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# Photocatalytic Degradation of Congo Red Textile Dye in Aqueous Solution Using $TiO_2$ Suspension

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## ABSTRACT

**Purpose of the study:** This study aims to investigate the photocatalytic degradation of Congo Red dye using $TiO_2$ suspension. It focuses on evaluating the effect of process conditions on degradation efficiency, examining the reaction kinetics of photodegradation, and analyzing the degradation behavior of Congo Red in aqueous solution.

**Methodology:** Photocatalytic experiments were conducted using $TiO_2$ catalyst suspension and Congo Red solution. UV-C lamp (36 W) was used as radiation source in a photocatalytic reactor. Absorbance was measured using a UV–Vis spectrophotometer at 499 nm. COD was determined by closed reflux titrimetric method using $K_2Cr_2O_7$, $Ag_2SO_4$, $H_2SO_4$, FAS, and ferroin indicator. Mixing employed a magnetic stirrer and pH meter.

**Main Findings:** $TiO_2$ photocatalysis successfully degraded Congo Red dye under UV irradiation. The optimum catalyst amount was 4.5 mg $TiO_2$ and the optimum irradiation time was 150 minutes. Under these conditions, degradation efficiency of Congo Red (20 ppm) reached 48.90%. COD reduction reached 84.1%, indicating significant removal of organic compounds. Increasing dye concentration decreased degradation efficiency due to higher pollutant load in the system.

**Novelty/Originality of this study:** This study provides a systematic evaluation of photocatalytic degradation of Congo Red using $TiO_2$ suspension by analyzing the effects of catalyst amount, irradiation time, and dye concentration. It integrates absorbance and COD analyses to evaluate degradation efficiency, offering a clearer understanding of photocatalytic performance for textile dye wastewater treatment.

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## 1. INTRODUCTION

The textile industry is a rapidly growing industrial sector and makes a significant contribution to the global economy [1], [2]. However, the textile production process also produces liquid waste containing various synthetic dyes at high concentrations [3], [4]. Synthetic dyes have complex and stable chemical structures, making them difficult to degrade naturally in the environment [5], [6]. One dye widely used in the textile industry is Congo Red, a member of the azo dye family. The presence of Congo Red in water can have negative impacts on the environment and human health due to its toxic, carcinogenic, and difficult-to-biodegrade properties.

Congo Red has a stable chemical structure with strong azo bonds (-N=N-), making it difficult to decompose using conventional wastewater treatment processes [7], [8]. The presence of this dye in water bodies can inhibit sunlight penetration and disrupt the photosynthesis process of aquatic organisms [9], [10]. Furthermore, the degradation products of azo dyes can also produce aromatic compounds that are potentially harmful to the environment [11], [12]. Therefore, effective wastewater treatment technologies are needed to remove these dyes from water bodies. Various methods have been developed to address dye pollution, such as adsorption, coagulation-flocculation, membrane filtration, and advanced oxidation processes.

Among the various methods that have been developed, photocatalytic processes are one promising technology for the degradation of dyes in water [13], [14]. This method utilizes light energy to activate a semiconductor catalyst, producing reactive radicals capable of oxidizing organic compounds [15], [16]. One of the most widely used photocatalytic materials is titanium dioxide ($TiO_2$) due to its high chemical stability, non-toxicity, and relatively low cost [17], [18]. When $TiO_2$ is irradiated with light of the appropriate energy, electrons in the valence band are excited to the conduction band, producing electron-hole pairs. These electron-hole pairs can then react with water and oxygen molecules to produce highly reactive hydroxyl radicals that degrade organic compounds.

The use of $TiO_2$ as a photocatalyst in dye degradation processes has been extensively researched in recent years [19], [20]. Various studies have reported that $TiO_2$ can effectively degrade various types of textile dyes through photocatalytic oxidation mechanisms [13], [21]. Photocatalytic systems can be implemented in various forms, such as thin films, immobilized on substrates, or in suspension [22], [23]. The use of $TiO_2$ in suspension has the advantage of a larger contact surface area between the catalyst and the solution. This can increase the efficiency of the dye degradation process in photocatalytic systems.

However, the efficiency of the dye photodegradation process using $TiO_2$ is significantly influenced by various operational parameters [24], [25]. These parameters include dye concentration, catalyst amount, light intensity, and reaction time. Variations in process conditions can affect the formation of reactive radicals and the rate of degradation reactions occurring in the system. Therefore, a deeper understanding of the effect of process conditions on degradation efficiency is essential [26], [27]. Reaction kinetics analysis is also crucial to understand the mechanisms and reaction rates occurring during the photodegradation process [28], [29].

Several previous studies have reported the use of $TiO_2$ for the degradation of azo dyes, but most have focused on increasing efficiency through catalyst modification or the use of composite materials [30], [31]. Studies specifically evaluating the effect of varying process conditions in a $TiO_2$ suspension system on the degradation of Congo Red are still relatively limited. Furthermore, information on the kinetic characteristics of the photodegradation reaction in this system has not been comprehensively reported. This indicates a research gap that requires further study to understand the dye degradation process more systematically. Therefore, research on the degradation of Congo Red using a $TiO_2$ suspension is crucial to provide a better understanding of the effectiveness and mechanisms of this process.

Based on the description, this study has an urgency to study in more depth the degradation process of Congo Red dye using a photocatalytic method with $TiO_2$ suspension. This study is expected to provide scientific contributions in understanding the effect of process conditions on the efficiency of dye degradation in photocatalytic systems. In addition, the study of reaction kinetics is expected to provide an overview of the mechanisms and reaction rates that occur during the photodegradation process. Therefore, the objectives of this study are to study the effect of variations in the conditions of the dye degradation process with $TiO_2$ catalyst in suspension [32], [33], to study the kinetics of the photodegradation reaction, and to study the degradation process of Congo Red dye using $TiO_2$ suspension. The results of this study are expected to be the basis for the development of more effective and environmentally friendly dye waste processing technology.

## 2. RESEARCH METHOD

### 2.1. Tools and materials

This research utilized various laboratory equipment to support the photodegradation process and sample analysis. The glassware used included beakers, volumetric flasks, Erlenmeyer flasks, graduated pipettes, and other glassware commonly used in chemistry laboratories. Solution concentration was measured using a visible light (UV–Vis) spectrophotometer [34]. The acidity of the solution was measured using a pH meter. Furthermore, the solution was mixed during the reaction using a magnetic stirrer to ensure the homogeneity of the reaction system.

The photocatalytic reaction system was operated using a 30-watt UV-C lamp as the radiation source, placed inside the reactor box. The degradation reaction took place in a reflux flask equipped with a condenser to prevent solvent loss during the heating and irradiation processes. All of the equipment was assembled into a photocatalytic reactor system to support the dye degradation process [13], [35]. Materials were weighed using an analytical balance to ensure accurate mass measurements. This equipment was used to achieve controlled experimental conditions and accurate analytical results.

The main materials used in this study are titanium dioxide ($TiO_2$) which functions as a catalyst in the photocatalytic process and Congo Red dye as the target compound to be degraded [36], [37]. The solvent used in making the solution is distilled water. In addition, several chemicals are used in the analysis process, including potassium bichromate ($K_2Cr_2O_7$) 0.1 N, silver sulfate ($Ag_2SO_4$), and concentrated sulfuric acid ($H_2SO_4$). Other materials used are ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2(H_2O)$), mercuric sulfate ($HgSO_4$), and ferroin indicator. All chemicals used in this study have analytical purity and are used without further purification processes.

## 2.2. Procedure

### 2.2.1. Sample Preparation

A stock solution of Congo Red dye was prepared by dissolving 0.5 g of Congo Red in 1000 mL of distilled water to obtain a solution with a concentration of 500 ppm. The stock solution was then diluted to obtain a working solution with a lower concentration. A total of 40 mL of 500 ppm Congo Red solution was pipetted and placed into a 1000 mL volumetric flask, then distilled water was added until it reached the limit mark. This dilution process produced a Congo Red solution with a concentration of 20 ppm which was used as the initial sample in the degradation process. This solution was then used in various photodegradation experiments using $TiO_2$ catalyst.

### 2.2.2. Determination of Control

A control experiment was conducted to determine the effect of catalyst adsorption on dyes without irradiation. A total of 8 mg of $TiO_2$ was added to 100 mL of Congo Red solution at a concentration of 20 ppm. The mixture was then stirred using a magnetic stirrer for 4 hours in a dark room without UV irradiation. After the stirring process was complete, the solution was separated from the catalyst. The absorbance of the solution was then measured using a UV–Vis spectrophotometer.

### 2.2.3. Determination of the Optimum Amount of $TiO_2$ Catalyst

The optimum catalyst amount was determined by varying the $TiO_2$ mass by 0, 1, 2, 3, 4, 5, 6, and 7 mg. Each catalyst mass was added to 100 mL of Congo Red solution with a concentration of 20 ppm. The mixture was then irradiated using a UV lamp with a power of 36 watts while stirring for 4 hours. After the irradiation process was completed, the solution was separated using a centrifugation process to separate the catalyst from the solution. Next, the pH of the solution was measured and the absorbance of the sample was analyzed using a UV–Vis spectrophotometer at a maximum wavelength of 499 nm.

### 2.2.4. Determining Optimal Time

The optimum time was determined by preparing six samples, each containing the optimum $TiO_2$ catalyst concentration obtained in the previous step. The samples were then irradiated using a 36-watt UV lamp in a reactor box. The irradiation process was carried out while stirring for 180 minutes. Every 30 minutes, one sample was taken for analysis. The samples were then centrifuged and their absorbance measured using a UV–Vis spectrophotometer, and their COD values were analyzed.

### 2.2.5. Effect of Variations in Dye Concentration

The effect of dye concentration on the degradation process was studied by preparing Congo Red solutions with concentrations of 20, 30, 40, 50, and 60 ppm. These solutions were prepared by dissolving 20, 30, 40, 50, and 60 mg of Congo Red in distilled water to a volume of 100 mL, respectively. The absorbance of each solution was then measured using a UV–Vis spectrophotometer and the initial COD value was analyzed using a titrimetric method. Next, $TiO_2$ catalyst with an optimum mass was added to each solution. The mixture was then irradiated using a 36-watt UV lamp in a reactor box for a predetermined optimum time. After the degradation process was complete, the absorbance and COD values of each sample were reanalyzed.

### 2.2.6. Determination of Chemical Oxygen Demand (COD)

COD determination was performed using a closed reflux titration method. A 5 mL sample was pipetted into a reflux flask, then 4 mL of 0.1 N $K_2Cr_2O_7$ solution, 0.1 g of $HgSO_4$, and boiling stones were added. Next, 7.5 mL of a cold $H_2SO_4$ mixture containing a small amount of $Ag_2SO_4$ was added. The mixture was then refluxed for 2 hours using a condenser. After the reflux process was complete, the solution was cooled and then titrated using a ferrous ammonium sulfate (FAS) solution with the addition of 2–3 drops of ferroin indicator. The titration was stopped when the color changed from blue-green to brown.

The COD value is calculated using the following equation:

$$COD\ (mg/L = \frac{(a-b)\ x\ N\ x\ 8000}{V_{Sample}} \ldots (1)$$

where a is the volume of FAS used for the blank, b is the volume of FAS used for the sample, N is the normality of the FAS solution, and V is the volume of sample used in the analysis.

### 2.2.7. Preparation of Reagents for COD Analysis

A 0.1 N potassium dichromate solution was prepared by dissolving 4.9047 g of $K_2Cr_2O_7$ previously heated at 103°C for 2 hours in distilled water to a volume of 1 liter. The $Ag_2SO_4$ reagent in $H_2SO_4$ was prepared by dissolving $Ag_2SO_4$ in 1 liter of concentrated $H_2SO_4$ and left for 1–2 days until the solution was homogeneous. A

0.1 N ferrous ammonium sulfate solution was prepared by dissolving 39.214 g of $Fe(NH_4)_2(SO_4)_2\cdot6H_2O$ in distilled water, then adding 20 mL of concentrated sulfuric acid and diluting to a volume of 1 liter. The ferroin indicator was prepared by dissolving 1.485 g of phenanthroline monohydrate and 695 mg of $FeSO_4\cdot7H_2O$ in distilled water to a volume of 100 mL. The FAS solution was then standardized using a standard $K_2Cr_2O_7$ solution by titration with the ferroin indicator. The normality of the FAS solution was calculated using the equation:

$$N_{FAS} = \frac{mLK_2Cr_2O_7 \; x \; NK_2Cr_2O_7}{mL \; FAS} \; ... \; (2)$$

## 3. RESULTS AND DISCUSSION

### 3.1. Determination of the Optimum Amount of TiO2 Catalyst

Determination of the optimum amount of TiO2 catalyst by varying the amount of TiO2 catalyst in the sample. The time used for stirring is 4 hours. To see the effect of UV on the sample, radiation was carried out with the addition of TiO2. The results of sample radiation with varying amounts of TiO2 catalyst are shown in the following table:

Table 1. Color Absorption Results of 36 Watt UV Radiation for 4 Hours at Variations in the Amount of TiO2 Catalyst

| $TiO_2$ (mg) | 0 | 1 | 2 | 3 | 3.5 | 4.5 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| Abs (λ=499nm) | 0.783 | 0.615 | 0.528 | 0.479 | 0.409 | 0.312 | 0.312 | 0.303 | 0.201 |
| pH | 7.31 | 7.18 | 7.48 | 7.56 | 7.28 | 7.32 | 7.59 | 7.29 | 7.32 |

Note: Abs=absorbance

From this data, a graph of the change in absorbance based on the amount of TiO2 catalyst was then made, as shown in Figure 1.

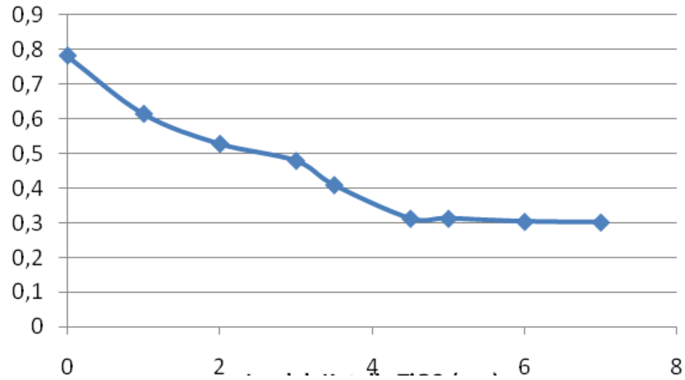

Figure 1. Graph of Changes in Absorbance Intensity of Congo Red Solution Against the Amount of TiO2 Catalyst

To see the percentage change in absorbance, a change graph is also made. The percentage decrease is obtained by calculation:

$$\% \, Loss \; = \frac{Abs_1 - Abs_2 \; X \; 100\%}{Abs_1}$$

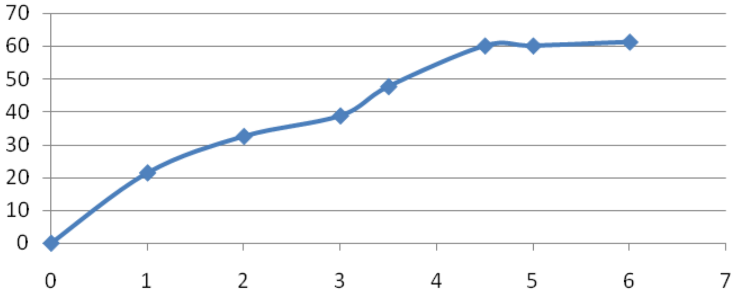

Figure 2. Graph of Percentage Change in Absorbance of TiO2 Catalyst Amount

The experimental control, a Congo red solution exposed only to UV light without the addition of a $TiO_2$ catalyst, is shown in Figure 4.2. Under these conditions, the degradation rate only reached 21.45%. These results indicate that UV radiation alone is capable of decomposing Congo red dye, but its effectiveness is still much lower than that of a system using a $TiO_2$ catalyst.

Based on the graph, increasing the amount of $TiO_2$ catalyst resulted in an increase in the Congo red degradation rate, reaching 60.15% with the addition of 4.5 mg of catalyst. However, with the addition of 5, 6, and 7 mg of catalyst, the increase was no longer significant, although the absorbance value still showed a trend towards an increase. Therefore, 4.5 mg of $TiO_2$ catalyst was determined as the optimum amount and used as a reference in subsequent experiments.

pH measurements after the degradation process were also conducted to determine the properties of the intermediates formed during the dye decomposition process. However, the pH value of the degradation results did not show any significant changes, so the properties of the intermediates formed from the degradation of Congo red cannot be determined with certainty.

### 3.2. Determining Optimal Time

The optimum time was determined by varying the radiation time using the optimum amount of $TiO_2$ catalyst of 4.5 mg obtained in the previous stage. This experiment aimed to determine the most effective radiation time in the degradation process of Congo Red dye. The optimum time was determined by starting the radiation process at 30 minutes and continuing until the highest absorbance change was obtained. The absorbance value was measured at each variation of radiation time with a sampling interval of every 30 minutes. The results of the radiation process using the optimum amount of $TiO_2$ catalyst with these time variations are presented in Table 2 below.

Table 2. Optimum TiO2 Radiation Results (4.5 mg) with Time Variations on a 36 Watt UV Lamp

| Time (minutes) | 0 | 30 | 60 | 90 | 120 | 150 | 180 |
|---|---|---|---|---|---|---|---|
| Abs (λ=499) | 0.773 | 0.731 | 0.614 | 0.528 | 0.421 | 0.395 | 0.375 |
| COD (ppm) | 176 | 131 | 111 | 87 | 67 | 47 | 28 |

The data was then graphed to show changes in absorbance and COD. The graph of changes in absorbance can be seen in Figure 3.

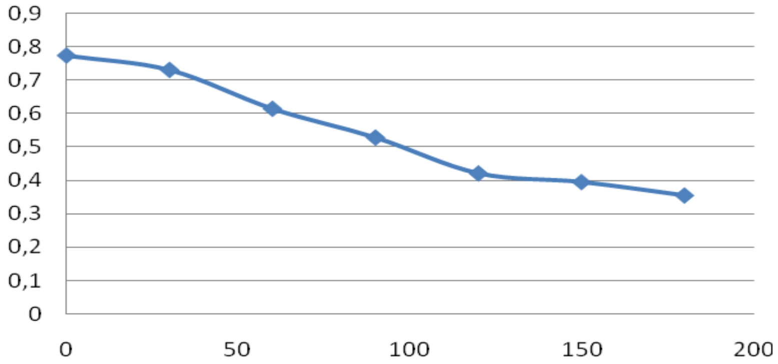

Figure 3. Graph of Absorbance Changes Per Minute

From the absorbance change graph above, a percentage absorbance change graph can be made, which is presented in Figure 4.

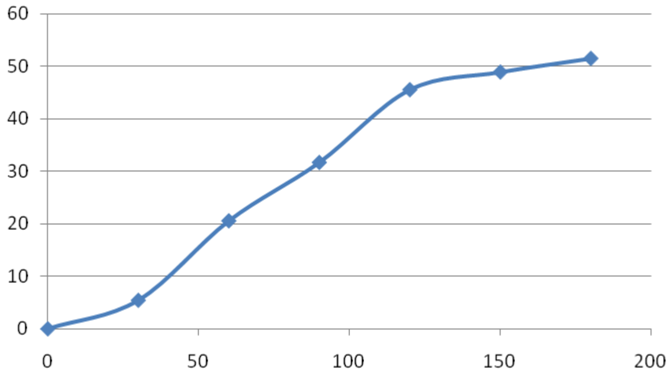

Figure 4. Graph of Percentage Change in Congo Red Color Intensity

The figure shows that with increasing irradiation time, the percentage of color change also increases. The search for the optimum time for absorbance change was stopped after 150 minutes, when the dye increased by 48.90%. 150 minutes of irradiation was determined as the optimum time because additional irradiation time did not significantly differ from the results obtained at 150 minutes.

To observe changes in organic matter content in the Congo red compound, COD was determined using the titration method, assuming that a high COD value in a sample indicates the presence of organic matter. Changes in COD values are presented in Figure 5, and the percentage change in COD values is shown in Figure 6.

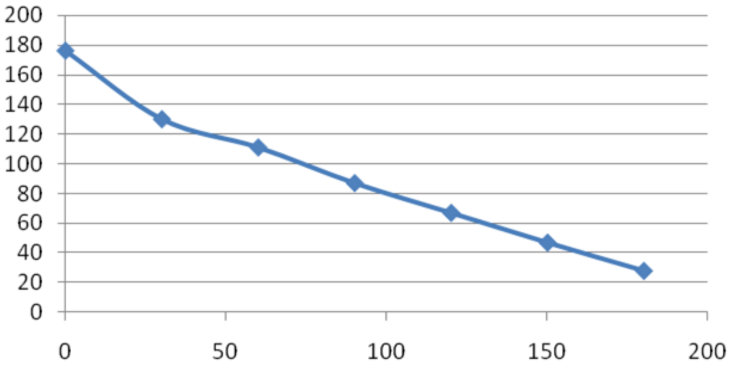

Figure 5. Graph of COD value changes per minute

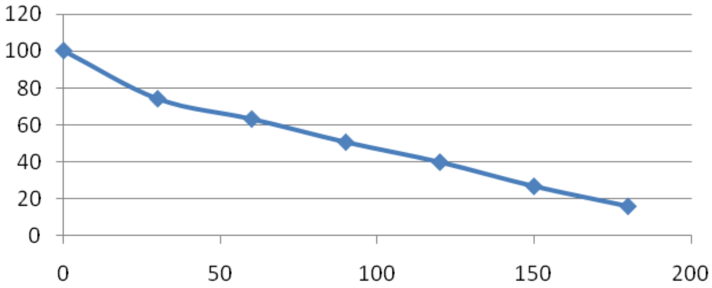

Figure 6. Graph of Percentage Change in COD Value Per Minute

The graph shows that the longer the irradiation time, the greater the COD value change. However, when compared to the percentage change in dye absorbance, there is a significant difference. The percentage change in dye absorbance showed a significant difference. The optimum TiO2 absorbance percentage change and the optimum time showed an increase of 48.90%, while the COD value changed by 84.1%. This indicates that although the color was reduced by 89.29%, little Congo red or organic matter remained (10.71%).

The system (atomic group) that causes light absorption is the chromophore or chromophore group. The reduced color intensity indicates that the chromophore group in the dye has disappeared. The relatively large COD remaining indicates that although the chromophore group has disappeared, there is still a significant amount of organic matter present.

### 3.3. Congo Red Concentration Variation

To assess the effectiveness of the optimum TiO2 addition and optimum time, these variables were used in the Congo red color reduction process with several concentrations. The reduction in absorbance and COD after the optimum TiO2 addition and optimum time are presented in Table 3 below:

Table 3. Optimum TiO2 Radiation Results and Optimum Time at Variations in Congo Red Concentration

| Sample (ppm) | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|
| Absawal (λ=499 nm) | 1,073 | 1,188 | 1,660 | 2,074 | 2,427 |
| Abs akhir (λ = 499 nm) | 1,042 | 1,069 | 1,235 | 1,395 | 1,425 |
| COD awal | 38 | 46 | 72 | 83 | 97 |
| COD akhir | 25 | 40 | 45 | 50 | 58 |

The graph of changes in Congo red absorbance at varying concentrations can be seen in Figure 7.

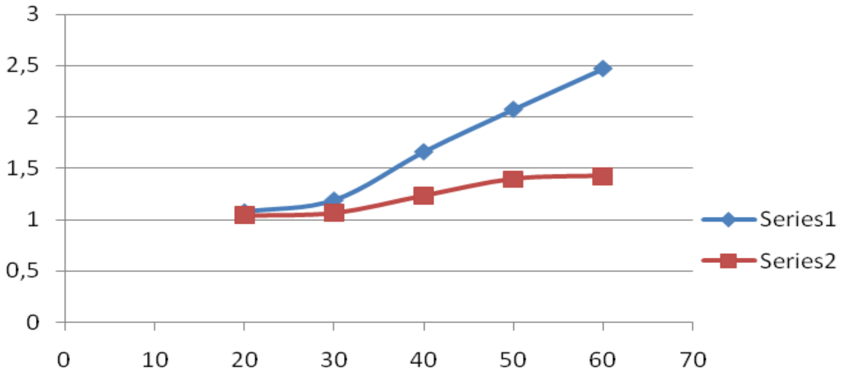

Figure 7. Graph of Changes in Color Intensity with Variations in Congo Red Concentration

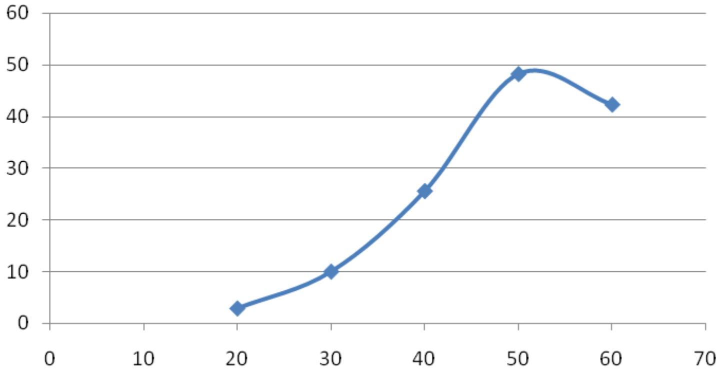

Figure 8. Graph of Percentage Change in Color Intensity with Variations in Congo Red Concentration

The graph shows that with increasing color concentration, the percentage of color change resulting from radiation increases. The optimum addition of TiO2 and the optimum time is still quite effective only at a concentration of 50 ppm, namely an increase of 48.28%. This increase can be concluded that the energy required to degrade the dye increases along with the increasing number of dye molecules. To see changes in organic matter content, a COD change graph is also made, which is presented in Figure 9.

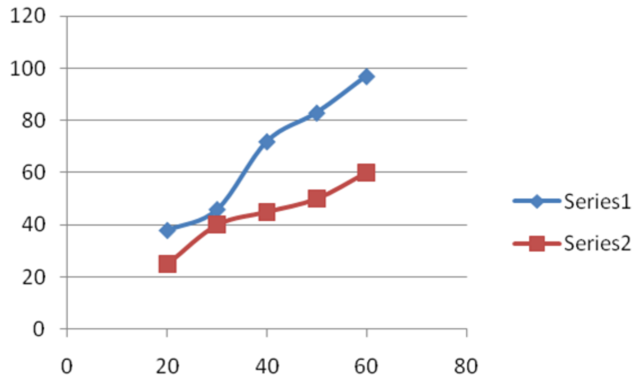

Figure 9. Graph of Changes in COD Values with Variations in Congo Red Dye Concentration

Increasing dye concentrations also decrease the tendency for organic degradation. Figure 10 shows the percentage decrease in the variation in Congo red concentration.

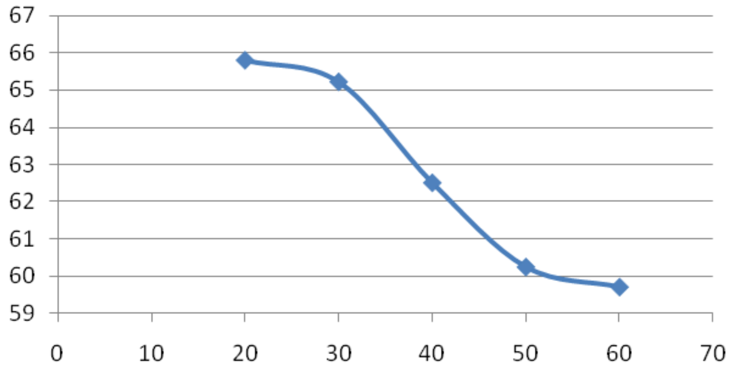

Figure 10. Percentage Change in COD Values with Variations in Congo Red Concentration

The decrease in COD in the variation of Congo red concentration with optimum TiO2 shows that the greater the Congo red concentration, the less organic content is degraded.

### 3.4. Characterization by Powder X-Ray Diffractometry (XRD)

Characterization with XRD aims to see whether damage occurs to the TiO2 catalyst. In addition, from the XRD data it can also be determined whether TiO2 is anatase or rutile. The basic principle of XRD is the scattering of electrons that hit the crystal surface. When light is passed to the crystal surface, some of the light will be scattered and some will be transmitted to the next layer. The scattered light will interfere constructively (strengthening) and destructively (weakening). This constructively interfered light scattering is used for analysis. The tool used is called an X-Ray Diffractometer (XRD). Through XRD analysis, the lattice dimensions (d = distance between lattices) in the mineral structure are known, so it can be determined whether a material has a high density or not. This can be known from the Bragg equation, namely the value of the diffraction angle θ which is inversely proportional to the value of d (the distance between lattices in the crystal), according to the Bragg equation:

$$n\lambda = 2 d \sin\theta$$

Table 4. d (Å) values from TiO2 measurement results and data interpretation cards

| Data Interpretation Card d (A°) | | Measurement of $TiO_2$ Synthesis d (Å) | Information |
|---|---|---|---|
| Anatase | Rutile | $TiO_2$ | |
| 3.520 | 3.240 | 3.544 | Anatase |
| 2.378 | 2.487 | 1.902 | Anatase |
| 1.892 | 2.188 | 1.708 | Anatase |
| 1.699 | 2.054 | 1.499 | Anatase |
| 1.666 | 1.687 | 1.674 | Anatase |
| 1.481 | 1.623 | 1.499 | Anatase |
| 1.364 | 1.479 | 1.487 | Rutile |

| | | | |
|---|---|---|---|
| 1.338 | 1.359 | 1.369 | Rutile |
| 1.265 | 1.346 | 1.344 | Rutile |

The XRD results show that the synthesized TiO2 crystals provide 12 diffraction peaks and the highest relative intensity is located at an angle of $2\theta = 25.29$o with a value of $d = 3.52$ which is a characteristic diffraction angle of anatase crystals and a diffraction angle of $2\theta = 44.61$o with a value of $d = 2.03$ which is a characteristic diffraction angle of rutile crystals. By comparing the $2\theta$ or d (Å) values of the significant peaks of the measurement results, with the standard TiO2 crystal data interpretation card, the results show that the crystal structure of the synthesized TiO2 is a mixture of anatase and rutile phases as can be seen in Table 4.

The photocatalytic degradation of Congo Red using $TiO_2$ under UV irradiation occurs through the generation of highly reactive species produced on the catalyst surface. When $TiO_2$ is exposed to UV light, electrons in the valence band are excited to the conduction band, leaving positive holes [38], [39]. These electron–hole pairs subsequently react with water molecules and dissolved oxygen to generate hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet-}$), which are well known as strong oxidizing agents capable of breaking down complex dye molecules into simpler compounds [40], [41]. The presence of $TiO_2$ therefore significantly enhances the oxidation process compared with UV irradiation alone, as the catalyst facilitates the formation of these reactive intermediates responsible for dye degradation [42], [43].

The amount of catalyst plays an important role in determining the efficiency of the photocatalytic process. Increasing the $TiO_2$ dosage generally increases the available active surface area for photon absorption and radical formation [44], [45]. A larger surface area allows more dye molecules to interact with the catalyst surface, which promotes more effective photochemical reactions. However, beyond a certain amount, the improvement in degradation efficiency tends to become limited. This phenomenon is commonly associated with light scattering and reduced penetration of UV radiation due to excess catalyst particles in suspension, which may hinder the activation of $TiO_2$ particles and reduce the overall photocatalytic efficiency.

The irradiation time is another important factor influencing the degradation process. Longer exposure to UV radiation allows more interactions between reactive radicals and dye molecules, leading to progressive breakdown of the chromophoric structure of Congo Red. The destruction of azo bonds (–N=N–), which are responsible for the characteristic color of the dye, is a key step in the degradation pathway [46], [47]. As irradiation continues, intermediate organic compounds may further undergo oxidation, gradually forming smaller molecules such as organic acids, carbon dioxide, and water [48], [49]. This process reflects the typical behavior of photocatalytic oxidation systems in degrading organic pollutants in aqueous environments.

The reduction of COD observed after the photocatalytic treatment indicates that the process not only decolorizes the dye but also reduces the overall organic load of the solution [50], [51]. This suggests that the photocatalytic system is capable of converting complex dye molecules into simpler and less harmful compounds [52], [53]. Nevertheless, the difference between color removal and COD reduction implies that some intermediate organic substances may still remain in the solution. Such intermediates are commonly formed during the stepwise degradation of azo dyes and may require longer irradiation times or additional treatment processes for complete mineralization.

Overall, the photocatalytic system using $TiO_2$ demonstrates considerable potential for the treatment of dye-containing wastewater. The ability of $TiO_2$ to generate reactive oxidative species under UV irradiation makes it an effective catalyst for degrading recalcitrant organic pollutants such as azo dyes. Therefore, the application of $TiO_2$-based photocatalysis could be considered a promising approach for environmental remediation, particularly in the treatment of textile wastewater containing synthetic dyes.

The results of this study provide important implications for the application of photocatalytic technology in the treatment of dye-containing wastewater. The use of $TiO_2$ as a photocatalyst offers an environmentally friendly and relatively simple approach for degrading synthetic dyes such as Congo Red, which are commonly found in textile industry effluents. The ability of $TiO_2$ to promote oxidative degradation under UV irradiation indicates its potential for reducing the environmental impact of dye pollutants in aquatic systems. Therefore, this method could contribute to the development of more sustainable wastewater treatment technologies, particularly for industries that generate colored effluents.

Despite these promising results, several limitations should be considered in this study. The photocatalytic experiments were conducted at a laboratory scale using controlled experimental conditions, which may differ from real wastewater systems that contain more complex mixtures of organic and inorganic substances. In addition, the study primarily focused on color removal and COD reduction, while the identification of intermediate degradation products was not investigated. Further studies are therefore necessary to examine the complete mineralization pathway, evaluate catalyst stability and reusability, and explore the effectiveness of the photocatalytic process in treating real industrial wastewater.

## 4. CONCLUSION

Based on the results of the research that has been done, it can be concluded that $TiO_2$ is able to degrade congo red dye through a photocatalytic method, which is indicated by a decrease in the intensity of the red color in the solution. The optimum condition of the degradation process was obtained at the amount of $TiO_2$ catalyst of 4.5 mg with an optimum radiation time of 150 minutes. Under these conditions, the degradation ability of the congo red solution with a concentration of 20 ppm reached 48.90%, while the COD value obtained was 84.1%, which indicates that the photocatalytic process using $TiO_2$ is quite effective in reducing the content of organic substances in the congo red solution. Further studies are recommended to investigate the identification of intermediate compounds formed during the photocatalytic degradation process in order to better understand the complete degradation pathway of Congo Red. In addition, future research should evaluate the effectiveness, stability, and reusability of $TiO_2$ catalysts in real wastewater systems to assess their practical application in large-scale wastewater treatment.

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Conceptualization, P.O.J.O.; Methodology, P.O.J.O.; Software, J.S.; Validation, P.O.J.O., J.S., and A.K.; Formal Analysis, P.O.J.O.; Investigation, P.O.J.O.; Resources, J.S.; Data Curation, P.O.J.O.; Writing – Original Draft Preparation, P.O.J.O.; Writing – Review & Editing, J.S. and A.K.; Visualization, J.S.; Supervision, A.K.; Project Administration, A.K.; Funding Acquisition, J.S.

## CONFLICTS OF INTEREST

"The authors declare no conflict of interest".

## USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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