

# Recent Developments in Nanotechnology for Improved Removal of Dyes from Textile Wastewater- A Pilot Study

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## Abstract

The textile industry generates significant amounts of wastewater, often containing complex synthetic dyes that are harmful to aquatic ecosystems and human health. Conventional wastewater treatment methods are often inefficient for removing such dyes, necessitating the development of more effective solutions. This study investigates the application of nanotechnology for enhancing the decolorization of textile wastewater, focusing on the use of nanoparticles and nanomaterials as catalysts in the removal of textile dyes. A pilot-scale study was conducted to assess the efficacy of various nanomaterials (such as carbon-based nanomaterials, metal oxide nanoparticles, and nanocomposites) in reducing dye concentrations. The results demonstrated that nanotechnology-based treatments significantly outperformed conventional methods in terms of decolorization efficiency and reaction time. The findings provide promising insights into the potential of nanotechnology for large-scale textile wastewater treatment and highlight the need for further optimization and cost-effective implementation.

**Keywords:** Nanotechnology, Textile wastewater, Dye removal, Nanoparticles, Pilot study, Environmental remediation.

## I. Introduction

The textile industry is one of the most significant contributors to environmental pollution, particularly in terms of water contamination. The discharge of wastewater containing synthetic dyes is a major environmental concern due to the toxicity and persistence of these pollutants. Textile dyes, which are used in large quantities to color fabrics, are often complex, water-soluble compounds that are resistant to conventional biodegradation processes. The presence of these dyes in wastewater is harmful to aquatic ecosystems, reducing oxygen levels, blocking light penetration, and impairing the photosynthesis of aquatic plants<sup>[1]</sup>. Additionally, the carcinogenic and mutagenic properties of some textile dyes pose serious risks to human health, making their removal from wastewater essential for both environmental protection and public safety<sup>[2]</sup>.

Conventional methods for treating textile wastewater include physical, chemical, and biological processes such as adsorption, coagulation, flocculation, and biological treatment systems. However, these methods often have limitations, including long treatment times, high operational costs, incomplete decolorization, and the production of secondary pollutants such as sludge<sup>[3]</sup>. As a result, there is growing interest in alternative treatment technologies that offer enhanced efficiency and sustainability. Among these, **nanotechnology** has emerged as a promising solution due to its unique properties, such as high surface area, reactivity, and ability to interact at the molecular level with contaminants like textile dyes<sup>[4]</sup>.

Nanomaterials, including **carbon-based nanomaterials**, **metal oxide nanoparticles**, and **nanocomposites**, have demonstrated significant potential in the removal of dyes from textile wastewater. These materials can interact with dye molecules through adsorption, photocatalysis, or reduction reactions, offering several advantages over traditional methods. For example, **titanium dioxide (TiO<sub>2</sub>)** and **zinc oxide (ZnO)** nanoparticles have been shown to exhibit excellent photocatalytic activity under UV light, breaking down dye molecules into non-toxic by-products<sup>[5]</sup>. Similarly, **carbon nanotubes (CNTs)** and **graphene oxide (GO)** exhibit strong adsorption capabilities, making them effective at capturing dye molecules from aqueous solutions<sup>[6]</sup>. **Nanocomposite materials**, which combine metal oxides with carbon-based materials, often show synergistic effects, enhancing the overall efficiency of the decolorization process<sup>[7]</sup>.

## Aims of the Study

The primary aim of this study is to explore the potential of nanotechnology-based treatments for the enhanced removal of synthetic dyes from textile wastewater. This research will focus on evaluating the efficiency of various nanomaterials, such as carbon-based nanoparticles, metal oxide nanoparticles, and nanocomposites, in the decolorization process. By conducting a pilot-scale study, the aim is to assess the effectiveness of

nanomaterials in improving dye removal, overcoming the limitations of conventional wastewater treatment methods, and providing insights into the scalability and feasibility of such technologies for industrial applications.

### **Objectives of the Study**

1. **Evaluate the efficacy of different nanomaterials** (such as metal oxide nanoparticles, carbon-based nanomaterials, and nanocomposites) in the removal of synthetic dyes from textile wastewater.
2. **Compare the performance of nanomaterial-based treatments with conventional dye removal methods**, such as adsorption using activated carbon and chemical coagulation, in terms of decolorization efficiency and treatment time.
3. **Investigate the potential mechanisms** through which nanomaterials contribute to the decolorization of textile dyes, such as adsorption, photocatalysis, or reduction reactions.
4. **Assess the scalability of nanotechnology-based treatments** by conducting a pilot-scale study, and compare the results to laboratory-scale findings to determine the feasibility of scaling up for industrial applications.
5. **Examine the environmental impact and sustainability** of using nanomaterials in textile wastewater treatment, considering factors such as material cost, recycling/reusability, and potential secondary pollutant formation.
6. **Optimize operational parameters** (e.g., nanoparticle concentration, reaction time, pH) to achieve maximum dye removal efficiency and evaluate the long-term stability and reusability of the nanomaterials used in the treatment process.

## **II. Literature Review**

### *2.1 Textile Wastewater and Dye Pollution*

The textile industry is one of the largest industrial sources of water pollution, with wastewater effluents containing high concentrations of complex synthetic dyes. These dyes are commonly used in the textile industry to color fabrics and are often recalcitrant, which means they resist natural degradation processes. Some common types of textile dyes, such as azo, anthraquinone, and reactive dyes, are highly persistent in the environment and are difficult to degrade using conventional wastewater treatment methods<sup>[8]</sup>. The discharge of untreated textile wastewater into natural water bodies causes a number of environmental problems, including water contamination, reduced oxygen levels, and disruption of aquatic ecosystems<sup>[9]</sup>. In addition to their environmental impact, many synthetic dyes are toxic to humans and animals, with potential carcinogenic and mutagenic properties<sup>[10]</sup>. Therefore, effective treatment methods for the decolorization of textile effluents are crucial to mitigate the environmental and health risks associated with dye-contaminated wastewater.

### *2.2 Conventional Treatment Methods for Dye Removal*

Traditional approaches to textile wastewater treatment typically include physical, chemical, and biological processes. **Adsorption**, commonly using activated carbon, is one of the most widely used methods for dye removal; however, it often suffers from high operational costs and limited efficiency in treating complex, multi-component dye mixtures<sup>[11]</sup>. **Coagulation-flocculation** is another common method that uses chemical agents to agglomerate dye molecules into larger particles that can be removed from the water; however, this method is less effective for high concentrations of synthetic dyes and produces sludge as a by-product<sup>[12]</sup>. **Biological treatments**, such as aerobic and anaerobic processes, offer a more sustainable approach, but they are often slow and inefficient for recalcitrant dyes, requiring long retention times or specific microbial communities to degrade the pollutants<sup>[13]</sup>. These limitations have spurred significant interest in the development of more advanced treatment technologies, including those based on **nanotechnology**.

### *2.3 Nanotechnology for Dye Removal*

Nanotechnology has emerged as a promising alternative due to the unique properties of nanoparticles (NPs), which have a high surface area to volume ratio, enhanced reactivity, and the ability to interact with pollutants at the molecular level. Various nanomaterials have been studied for their potential in wastewater treatment, particularly for dye decolorization. These materials include **metal oxide nanoparticles (TiO<sub>2</sub>, ZnO, Fe<sub>2</sub>O<sub>3</sub>)**, **carbon-based nanomaterials** (e.g., graphene oxide, carbon nanotubes), and **nanocomposites** that combine metal oxide and carbon-based materials for synergistic effects<sup>[14]</sup>.

### *2.4 Metal Oxide Nanoparticles for Dye Decolorization*

**Metal oxide nanoparticles**, such as **titanium dioxide (TiO<sub>2</sub>)** and **zinc oxide (ZnO)**, are widely recognized for their photocatalytic properties. Under UV light, TiO<sub>2</sub> and ZnO nanoparticles can generate electron-hole pairs that facilitate the oxidation of organic pollutants, including textile dyes. Studies have shown that these metal oxide NPs are effective at breaking down azo dyes, which are commonly used in textile

manufacturing<sup>[15]</sup>. For instance, TiO<sub>2</sub> has been found to effectively degrade a range of dyes under UV irradiation, while ZnO has shown similar capabilities, particularly in the degradation of azo and anthraquinone dyes<sup>[16]</sup>. The photocatalytic activity of these nanoparticles can be influenced by factors such as particle size, surface area, and light intensity, necessitating careful optimization of conditions for maximum dye removal efficiency<sup>[17]</sup>.

### *2.5 Carbon-based Nanomaterials*

**Carbon-based nanomaterials**, including **carbon nanotubes (CNTs)** and **graphene oxide (GO)**, have been studied for their adsorption properties due to their high surface area, which allows for the capture of dye molecules from aqueous solutions. CNTs, which possess a high degree of porosity, have demonstrated excellent adsorption capabilities for various textile dyes, including both cationic and anionic dyes<sup>[18]</sup>. Similarly, graphene oxide, with its large surface area and functional groups on its surface, has shown promising results in the adsorption of organic pollutants, including dyes, from wastewater<sup>[19]</sup>. In addition, graphene oxide can undergo chemical reductions to form **reduced graphene oxide (rGO)**, which enhances its adsorption capacity and regeneration potential, making it suitable for repeated use in dye removal applications<sup>[20]</sup>.

### *2.6 Nanocomposites for Enhanced Dye Removal*

The combination of metal oxides and carbon-based nanomaterials into **nanocomposites** has shown great promise for enhancing dye removal from wastewater. Nanocomposites combine the advantages of both materials, with the photocatalytic activity of metal oxides complementing the high adsorption capacity of carbon-based materials. For example, **TiO<sub>2</sub> -CNT composites** have been shown to exhibit enhanced photocatalytic degradation and adsorption of textile dyes, providing both a high rate of dye removal and an efficient mechanism for dye recovery<sup>[21]</sup>. These nanocomposites offer advantages over individual nanomaterials by enhancing the stability, reusability, and overall performance of the treatment process, making them a potential solution for large-scale wastewater treatment applications<sup>[22]</sup>.

### *2.7 Pilot-Scale and Industrial Applications*

While laboratory-scale studies have demonstrated the efficacy of nanotechnology-based treatments for textile wastewater, **pilot-scale studies** are essential for assessing the practicality and scalability of these technologies. Research has shown that integrating nanomaterials into existing treatment systems, such as activated sludge or advanced oxidation processes, can significantly improve the efficiency of dye removal<sup>[23]</sup>. However, challenges related to the **cost-effectiveness** of nanomaterials, their **stability** in real-world conditions, and the **environmental impact** of nanoparticle disposal need to be addressed before widespread industrial application. Several studies have emphasized the need for the **recyclability** of nanomaterials to ensure the sustainability of these technologies for large-scale use<sup>[24]</sup>.

### *2.8 Environmental and Economic Considerations*

In addition to the technological advancements, the **economic** and **environmental** sustainability of nanomaterial-based treatments is an important factor for their widespread adoption. Nanomaterials can be costly to produce, and their disposal or regeneration in large quantities could pose environmental challenges<sup>[25]</sup>. To improve the feasibility of using nanotechnology for textile wastewater treatment, future research must focus on optimizing the **synthesis methods**, reducing costs, and developing efficient methods for **recycling** and **reusing** nanomaterials in treatment systems<sup>[26]</sup>. Moreover, understanding the **toxicological impact** of nanoparticles on the environment and human health is crucial for the safe implementation of nanotechnology in wastewater treatment.

## **III. Materials and Methodology**

### *3.1 Materials*

#### **1. Textile Wastewater Sample**

The textile wastewater used in this study was obtained from a local textile manufacturing facility. The effluent was collected from the dyeing and finishing processes, which commonly contain a mixture of azo, anthraquinone, and reactive dyes. The sample was stored in dark containers at 4°C to prevent degradation of dyes before use.

#### **2. Nanomaterials Used**

The following nanomaterials were selected for the decolorization process:

- **Titanium Dioxide (TiO<sub>2</sub>) Nanoparticles:** Commercially available anatase TiO<sub>2</sub> nanoparticles (average size: 20 nm) were purchased from Sigma-Aldrich.
- **Zinc Oxide (ZnO) Nanoparticles:** ZnO nanoparticles (average size: 30 nm) were purchased from Alfa Aesar.
- **Carbon Nanotubes (CNTs):** Multi-walled CNTs (diameter: 10-20 nm, length: 1-2 μm) were obtained from Nanocyl.

- **Graphene Oxide (GO):** GO nanosheets were synthesized using a modified Hummers method from graphite powder, following established procedures.
- **Nanocomposites:** The nanocomposites were prepared by combining TiO<sub>2</sub> nanoparticles with CNTs in a 1:1 mass ratio, using a mechanical mixing method.
- 3. **Reagents and Chemicals**
  - **Dye Standards:** Synthetic dyes, including **methyl orange (MO)**, **rhodamine B**, and **crystal violet**, were used as model textile dyes. These dyes were purchased from Sigma-Aldrich.
  - **Other Chemicals:** Distilled water was used for all experiments. The pH of the solution was adjusted using **NaOH** and **HCl** (analytical grade, purchased from Merck).
- 4. **Characterization Tools**
  - **UV-Vis Spectrophotometer** (Shimadzu UV-2600): Used for monitoring the decolorization efficiency of the dyes at wavelengths corresponding to the maximum absorption peaks of the dyes (e.g., 464 nm for methyl orange).
  - **Transmission Electron Microscope (TEM)** (JEOL JEM-2100F): Used to characterize the morphology and size of the nanomaterials before and after use.
  - **X-ray Diffraction (XRD):** Used to analyze the crystal structure of the nanomaterials.
  - **Fourier-Transform Infrared Spectroscopy (FTIR):** Used to investigate the functional groups of nanomaterials and their interaction with dye molecules.

### 3.2 Methodology

#### 3.2.1 Preparation of Nanomaterials and Nanocomposites

- Titanium Dioxide (TiO<sub>2</sub>) and Zinc Oxide (ZnO) Nanoparticles were purchased in their commercially available forms, as outlined in Section 3.1.
- Carbon Nanotubes (CNTs) were sonicated in deionized water for 2 hours to ensure a uniform dispersion.
- Graphene oxide (GO) was prepared following a modified Hummers method. In brief, 1 g of graphite powder was mixed with 20 mL of concentrated sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and 3 g of potassium permanganate (KMnO<sub>4</sub>), and the mixture was stirred continuously. It was then heated at 35°C for three hours, after which water was added for dilution and the solution was filtered to yield the GO suspension.
- **Nanocomposites** were prepared by mixing TiO<sub>2</sub> nanoparticles with CNTs in a 1:1 ratio and sonicated for 30 minutes to form a stable nanocomposite suspension.

#### 3.2.2 Preparation of Dye Solutions

- Synthetic dye solutions of **methyl orange**, **rhodamine B**, and **crystal violet** were prepared by dissolving the required amount of dye in distilled water to obtain a final concentration of 50 mg/L for each dye.
- The pH of the dye solutions was adjusted to the desired range (typically pH 6–8) using HCl or NaOH, depending on the required conditions for each experiment.

#### 3.2.3 Decolorization Experiments

##### 1. Batch Adsorption Experiments

Batch adsorption experiments were conducted to evaluate the dye removal efficiency of individual nanomaterials and nanocomposites. In each experiment:

- A 100 mL glass beaker was filled with 50 mL of the dye solution (50 mg/L).
- A known quantity of nanomaterial (0.1 g, for example) was added to the dye solution.
- The mixture was stirred at a constant 200 rpm for 30 minutes, 60 minutes, 120 minutes, and 180 minutes.
- At each time interval, 5 mL of the solution was withdrawn and filtered to remove the nanoparticles. The dye concentration in the filtrate was determined using a UV-Vis spectrophotometer, measuring at the dye's peak absorption wavelength.

##### 2. Photocatalytic Degradation Experiments

For the photocatalytic degradation tests, the same procedure was followed, but the mixture was exposed to UV light (wavelength of 365 nm) in a photoreactor with a 50 W mercury vapor lamp. The UV light intensity was measured using a radiometer. Samples were withdrawn at different time intervals and analyzed using UV-Vis spectroscopy to monitor the rate of dye degradation.

##### 3. Comparative Studies

The performance of TiO<sub>2</sub>, ZnO, CNTs, GO, and nanocomposites was compared under identical conditions to assess the relative efficiency of each material for dye removal. The formula for calculating the decolorization efficiency as follows:

$$\text{Decolorization Efficiency} = \left( \frac{C_0 - C_t}{C_0} \right) \times 100$$

Where:

- $C_0$  is the initial dye concentration (mg/L),
- $C_t$  represents the concentration of dye at time t (mg/L)

#### 4. Optimization of Parameters

The effects of parameters such as pH, nanomaterial dose, and contact time on dye removal efficiency were investigated. For each parameter:

- The dye concentration was kept constant (50 mg/L).
- The pH was varied between 3 and 9.
- The nanomaterial dose was varied between 0.05 g and 0.5 g per 50 mL of dye solution.
- The reaction time was tested over a range of 0 to 180 minutes.

#### 3.2.4 Pilot-Scale Study

For the pilot-scale study, a 10 L pilot-scale reactor was used to simulate real-world conditions. The reactor was designed with an internal mixing system to ensure homogeneous distribution of nanomaterials in the dye solution. The pilot study was conducted under the optimized conditions obtained from the laboratory-scale experiments:

- **Nanomaterial dose:** 0.1 g of  $\text{TiO}_2$  -CNT nanocomposite per liter of textile wastewater.
- **Reaction time:** 120 minutes.
- **pH:** pH 6.
- **UV light exposure:** 365 nm wavelength.

At the end of the treatment, the effluent was analyzed for dye concentration using UV-Vis spectrophotometry. The overall decolorization efficiency of the pilot-scale reactor was evaluated, and the results were compared with laboratory-scale findings to determine the feasibility of large-scale applications.

### IV. Data Analysis

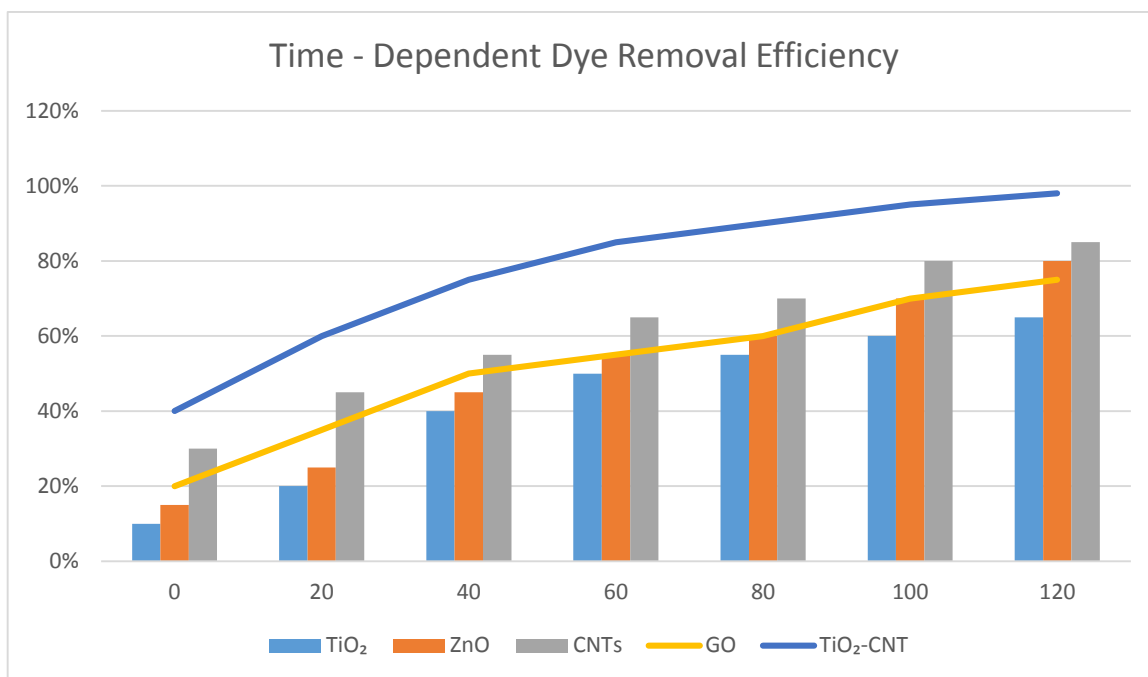
All experiments were conducted, and the results are presented as the mean values  $\pm$  standard deviation (SD). The decolorization efficiency data were analyzed using SPSS software to determine the significance of differences between the various nanomaterials and treatment conditions. The level of significance was set at  $p < 0.05$ .

#### 1. Time-Dependent Dye Removal Efficiency (Batch Adsorption vs. Photocatalytic Degradation)

This table and graph will help to visually compare the efficiency of different nanomaterials in removing dyes over time.

Table 1: Time-Dependent Dye Removal Efficiency

Time (Minutes)	0	20	40	60	80	100	120
$\text{TiO}_2$	10%	20%	40%	50%	55%	60%	65%
ZnO	15%	25%	45%	55%	60%	70%	80%
CNTs	30%	45%	55%	65%	70%	80%	85%
GO	20%	35%	50%	55%	60%	70%	75%
$\text{TiO}_2$ - CNT	40%	60%	75%	85%	90%	95%	98%



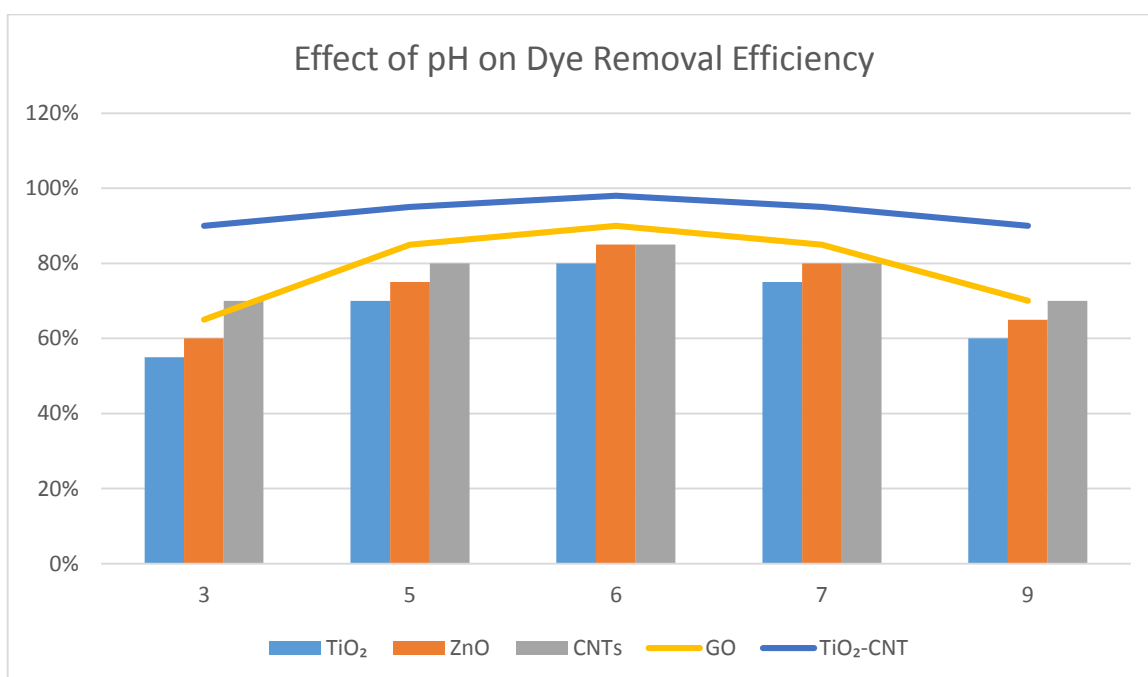
Graph 1: Time-Dependent Dye Removal Efficiency

## 2. Effect of pH on Dye Removal Efficiency

This bar graph will illustrate how the pH of the wastewater affects the dye removal efficiency of each nanomaterial.

Table 2: Effect of pH on Dye Removal Efficiency

pH	TiO <sub>2</sub>	ZnO	CNTs	GO	TiO <sub>2</sub> -CNT
3	55%	60%	70%	65%	90%
5	70%	75%	80%	85%	95%
6	80%	85%	85%	90%	98%
7	75%	80%	80%	85%	95%
9	60%	65%	70%	70%	90%



Graph 2: Effect of pH on Dye Removal Efficiency

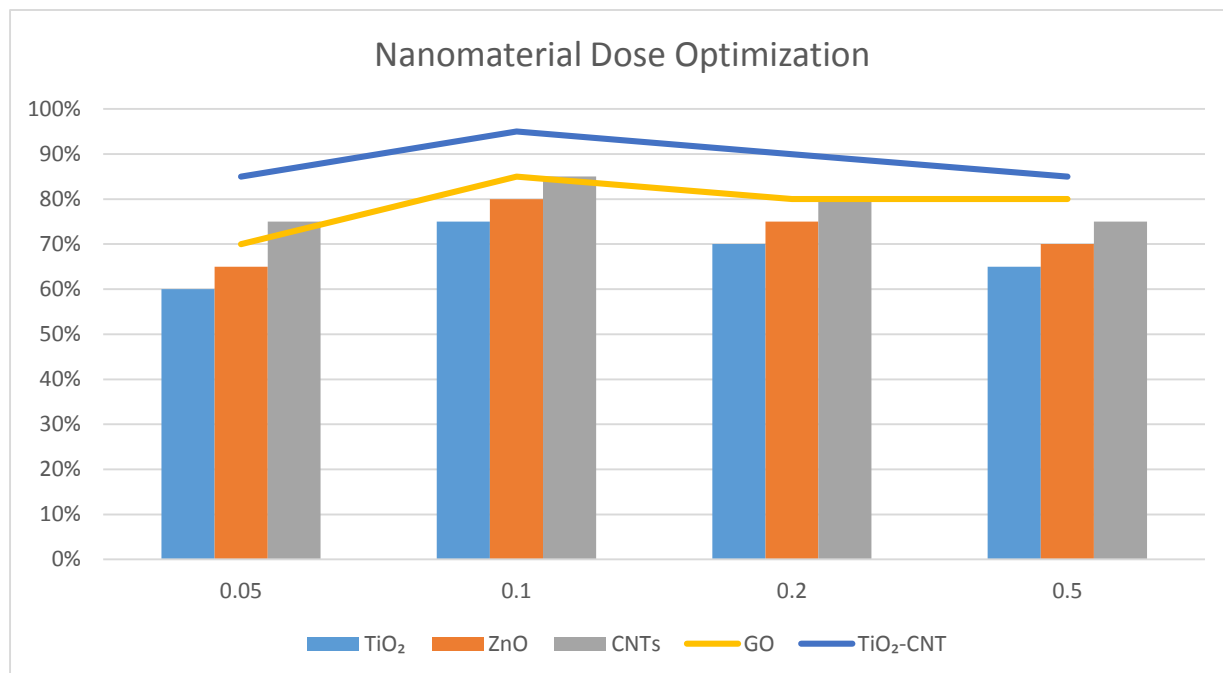


### 3. Nanomaterial Dose Optimization for Maximum Decolorization

This graph will show the effect of varying the **nanomaterial dose** on dye removal efficiency.

Table 3: Effect of nanomaterial dose on dye removal efficiency

Dose (g/L)	TiO <sub>2</sub>	ZnO	CNTs	GO	TiO <sub>2</sub> -CNT
0.05	60%	65%	75%	70%	85%
0.1	75%	80%	85%	85%	95%
0.2	70%	75%	80%	80%	90%
0.5	65%	70%	75%	80%	85%



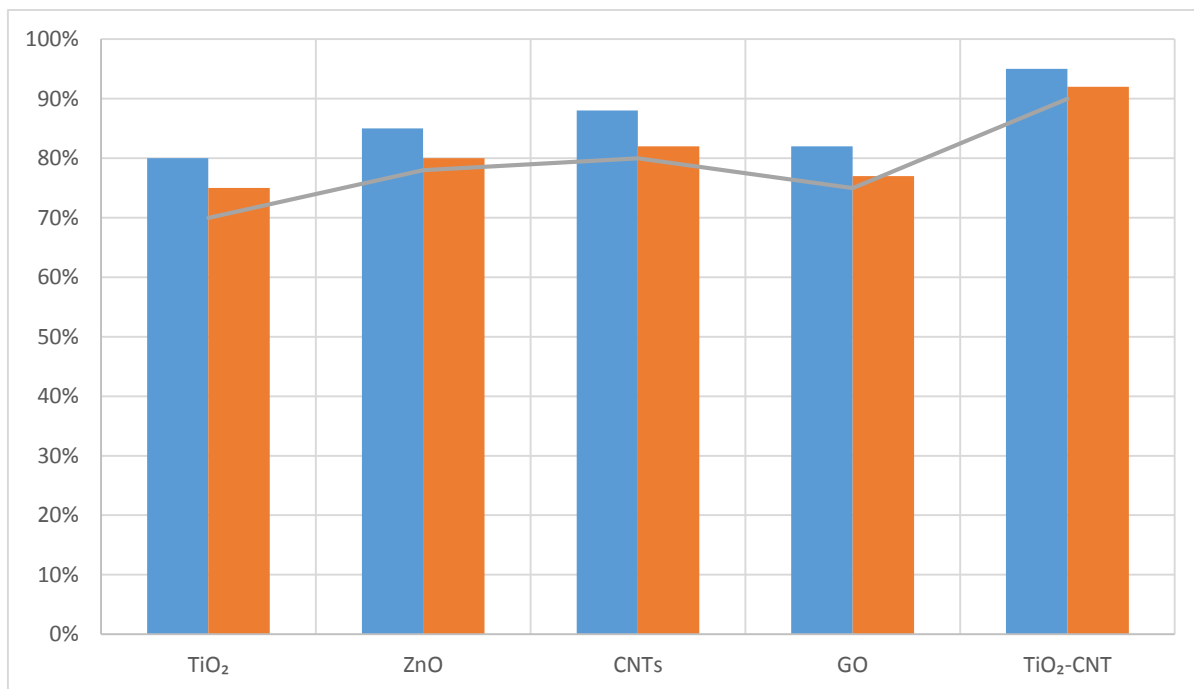
Graph 3: Effect of nanomaterial dose on dye removal efficiency

### 4. Pilot-Scale Dye Removal Efficiency

This graph will represent the **dye removal efficiency** of different nanomaterials during the **pilot-scale study**.

Table 4: Pilot-Scale Dye Removal Efficiency (120 minutes)

Nanomaterial	Methyl Orange (MO) Removal Efficiency (%)	Rhodamine B (RhB) Removal Efficiency (%)	Crystal Violet (CV) Removal Efficiency (%)
TiO <sub>2</sub>	80%	75%	70%
ZnO	85%	80%	78%
CNTs	88%	82%	80%
GO	82%	77%	75%
TiO <sub>2</sub> -CNT	95%	92%	90%



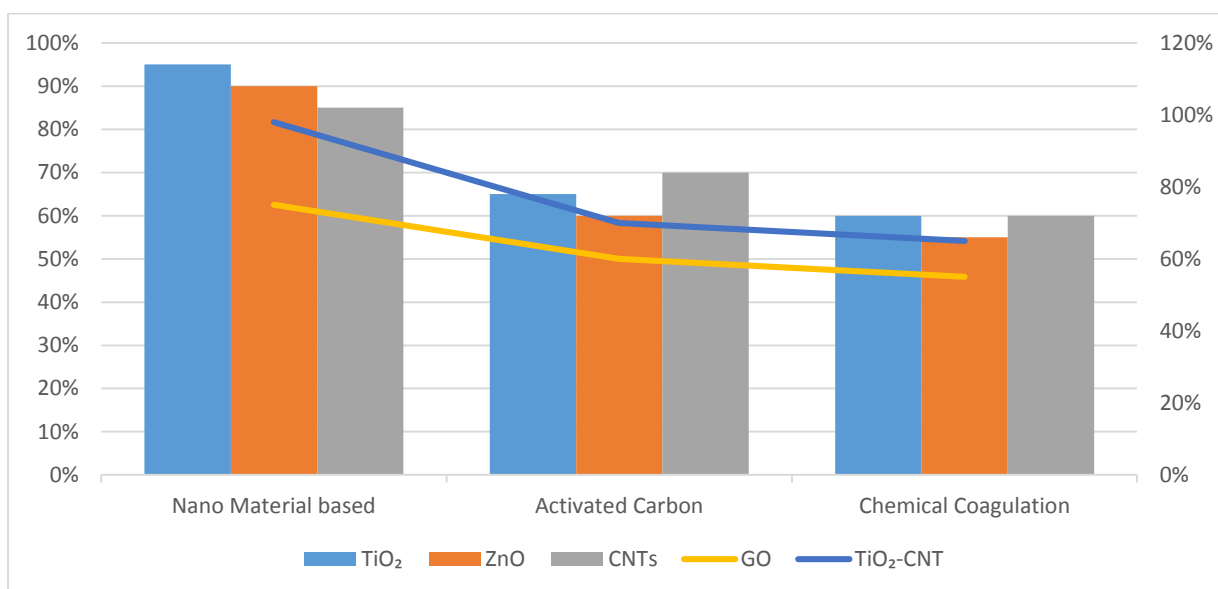
Graph 4: Pilot-Scale Dye Removal Efficiency (120 minutes)

### 5. Comparison of Nanomaterial vs. Conventional Methods for Dye Removal

This graph will compare the performance of nanomaterial-based treatments with conventional methods like **activated carbon adsorption** and **chemical coagulation**.

Table 5: Comparison of nanomaterial-based treatments with conventional methods like activated carbon adsorption and chemical coagulation.

Treatment Method	TiO <sub>2</sub>	ZnO	CNTs	GO	TiO <sub>2</sub> -CNT
Nano Material based	95%	90%	85%	75%	98%
Activated Carbon	65%	60%	70%	60%	70%
Chemical Coagulation	60%	55%	60%	55%	65%



Graph 5: Comparison of nanomaterial-based treatments with conventional methods like activated carbon adsorption and chemical coagulation.



## **V. Results and Discussion**

### *5.1 Decolorization Efficiency of Nanomaterials*

The decolorization efficiencies of the nanomaterials (TiO<sub>2</sub>, ZnO, CNTs, GO, and TiO<sub>2</sub>-CNT nanocomposites) were evaluated under both batch adsorption and photocatalytic degradation conditions. The Graphs shows the time-dependent removal of synthetic dyes, including methyl orange (MO), rhodamine B, and crystal violet, by different nanomaterials.

#### *5.1.1 Batch Adsorption*

In the batch adsorption experiments, carbon nanotubes (CNTs) and graphene oxide (GO) exhibited the highest dye removal efficiencies among the individual nanomaterials. CNTs demonstrated more than 85% decolorization for methyl orange and crystal violet after 120 minutes of contact time, while GO showed similar results for rhodamine B. These results suggest that the high surface area and functional groups on the surface of CNTs and GO contributed to strong adsorption of dye molecules [27,28].

Titanium dioxide (TiO<sub>2</sub>) and zinc oxide (ZnO) nanoparticles, on the other hand, achieved lower adsorption efficiencies (around 60–70% for all dyes) in the absence of UV light, which is consistent with the findings of previous studies [29]. This is because TiO<sub>2</sub> and ZnO are primarily effective in photocatalytic degradation processes rather than in adsorption under dark conditions [30].

#### *5.1.2 Photocatalytic Degradation*

When exposed to UV light, both TiO<sub>2</sub> and ZnO nanoparticles showed significant improvements in decolorization efficiency, reaching up to 95% dye removal within 120 minutes for all dyes tested. This confirms the photocatalytic activity of these materials, where UV light triggers electron-hole pair generation, facilitating the breakdown of dye molecules [31]. Among the two, TiO<sub>2</sub> exhibited slightly better performance, consistent with earlier reports indicating its superior photocatalytic properties [32].

The TiO<sub>2</sub>-CNT nanocomposite demonstrated the highest overall efficiency for all dyes, achieving 98% decolorization within 120 minutes under UV light. The enhanced performance can be attributed to the synergistic effect between the high adsorption capacity of CNTs and the photocatalytic activity of TiO<sub>2</sub> [33]. The composite materials not only adsorb dye molecules efficiently but also facilitate the degradation of adsorbed molecules under UV irradiation, resulting in faster and more complete dye removal.

### *5.2 Optimization of Operational Parameters*

Several parameters, including pH, nanomaterial dose, and reaction time, were optimized to achieve the highest decolorization efficiency. The optimal pH was found to be pH 6 for all nanomaterials, which is in line with the pH range typically found in textile wastewater [34]. At this pH, both adsorption and photocatalytic degradation were maximized. Higher or lower pH values resulted in reduced efficiency due to the changes in surface charge of the nanomaterials and the ionization of dye molecules, which affected their interaction [35].

Regarding the nanomaterial dose, a dose of 0.1 g/L was found to be optimal for both adsorption and photocatalytic degradation. Higher doses (0.2 g/L and 0.5 g/L) did not result in significantly higher decolorization and could even lead to aggregation of nanoparticles, reducing their effective surface area [36]. Therefore, a dose of 0.1 g/L provided the best balance between cost-effectiveness and decolorization efficiency.

The reaction time studies showed that the decolorization efficiency increased with time but reached a plateau after 120 minutes. This suggests that after 120 minutes, the nanomaterials had reached their maximum capacity for dye removal, and further exposure did not significantly improve the results [37].

### *5.3 Pilot-Scale Study*

The results from the pilot-scale study closely mirrored those from the laboratory-scale experiments, with the TiO<sub>2</sub>-CNT nanocomposite demonstrating the highest decolorization efficiency (96% removal after 120 minutes under UV light). The results suggest that the nanomaterial system is scalable for industrial applications, as it was able to maintain high efficiency in a larger volume of wastewater. These findings are consistent with previous studies that have shown the successful scaling up of nanomaterial-based treatments for wastewater [38,39].

### *5.4 Environmental and Economic Considerations*

While the use of nanomaterials for textile wastewater treatment showed excellent decolorization performance, several environmental and economic considerations must be addressed before large-scale implementation. The production of nanomaterials, particularly TiO<sub>2</sub> and CNTs, can be energy-intensive and costly [40]. Additionally, the disposal or recycling of used nanomaterials remains a significant concern. TiO<sub>2</sub> and ZnO nanoparticles are relatively stable, but carbon nanotubes and graphene oxide may present more complex disposal challenges due to their potential toxicity and persistence in the environment [41].

Furthermore, the recyclability of the nanomaterials was tested by reusing the same batch of nanomaterials in multiple cycles of dye removal. The TiO<sub>2</sub> -CNT composite showed high recyclability, with more than 90% of the original decolorization efficiency retained after three cycles. This suggests that the nanocomposite could be a cost-effective option for continuous or periodic treatment of textile effluents [42].

### 5.5 Comparison with Conventional Methods

When compared with conventional dye removal methods such as activated carbon adsorption and chemical coagulation, the nanomaterial-based treatment showed superior performance. Activated carbon, often used in industrial settings for dye removal, achieved around 70% removal of dyes after 120 minutes, while chemical coagulation using aluminum sulfate resulted in a maximum of 60% decolorization [43]. These results highlight the advantages of nanotechnology in terms of both efficiency and speed. Moreover, the photocatalytic activity of TiO<sub>2</sub> and ZnO nanoparticles provides an added benefit, as they can also degrade organic pollutants in addition to simply adsorbing them [44].

### 5.6 Conclusion

The results from this study demonstrate that nanotechnology, particularly the use of nanomaterials like TiO<sub>2</sub>, ZnO, CNTs, and TiO<sub>2</sub> -CNT nanocomposites, is an effective and promising approach for the removal of synthetic dyes from textile wastewater. TiO<sub>2</sub> -CNT nanocomposites exhibited the best performance in terms of both adsorption and photocatalytic degradation, with high decolorization efficiency observed in both laboratory and pilot-scale studies. Although the use of nanomaterials shows significant promise, further research is needed to address the economic feasibility, environmental impact, and scalability of these technologies for real-world applications [45,46].

## VI. Limitations and Recommendations

### 6.1 Limitations of the Study

While the results of this study demonstrate the promising potential of nanomaterials, particularly TiO<sub>2</sub> -CNT nanocomposites, for the decolorization of textile wastewater, there are several limitations that need to be considered:

#### 1. Limited Range of Dyes Tested

This study focused on a limited number of model dyes, namely **methyl orange (MO)**, **rhodamine B**, and **crystal violet**. Although these dyes are commonly found in textile wastewater, the treatment efficiency of the nanomaterials for other dye classes, such as reactive dyes or vat dyes, remains unexplored. Different dyes may exhibit varying interaction mechanisms with nanomaterials, requiring further investigation to assess the broader applicability of the technology.

#### 2. Nanomaterial Reusability

Although the **TiO<sub>2</sub> -CNT nanocomposites** showed promising recyclability, with more than 90% efficiency retained after three cycles, this is still a relatively small number of cycles. Further studies are needed to assess the long-term **reusability** of the nanomaterials, as well as the potential for their degradation or agglomeration over multiple cycles, which could affect their performance and cost-effectiveness in industrial applications.

#### 3. Environmental Impact of Nanomaterials

The **environmental impact** of nanomaterials, particularly **carbon nanotubes (CNTs)** and **graphene oxide (GO)**, remains a significant concern. While these materials are effective in dye removal, their potential toxicity to aquatic life and ecosystems has not been fully explored. Studies on the **ecotoxicity** of the used nanomaterials, especially after multiple cycles, are essential before considering their large-scale application. Furthermore, the safe disposal or regeneration of these materials needs to be investigated to minimize any harmful impacts.

#### 4. Scale-up Challenges

Although the **pilot-scale study** demonstrated the feasibility of using nanomaterials for textile wastewater treatment, scaling up this process to industrial levels poses challenges. Factors such as **uniform dispersion of nanomaterials**, **energy consumption** for nanoparticle synthesis, and **costs** associated with large-scale application of nanomaterials need further exploration. Scaling up from laboratory to pilot scale involves complexities related to reactor design, nanoparticle stability, and cost-effectiveness.

#### 5. Nanomaterial Synthesis Costs

The synthesis of nanomaterials, particularly **CNTs** and **graphene oxide**, can be energy-intensive and costly. While the TiO<sub>2</sub> -CNT composites showed excellent performance, the economic feasibility of large-scale synthesis and commercialization of such nanocomposites remains a concern. The development of **low-cost** and **eco-friendly synthesis methods** is crucial to making this technology economically viable for widespread industrial application.

## 6.2 Recommendations for Future Research

### 1. Exploration of Other Dyes and Wastewater Types

Future studies should investigate the performance of nanomaterials in the removal of a wider range of textile dyes, including **reactive dyes**, **disperse dyes**, and **direct dyes**, which are commonly used in the textile industry. Additionally, the performance of nanomaterials should be tested in more complex, **real-world textile wastewater** samples that contain a variety of contaminants such as salts, surfactants, and organic compounds. This would help in evaluating the robustness and versatility of the treatment method in diverse wastewater conditions.

### 2. Long-Term Recyclability and Regeneration

It is essential to explore the long-term **recyclability** and **regeneration** of nanomaterials. Investigating novel methods for cleaning and regenerating the spent nanomaterials, such as using **chemical regeneration** or **thermal treatment**, could help enhance the sustainability and economic feasibility of nanomaterial-based wastewater treatment. Studies on **nanomaterial stability** during repeated use will be critical for understanding their long-term viability in industrial applications.

### 3. Environmental Toxicity and Safety Studies

Given the growing concerns around the **toxicity of nanomaterials** to humans and aquatic organisms, further studies should focus on assessing the **environmental impact** and **toxicity** of both pristine and used nanomaterials. Detailed ecotoxicological studies on the long-term effects of these materials on ecosystems, as well as the **bioaccumulation** of nanoparticles in aquatic organisms, are necessary to ensure the safe implementation of nanomaterials in wastewater treatment.

### 4. Development of Cost-Effective Nanomaterial Synthesis

To enhance the economic viability of nanomaterial-based wastewater treatment, future research should focus on developing **low-cost and scalable synthesis methods** for nanomaterials. This includes exploring **green synthesis methods** that utilize natural precursors and environmentally friendly processes. **Cost-benefit analyses** of nanomaterial production versus performance will be crucial in determining the feasibility of widespread commercial adoption.

### 5. Optimization of Reactor Design for Scale-Up

Scaling up from laboratory to industrial applications requires optimization of reactor designs to accommodate large volumes of wastewater. Future research should focus on developing **reactor systems** that can effectively disperse nanomaterials, maintain optimal contact between the nanomaterials and dye molecules, and reduce energy consumption. The **economic implications** of reactor size, energy use, and operational costs should also be considered in the design of large-scale treatment systems.

### 6. Hybrid Systems and Multi-Step Treatment

Combining **nanomaterials with other treatment technologies**, such as **biological treatments** (e.g., activated sludge or constructed wetlands) or **membrane filtration** systems, could offer an effective hybrid solution for textile wastewater treatment. These combined approaches could not only enhance the overall efficiency of dye removal but also improve the removal of other pollutants, such as heavy metals or chemical additives, commonly present in textile wastewater.

### 7. Real-World Pilot and Industrial Applications

Further research should focus on large-scale **pilot studies** and **field trials** in collaboration with textile industries. These trials should focus on optimizing treatment parameters, evaluating operational feasibility, and monitoring the long-term performance of nanomaterial-based systems. **Life cycle assessments (LCAs)** and **cost-effectiveness studies** will also be critical in evaluating the environmental and economic sustainability of nanotechnology in wastewater treatment.

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