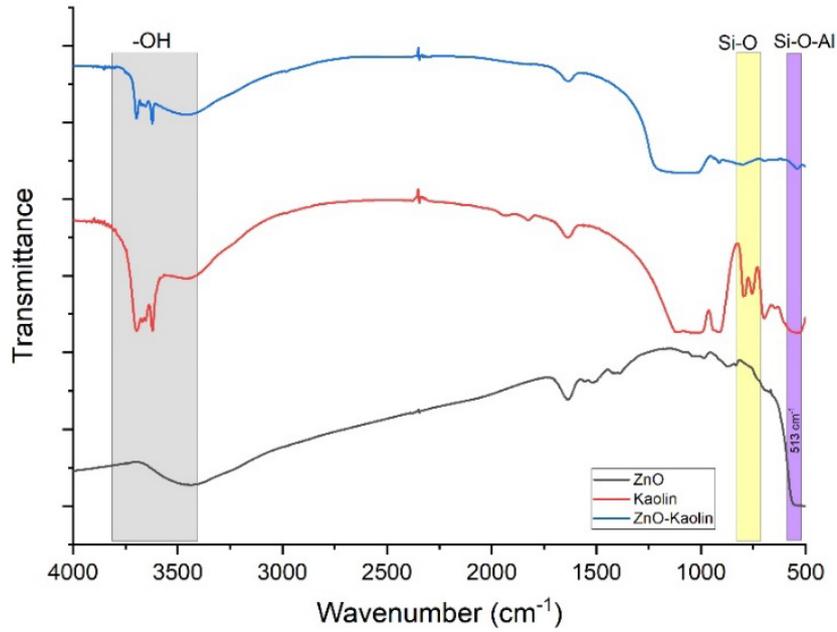


Fig. 2 FTIR spectra of ZnO, Kaolin and ZnO-kaolin

The crystallinity of ZnO-kaolin was analyzed using X-ray diffraction (XRD). Fig. 3 displays the XRD patterns of ZnO, kaolin, and ZnO-kaolin. The XRD peak of ZnO typically appears at 2θ values of $x = 31.85^\circ, 34.51^\circ, 36.38^\circ, 47.59^\circ, 56.64^\circ, 62.86^\circ, 66.38^\circ, 68.11^\circ,$ and 69.18° and matches with the pattern of JCPDS card no. 36-1451 with high crystallinity. For the pattern of kaolin, the absorption peaks were found at $2\theta^\circ = 12.39^\circ, 24.88^\circ, 35.91^\circ,$ and 38.35° . The maximum crystallinity shows at the absorption peak of 24.88° . The ZnO and kaolin nanocomposites successfully formed a mixed-phase structure, as demonstrated by an XRD pattern analysis [8]. This finding suggests that the combination of kaolin and ZnO resulted in the formation of a composite material with distinct crystalline phases [7]. The incorporation of kaolin significantly reduced crystallinity. The XRD pattern, which is a powerful technique for characterizing the crystal structure of materials, revealed the presence of both kaolin and ZnO phases in the nanocomposites. This confirms the effective incorporation of ZnO and kaolin.

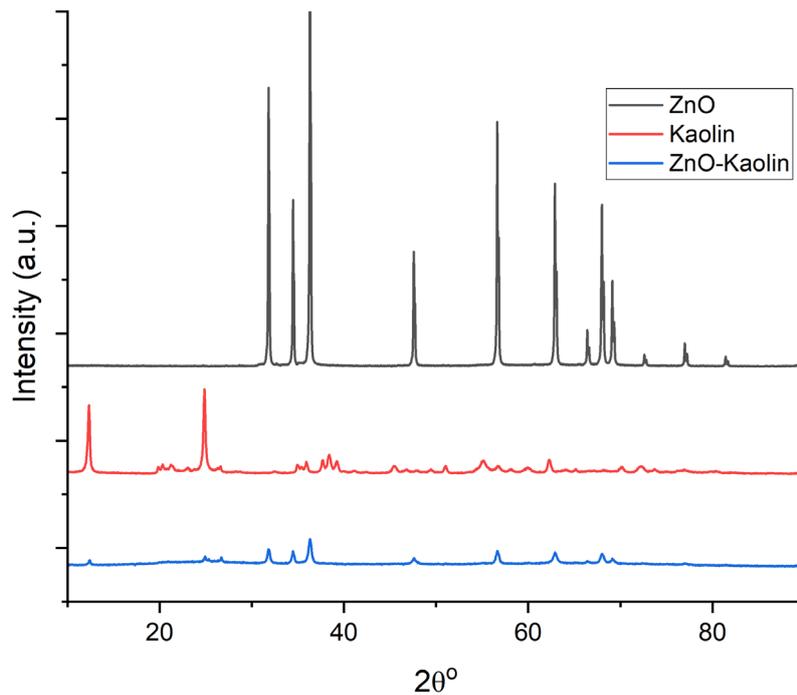


Fig. 3 XRD spectrum of ZnO, Kaolin and ZnO-Kaolin

3.2 Effect of Initial pH on the Reduction Performance

Figure 4 illustrates the decrease in initial pH of ZnO-kaolin, providing an evaluation of the efficiency of the treatment. Figure 4 demonstrates a significant reduction in turbidity at pH levels 6, 7, and 8, approaching a 100% decrease. Efficient water treatment methods can achieve a turbidity reduction of approximately 100% by removing suspended particles and clarifying the water [9]. The decrease in conductivity and total dissolved solids (TDS) was more pronounced at a pH of 8 than at pH 6 and 7. The color reduction percentages at pH 8, pH 6, and pH 7 were 68.18%, 60.47%, and 58.86%, respectively. The untreated wastewater exhibited an initial pH of 8, consistent with the optimal pH level for this study. No chemical modifications are required to attain optimal removal efficiency. The experiment's results indicate that at pH 6, the COD removal efficiency was significantly higher, achieving 84.33%. The removal efficiency at pH 7 was 56.05%, while at pH 8 it increased to 75.16%. The findings demonstrate that the solution's pH substantially influences COD removal, with decreased pH values resulting in enhanced removal efficiency. Further investigation is required to understand the mechanisms that lead to differences in COD removal efficiency across varying pH levels [10]. The analysis of Figure 4 identified the optimal pH value as 8.

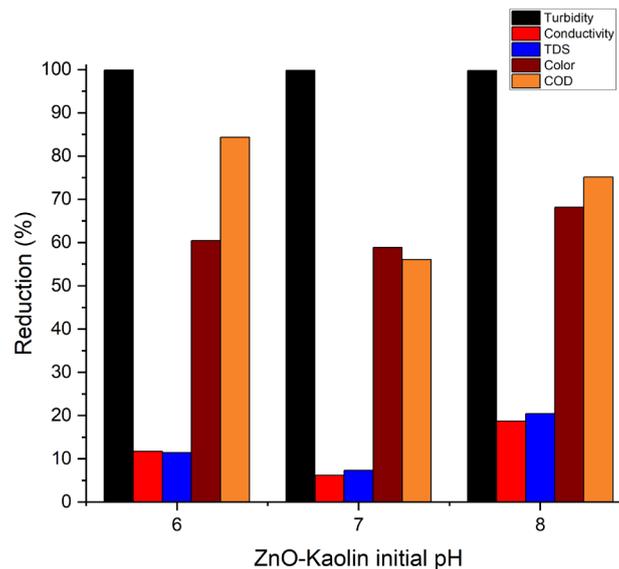


Fig. 4 Effect of initial pH on the color, turbidity, total dissolve solid (TDS), chemical oxygen demand (COD), and conductivity reduction percentage (%) at dosage 0.05 (g/L)

3.3 Effect of ZnO-Kaolin Dosage on the Reduction Performance

Figure 5 shows how different amounts of photocatalyst change several important factors, such as color, turbidity, total dissolved solids (TDS), chemical oxygen demand (COD), and the percentage decrease in conductivity. The measurements were conducted at pH 8. The graph reveals the correlation between the dosage of photocatalyst and the reduction observed in each parameter. This study administered four different dosages: 0.05 g/L, 0.1 g/L, 0.15 g/L, and 0.2 g/L. The experimental investigation found that a dosage of 0.1 g/L of ZnO-kaolin resulted in the greatest reduction compared to other dosages. This finding indicates that the dosage of ZnO-kaolin has a significant impact on the efficiency of color reduction. All ZnO-kaolin dosages were found to be highly effective in reducing turbidity. The study found that a dosage of 0.1 g/L achieved the greatest reduction percentages in total dissolved solids (TDS) and conductivity. The TDS reduction percentage was 41.09%, and the conductivity reduction percentage was 40.11%. These findings indicate that the mentioned dosage level effectively reduces TDS and conductivity levels in the system. The COD analysis results show that the 0.1 g/L dosage had the highest reduction in COD, with a significant decrease of 89.43%. The subsequent dosage of 0.2 g/L resulted in an 86.88% reduction. Furthermore, a dosage of 0.15 g/L led to an 85.61% reduction in COD, while a dosage of 0.05 g/L resulted in a lower reduction of 75.20%. This study attributed the improved efficiency of photocatalytic removal to the increased dosage of catalyst. This increase results in a larger surface area and more active sites on the catalyst surface, which enhances the absorption of optical photons. UV light exposure leads to an increased generation of electron holes, resulting in a higher concentration of oxidizing radicals and subsequent breakdown [11]. The optimal photocatalyst dosage, as determined by the analysis in Fig. 5, was 0.1 g/L.

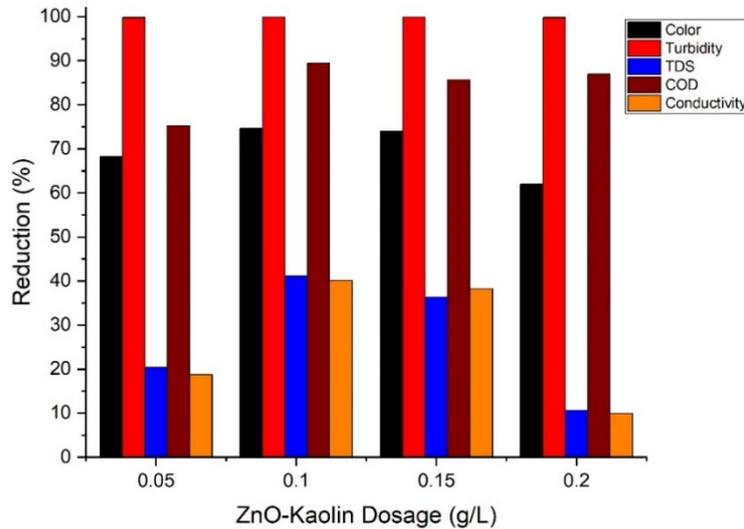


Fig. 5 Effect of photocatalyst dosage on the color, turbidity, total dissolve solid (TDS), chemical oxygen demand (COD), and conductivity reduction percentage (%) at pH 8.

3.4 Effect of Initial Concentration on the Reduction Performance

Figure 6 shows the influence of different initial concentrations on various parameters, including color, turbidity, total dissolved solids (TDS), chemical oxygen demand (COD), and conductivity reduction percentage (%). The measurements were obtained under specific experimental conditions, specifically at pH 8 and a dosage of 0.1 g/L. By analyzing the graph, one can understand the connection between the initial concentration and the mentioned parameters, which provides insights into the effectiveness of the treatment process. In the context of color reduction, it has been observed that a concentration of 95% achieves the most significant reduction in color intensity compared to concentrations of 90% and 100%. This finding indicates that a 95% concentration is ideal for achieving the desired color reduction. All concentrations of ZnO-kaolin caused a significant 100% reduction in turbidity. The graph depicts the decline in total dissolved solids (TDS) at different concentrations. The concentration of 95% resulted in the greatest reduction, 50.61%. Subsequently, reductions of 41.08% and 20% were observed at concentrations of 100% and 90%, respectively. The solution with an initial concentration and conductivity of 95% showed the greatest decrease compared to solutions with conductivities of 100% and 90%. COD is a commonly employed metric for quantifying organic pollutants in water. The study found that the greatest decrease in COD occurred when the initial concentration was 90%, resulting in a significant reduction of 92.23%. Subsequent to this, the initial concentrations of 100% and 90% also experienced noteworthy decreases in COD. These findings demonstrate the efficacy of the treatment process in reducing organic pollutants in the water samples. The optimal performance was observed at a concentration of 95%. Additional research is necessary to investigate the underlying mechanisms that cause variations in COD reduction at different initial concentrations.

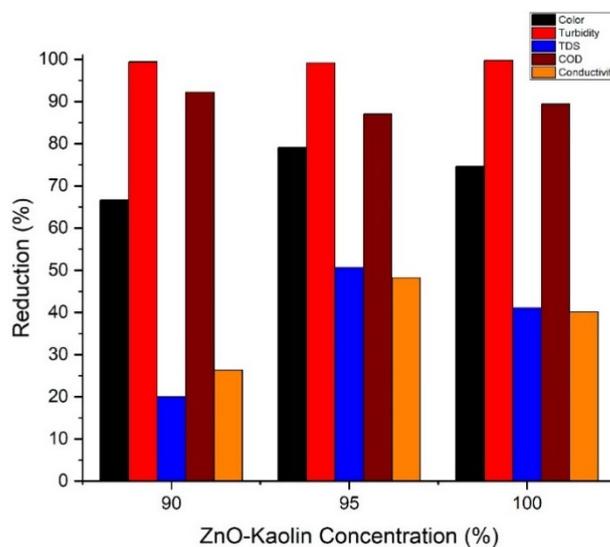


Fig. 6 Effect of initial concentration on the color, turbidity, total dissolve solid (TDS), chemical oxygen demand (COD), and conductivity reduction percentage (%) at pH 8 and dosage 0.1 (mg/L)

4. Conclusion

In conclusion, the utilization of a membrane photocatalytic reactor (MPR) integrated with a ZnO-kaolin composite proves to be a remarkably efficient and innovative approach for the treatment of textile wastewater. This study has made significant progress in removing pollutants commonly found in textile effluents by thoroughly investigating the combined effects of MPR, ZnO, and kaolin. ZnO-kaolin photocatalyst was successfully produced and characterized using FTIR and XRD. The performance was evaluated based on the reduction in color, turbidity, conductivity, total dissolved solids (TDS), pH, and chemical oxygen demands (COD). The study determined that pH 8 is the optimal pH level. Researchers determined that 0.1 g/L was the optimal dosage for achieving the desired effect. Furthermore, it was found that a concentration of 95% produced the most optimal results for treating textile wastewater. The incorporation of ZnO-kaolin in MPR proved to be efficient in treating textile wastewater. Hence, the outcomes of this research offer promising opportunities for the textile sector to reduce its environmental impact and make progress toward attaining sustainability.

Acknowledgement

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2021/WAB05/UTHM/02/1). The authors also gratefully acknowledge the technical and administrative support from Universiti Tun Hussein Onn Malaysia (UTHM).

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Ahmad Rafiq Azman, Rais Hanizam Madon; **data collection:** Ahmad Rafiq Azman; **analysis and interpretation of results:** Siti Nurfatimah Nadhirah Mohd Makhtar, Mohamad Alif Hakimi Hamdan, Nur Hanis Hayati Hairom; **draft manuscript preparation:** Nor Afzanizam Samiran, MZahar Abd. Jalal. All authors reviewed the results and approved the final version of the manuscript.

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