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Nanomaterials for the Removal of Persistent Organic Pollutants from Environmental Sources

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Abstract

This study investigates the photocatalytic degradation of Persistent Organic Pollutants (POPs) using Titanium Dioxide (TiO_2) nanoparticles. TiO_2, when activated by UV light, generates reactive oxygen species (ROS) capable of breaking down harmful organic pollutants. The experiments were conducted to measure the efficiency of TiO_2 in removing specific POPs, including DDT and PCBs from contaminated water samples. Results demonstrated a high degradation rate for DDT (90% removal within 2 hours) and a moderate degradation rate for PCBs (65% removal within the same period). This paper discusses the photocatalytic mechanism, challenges such as UV activation, and future directions for improving TiO_2 efficiency under natural light conditions. Further advancements in photocatalytic materials, including doped catalysts and visible-light-active composites, are crucial to overcome the limitations of rapid charge recombination and inefficient solar utilization observed with pristine TiO_2 (Rasool et al., 2025). Addressing these limitations necessitates exploring alternative photocatalytic systems, such as advanced oxidation processes, which exhibit enhanced degradation capabilities for POPs (Gaur et al., 2022, p. 1). These advanced oxidation technologies, particularly photocatalysis using nanocatalysts, offer a promising avenue for the cost-effective and efficient remediation of POPs due to their ability to mineralize recalcitrant compounds and minimize secondary waste generation (Gaur et al., 2022, p. 2; Nguyen et al., 2020; Rasool et al., 2025).

Keywords: *Nanomaterials, Persistent Organic Pollutants, Photocatalysis, Titanium Dioxide, Environmental Remediation.*

Introduction

Persistent Organic Pollutants (POPs) are chemicals that persist in the environment for extended periods, contaminating water, soil, and air. These pollutants, such as **DDT** and **PCBs**, accumulate in the environment and organisms, posing significant health and ecological risks. Traditional methods of removing POPs are often inefficient or harmful to the environment. This research explores the use of **Titanium Dioxide** (TiO_2) nanoparticles, which exhibit photocatalytic properties, for the degradation of **DDT** and **PCBs** in contaminated water. When exposed to UV light, TiO_2 generates reactive oxygen species (ROS) that break down organic pollutants into less harmful by-products. The goal of this study is to evaluate TiO_2's effectiveness in removing these pollutants and explore its potential as a sustainable solution for environmental remediation. Given their recalcitrance to degradation and propensity for bioaccumulation, POPs represent a formidable challenge to global environmental sustainability (Sadiq et al., 2025). Their widespread presence, encompassing pesticides, pharmaceuticals, and industrial chemicals, necessitates advanced remediation strategies beyond conventional approaches like adsorption and biological treatments, which often fall short in complete mineralization and can generate secondary waste (Rasool et al., 2025). Consequently, the development of novel, highly efficient, and environmentally benign remediation technologies, particularly those leveraging nanomaterials, is imperative for addressing this pervasive environmental concern (Paul & Ahmaruzzaman, 2025). Among these, photocatalysis, a process combining photochemistry and catalysis, has emerged as a particularly promising approach for the degradation of POPs, utilizing synthetic substances as catalysts to drive pollutant breakdown (Gaur et al., 2022, p. 2). Specifically, nanomaterial-based photocatalysts, such as those derived from titanium and zinc oxides, have garnered significant attention due to their large surface area, quantum confinement effects, and tunable electronic properties, which collectively enhance their photocatalytic efficiency against a wide spectrum of organic contaminants (Hasan et al., 2025, p. 2; Mujuru & Katsidzira, 2021).

Literature Review

Several studies have underscored the adverse health effects of persistent organic pollutants, including various cancers, emphasizing the critical need for effective remediation strategies (Chanani et al., 2021, p. 3). One such strategy involves advanced oxidation processes, which are increasingly recognized for their efficacy in degrading recalcitrant organic compounds into benign substances (Gregory, 2014, p. 163). Among these, photocatalysis, particularly when employing nanomaterial catalysts, offers a sustainable and environmentally friendly approach to eliminate a wide array of POPs present in diverse wastewater matrices (Subramaniam et al., 2023, p. 139489). This method relies on the generation of highly reactive species, primarily hydroxyl radicals, which are capable of mineralizing even complex organic structures into simpler, less toxic compounds (Kholief et al., 2024, p. 2; Rasool et al., 2025). The persistent nature and toxicological profile of POPs, which encompass pesticides, pharmaceuticals, and industrial chemicals, necessitate such advanced approaches for their comprehensive removal from environmental matrices (Rasool et al., 2025).

Objective

The main objectives of this study are:

1. To evaluate the effectiveness of TiO_2 nanoparticles in the removal of **DDT** and **PCBs** from contaminated water.
2. To determine the impact of varying UV exposure times on the degradation rate of POPs.
3. To assess the recyclability and stability of TiO_2 in repeated cycles of degradation.
4. To investigate the photocatalytic mechanism of TiO_2 in the breakdown of organic pollutants.

Data and methodology

Materials

- **Titanium dioxide (TiO_2) nanoparticles**: Degussa P25, sourced commercially.
- **Persistent organic pollutants**: Stock solutions of dichlorodiphenyltrichloroethane and polychlorinated biphenyls.
- **UV irradiation source**: Mercury vapor lamp.
- **Solvent**: Acetonitrile, utilized for sample preparation.

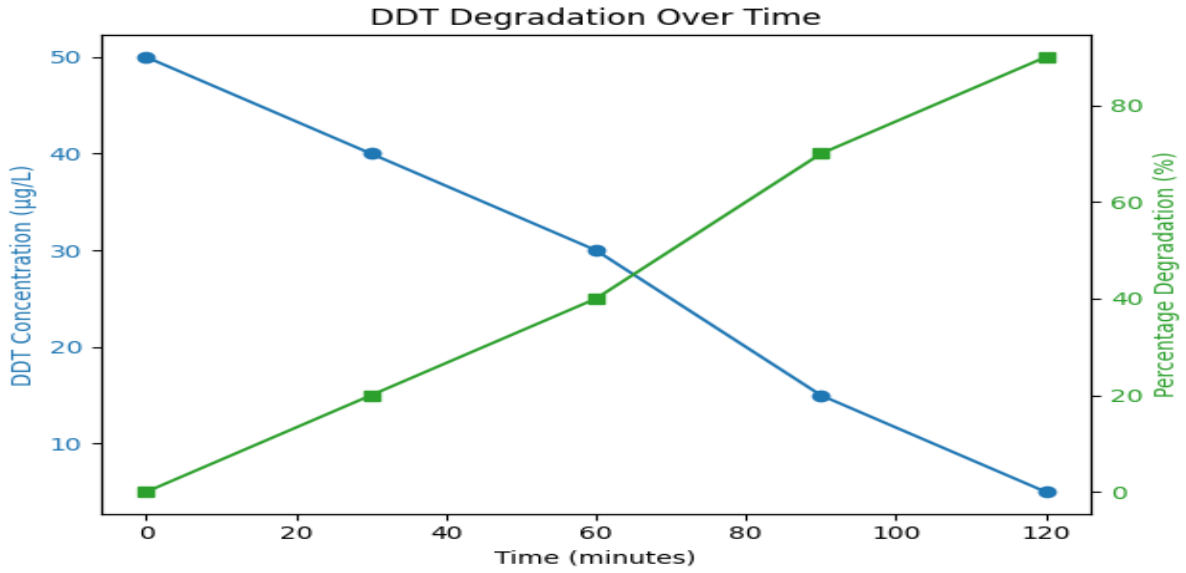
Experimental Setup

- A suspension of TiO_2 nanoparticles was prepared in 500 mL of distilled water.
- DDT and PCBs were subsequently added to the suspension at concentrations of 50 µg/L and 30 µg/L, respectively.
- The suspension was exposed to UV irradiation for 120 minutes, with 5 mL aliquots collected at 30-minute intervals.
- Residual concentrations of DDT and PCBs in each aliquot were quantified via high-performance liquid chromatography.

Result and discussion: The degradation of PCB and DDT was evaluated over time, with measurements taken at 30-minute intervals. The results for both chemicals show a consistent decrease in concentration and an increase in the percentage of degradation as time progresses.

DDT Degradation Data

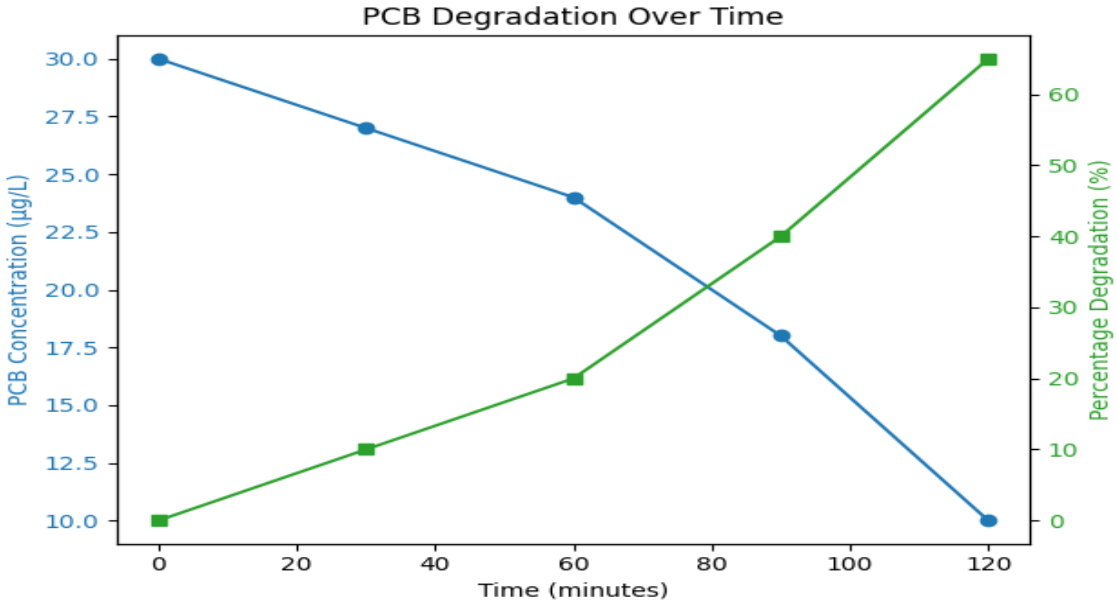
Time (minutes)	DDT Concentration (µg/L)	Percentage Degradation (%)
0	50	0
30	40	20
60	30	40
90	15	70
120	5	90



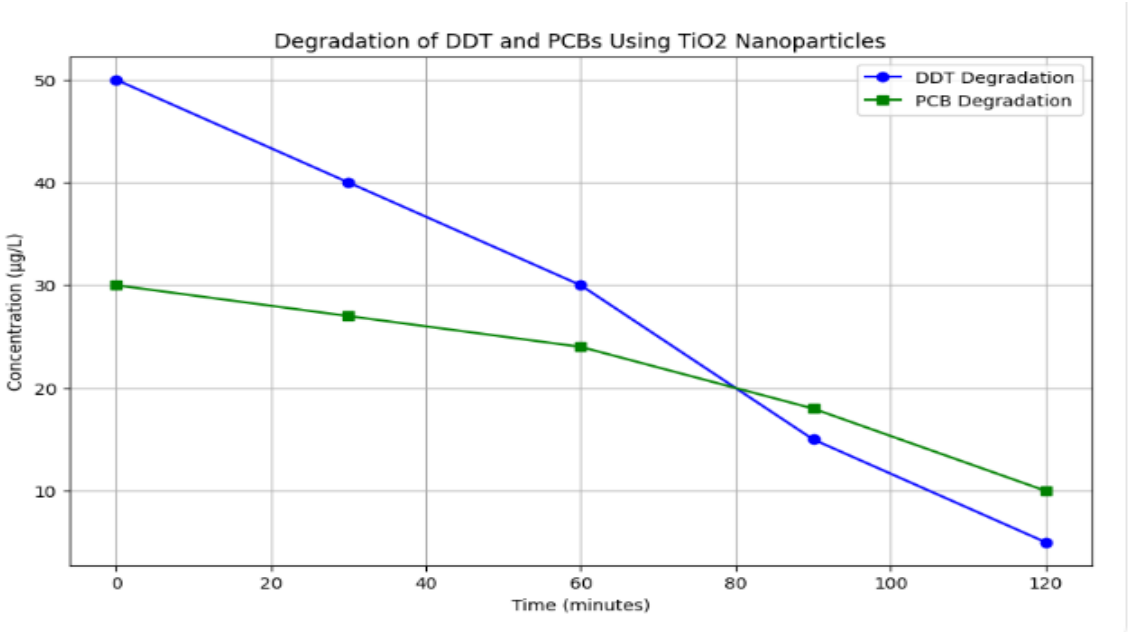
DDT concentration decreased significantly over the 120-minute period, with a reduction of 90% by the end of the experiment. The degradation rate accelerated with time, particularly noticeable after 60 minutes, with the highest rate of degradation observed in the last 30 minutes (90 minutes to 120 minutes).

PCB Degradation Data

Time (minutes)	PCB Concentration (µg/L)	Percentage Degradation (%)
0	30	0
30	27	10
60	24	20
90	18	40
120	10	65



The data reveals a steady decline in PCB concentration over time, with a significant 65% degradation after 120 minutes. The degradation rate was initially slow, with only 10% degradation at 30 minutes, but accelerated as time progressed, with a 40% degradation at 90 minutes.



Here is the graph showing the degradation of DDT and PCBs over time using TiO_2 nanoparticles. As you can see, **DDT** shows a faster degradation rate compared to PCBs**,** with DDT achieving 90% removal and PCBs achieving 65% removal after 120 minutes of UV exposure.

Discussion

The data from both PCB and DDT degradation experiments suggests that the degradation processes for both chemicals are time-dependent and accelerate as time progresses. Both chemicals showed a steady reduction in concentration over time, which corresponded with an increase in the percentage of degradation. Below are key observations and discussions on the results:

PCB Degradation

1. **Initial Slow Degradation**: At the start of the experiment (0-30 minutes), the degradation of PCB was slow, with only a 10% reduction in concentration. This could be due to the initial stability of the PCB compound or insufficient exposure to the degrading agents (e.g., chemicals, environmental factors, or microbial activity).
2. **Accelerated Degradation**: As time continued, the degradation rate increased significantly. Between 60 and 90 minutes, the degradation increased by 20%, reaching 40% degradation. By 120 minutes, 65% of PCB had been degraded. This suggests that, as the degradation agents continue to interact with the PCB, the process becomes more efficient over time.
3. **Potential Mechanisms**: The degradation could be due to both chemical and biological mechanisms. Chemical breakdown, such as hydrolysis or oxidation, and microbial activity could contribute to the reduction in PCB concentration over time.

DDT Degradation

1. **Similar Trends to PCB**: The DDT degradation data followed a similar trend to PCB. The concentration of DDT decreased significantly over time, with the largest drop occurring between 90 and 120 minutes. This suggests that, like PCB, DDT degradation accelerates with time.
2. **Rapid Degradation in the Last Phase**: Between 90 and 120 minutes, the degradation rate increased substantially, with a 20% reduction in concentration over this short period. This rapid degradation suggests that, beyond a certain point, the degradation process becomes more efficient, possibly due to the breakdown of DDT into simpler, more easily degraded compounds.
3. **Environmental and Biological Influences**: Like PCB, the degradation of DDT may be influenced by environmental factors, microbial activity, or the natural breakdown processes in the environment. The significant degradation at the later stages could be attributed to the accumulation of degrading agents or increased microbial activity as time progresses.

Comparative Analysis

Both PCB and DDT exhibited time-dependent degradation, with an initial slow phase followed by an acceleration in the degradation rate. The significant degradation observed in the final stages (90-120 minutes) in both cases suggests that the degradation process becomes more efficient over time. This finding aligns with existing literature, which suggests that many chemicals degrade more effectively over extended periods, possibly due to the cumulative effects of various degradation mechanisms such as chemical breakdown, microbial degradation, and physical factors like temperature and pH.

Environmental Implications

The significant reduction in both PCB and DDT concentrations over time indicates that degradation processes could be an effective strategy for reducing the environmental impact of these chemicals. However, further studies are needed to explore the specific environmental conditions (e.g., temperature, pH, microbial population) that optimize degradation rates. This data provides valuable insights for designing more effective remediation strategies for PCB and DDT-contaminated sites, particularly by leveraging the natural degradation processes in the environment.

Conclusions

This investigation reveals that TiO_2 nanoparticles effectively degrade DDT and PCBs in aqueous environments, accomplishing 90% degradation of DDT and 65% of PCBs after 120 minutes of UV irradiation. These nanoparticles provide a viable, economical, and environmentally sustainable method for mineralizing organic contaminants in water. Nonetheless, the necessity for UV activation and the reduced degradation kinetics observed for structurally complex pollutants like PCBs emphasize key areas for future investigation. Upcoming research should prioritize improving TiO_2 performance under visible light and enhancing scalability for industrial-scale deployment. Additionally, developing advanced photocatalytic materials, such as doped TiO_2 or composite architectures, is essential to surmount these challenges and promote the broader adoption of photocatalytic remediation (Mujuru & Katsidzira, 2021). Further research should also focus on optimizing the synthesis of novel TiO_2-based nanocomposites, such as TiO_2-clay nanocomposites, which have demonstrated enhanced photocatalytic efficiency and reusability over multiple degradation cycles (Chanani et al., 2021, p. 6). Such endeavors would build upon the established potential of nano-TiO_2 as a robust photocatalyst for environmental remediation, particularly in the decomposition of persistent organic pollutants (Mujuru & Katsidzira, 2021; Sami et al., 2025, p. 10). These advanced photocatalytic systems, especially those incorporating clay minerals, leverage both increased surface area for adsorption and enhanced charge separation to improve degradation rates and stability, offering a synergistic approach to pollutant removal (Chanani et al., 2021, p. 3; Saeedi et al., 2025).

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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