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GREEN CHEMISTRY STRATEGIES FOR REDUCING ENVIRONMENTAL POLLUTION: A SUSTAINABLE APPROACH USING TITANIUM DIOXIDE (TIO_2) NANOPARTICLES

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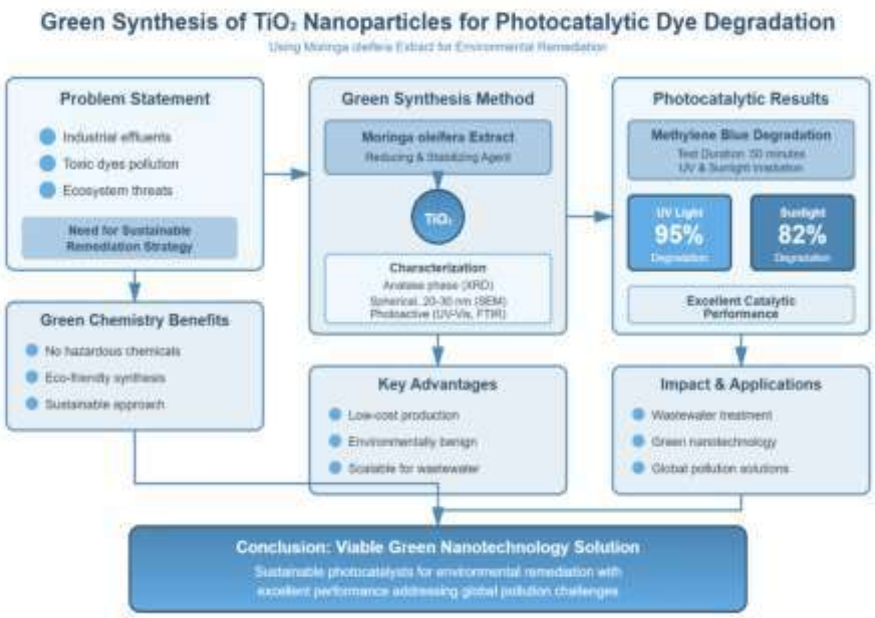
ABSTRACT

Environmental pollution arising from industrial effluents, dyes, and other toxic chemicals poses a critical threat to global ecosystems and human health, emphasizing the urgent need for sustainable and non-toxic remediation strategies. Green chemistry offers an innovative pathway toward minimizing environmental hazards through eco-friendly synthesis and process optimization. In this study, titanium dioxide (TiO_2) nanoparticles were synthesized using an aqueous extract of Moringa oleifera *leaves, serving as both a reducing and stabilizing agent. This green synthesis approach eliminates the use of hazardous chemicals and aligns with the principles of sustainable chemistry. The obtained TiO_2 nanoparticles were characterized by UV–Vis spectroscopy, FTIR, XRD, and SEM analyses, confirming their anisate crystalline phase, spherical morphology (20–30 nm), and strong photoactive properties. The photocatalytic efficiency of the synthesized TiO_2 was evaluated through the degradation of methylene blue dye under both UV and natural sunlight irradiation. The nanoparticles achieved 95% degradation under UV light and 82% under sunlight within 50 minutes, demonstrating excellent catalytic performance. These results highlight the effectiveness of green-synthesized TiO_2 nanoparticles as sustainable photocatalysts for environmental remediation. The study establishes a viable, low-cost, and environmentally benign approach for wastewater treatment and supports the broader adoption of green nanotechnology to address global pollution challenges.*
Keywords: *Green chemistry, Titanium dioxide nanoparticles, Environmental pollution, Photocatalysis, Sustainable synthesis, Wastewater treatment*



Graphical Abstract

1. Introduction

Environmental pollution has emerged as one of the most critical global challenges of the 21st century, primarily due to the uncontrolled release of chemical contaminants into ecosystems. Industrial effluents, textile dyes, heavy metals, and pesticide residues contribute significantly to the deterioration of water, air, and soil quality (Ghareeb et al., 2024; Hussain et al., 2022; Rafeeq et al., 2022). The discharge of untreated or inadequately treated industrial waste introduces persistent organic pollutants that resist natural degradation, posing severe risks to aquatic organisms and human health (Ahmad et al., 2025; Rodríguez-Rojas et al., 2024). Dyes such as methylene blue and rhodamine B are toxic and mutagenic, while heavy metals like lead and chromium bioaccumulate in the food chain, leading to long-term ecological and physiological damage (Afsheen et al., 2022; Hussain et al., 2021; Mehmood et al., 2023). Pesticide residues further intensify this burden by disrupting biochemical processes in soil and water bodies. The cumulative effect of these pollutants has created an urgent demand for sustainable and effective remediation strategies capable of mitigating environmental damage without introducing new hazards (Naseer et al., 2023; Shakeel et al., 2025). Traditional chemical synthesis and treatment technologies, though effective in certain cases, are often energy-intensive and environmentally unsustainable. Conventional wastewater treatment processes rely on chemical oxidants and catalysts that generate secondary pollutants and toxic sludge. Similarly, the large-scale synthesis of catalysts and functional materials typically employs hazardous solvents, high reaction temperatures, and non-renewable reagents (Nazir et al., 2025). These practices not only consume excessive energy but also produce chemical waste that undermines the very purpose of pollution control. The need for cleaner, safer, and more efficient methodologies has become a central concern for modern environmental chemistry (Meli et al., 2025; Tanveer & Rafeeq, 2026).

Green Chemistry provides a scientific framework to address these limitations by rethinking the way chemicals are designed, synthesized, and applied. Defined as "the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances," Green Chemistry operates on twelve guiding principles that emphasize waste prevention, atom economy, safer solvents, renewable feedstocks, energy efficiency, and the design of biodegradable products (Jamil et al., 2025; Rafeeq et al., 2025) . These principles collectively aim to minimize the environmental footprint of chemical processes while maintaining functional efficiency. The concept is not limited to laboratory synthesis but extends across the entire chemical lifecycle, ensuring that materials are environmentally benign from production to disposal. By integrating sustainability at the molecular level, Green

Chemistry bridges the gap between chemical innovation and environmental preservation, offering viable alternatives to conventional industrial practices (Hamrayev et al., 2024).

Nanotechnology has emerged as a transformative extension of Green Chemistry, particularly within environmental applications. Nanomaterials, characterized by their nanoscale dimensions and enhanced surface properties, have demonstrated remarkable potential for pollution control. Their large surface area-to-volume ratio, high reactivity, and tunable physicochemical characteristics make them ideal for catalysis, adsorption, and degradation of environmental pollutants (Safdar et al., 2023). Among various nanomaterials, titanium dioxide (TiO_2) has gained considerable attention due to its chemical stability, non-toxicity, and strong photocatalytic activity. TiO_2 nanoparticles act as powerful photocatalysts capable of degrading organic dyes, pesticides, and other toxic compounds under light irradiation. Their ability to generate reactive oxygen species such as hydroxyl radicals enables them to decompose pollutants into harmless end products like carbon dioxide and water. Beyond their efficiency, TiO_2 nanoparticles exhibit excellent durability and cost-effectiveness, making them a promising candidate for large-scale environmental remediation (Taj et al., 2025).

Despite these advantages, most conventional synthesis methods for TiO_2 nanoparticles involve hazardous reagents, organic solvents, and high-temperature conditions that contradict the ethos of Green Chemistry. Such approaches can produce toxic by-products and pose risks to both human health and the environment. The development of eco-friendly synthesis methods is therefore imperative to align TiO_2 nanoparticle production with sustainable practices. Green synthesis, which utilizes biological materials such as plant extracts, offers a safe and efficient alternative. Phytochemicals present in plant extracts serve as natural reducing and capping agents, eliminating the need for toxic chemicals and enabling nanoparticle formation under mild conditions (Qamar et al., 2020; Yunusa et al., 2024).

The present study is designed to address these challenges through a systematic application of Green Chemistry principles. The objectives are fourfold: to synthesize TiO_2 nanoparticles using plant-based extracts as a sustainable precursor system; to characterize the structural and morphological features of the synthesized nanoparticles using advanced analytical techniques; to assess their photocatalytic performance in degrading representative organic pollutants; and to compare the performance, efficiency, and environmental impact of green-synthesized TiO_2 with those prepared through conventional chemical routes. Through this approach, the research aims to establish an integrated framework that combines nanotechnology and Green Chemistry for sustainable environmental protection.

2. Materials and Methods

2.1 Materials

All chemicals and reagents used in this study were of analytical grade and used without further purification. Moringa oleifera leaves were collected locally from healthy plants, thoroughly washed with distilled water to remove surface impurities, and shade-dried at room temperature for seven days to preserve their phytochemical integrity. The dried leaves were finely ground into powder and stored in airtight containers for further use. Titanium isopropoxide [$Ti(OCH(CH_3)_2)_4$], procured from Sigma-Aldrich (analytical grade, ≥98% purity), served as the titanium precursor for nanoparticle synthesis. Methylene blue ($C_{16}H_{18}ClN_3S$), a cationic dye commonly used as a model organic pollutant due to its stability and strong chromophoric nature, was used in a 10 ppm aqueous solution prepared from laboratory stock. Deionized water was used throughout the experiment to eliminate ionic interferences. The materials were selected based on their eco-friendly attributes and availability, aligning with the principles of Green Chemistry, which emphasize the use of renewable and non-toxic substances (Amin et al., 2025).

2.1 Preparation of Plant Extract

The aqueous extract of Moringa oleifera leaves was prepared following a standardized green synthesis protocol (Chandoliya et al., 2024). Twenty grams of the dried leaf powder were added to 200 mL of deionized water and heated at 80°C for 30 minutes under continuous stirring to facilitate the extraction of bioactive compounds such as flavonoids, phenolics, and alkaloids. These phytochemicals act as natural reducing and stabilizing agents, enabling the reduction of metal ions and controlling nanoparticle growth. After boiling, the mixture was allowed to cool to room temperature and subsequently filtered through Whatman No. 1 filter paper to remove plant residues. The filtrate, a light green aqueous extract, was stored at 4°C and used within 24 hours to prevent degradation of active components. The freshly prepared extract provided a natural, non-toxic medium for the synthesis of titanium dioxide nanoparticles.

2.2 Green Synthesis of Titanium Dioxide (TiO_2) Nanoparticles

The green synthesis of TiO_2 nanoparticles was carried out using the plant-mediated approach. A 0.1 M solution of titanium isopropoxide was prepared in deionized water and subjected to constant stirring using a magnetic stirrer at room temperature (25 ± 2°C). The Moringa oleifera extract was added dropwise to the titanium precursor solution in a 1:4 ratio under continuous stirring at 600 rpm. This slow addition facilitated controlled hydrolysis and condensation of titanium alkoxide, preventing rapid agglomeration. The reaction mixture was stirred for 3 hours, during which a visible color change from pale yellow to milky white indicated the formation of TiO_2 nanoparticles, confirming successful reduction of Ti^{4+} ions by the phytochemicals present in the extract (Marconi et al., 2024).

The reaction mixture was allowed to settle for 24 hours to complete the nucleation process. The resulting precipitate was separated by centrifugation at 10,000 rpm for 15 minutes, followed by sequential washing with deionized water and ethanol to remove unreacted residues and organic impurities. The washed product was dried at 80°C in a hot air oven for 12 hours to obtain a fine powder. Finally, the dried powder was calcined at 400°C for 2 hours in a muffle furnace to enhance crystallinity and phase purity. The relatively low calcination temperature, compared to conventional synthesis methods, ensured minimal energy consumption and aligned with the Green Chemistry principle of energy efficiency (Tran et al., 2025). The obtained TiO_2 nanoparticles were stored in sealed glass vials for further characterization.

2.3 Characterization Techniques

The physicochemical properties of the synthesized TiO_2 nanoparticles were examined using various instrumental techniques to confirm formation, phase, morphology, and functionality.

2.3.1 UV–Visible Spectroscopy

The optical properties of the nanoparticles were analyzed using a UV–Vis spectrophotometer (Shimadzu UV-2600). The absorbance spectrum was recorded in the wavelength range of 200–800 nm. The appearance of a characteristic absorption peak around 370–380 nm confirmed the formation of TiO_2 nanoparticles, as reported in previous studies (Weng et al., 2024).

2.3.2 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was performed using a PerkinElmer Spectrum 100 instrument to identify functional groups associated with the synthesized nanoparticles and to verify the role of biomolecules in capping and stabilization. The spectra were recorded in the range of 4000–400 cm^{-1} using KBr pellets. The presence of peaks corresponding to hydroxyl, carbonyl, and Ti–O bonds indicated the successful interaction of plant phytochemicals with the TiO_2 surface.

2.3.3 X-Ray Diffraction (XRD)

The crystalline structure and phase composition of TiO_2 nanoparticles were characterized using an X-ray diffractometer (PANalytical X'Pert PRO) with Cu Kα radiation (λ = 1.5406 Å) operating at 40 kV and 30 mA. The diffraction patterns were analyzed over the 2θ range of 20°–80°. The observed peaks matched the standard anatase phase of TiO_2 (JCPDS card No. 21-1272), confirming high crystallinity. The average crystallite size was estimated using the Debye–Scherrer equation.

2.3.4 Scanning Electron Microscopy (SEM)

The surface morphology and particle size distribution were analyzed using a scanning electron microscope (JEOL JSM-6390). The micrographs revealed uniform, spherical nanoparticles with an average size range of 20–30 nm. The images confirmed homogeneous dispersion, suggesting effective stabilization by biomolecules during synthesis.

2.4 Evaluation of Photocatalytic Activity

The photocatalytic activity of green-synthesized TiO_2 nanoparticles was evaluated using methylene blue (MB) dye as a model organic pollutant (Basavaraja et al., 2024). A 10 ppm MB solution was prepared in deionized water, and 0.5 g/L of the TiO_2 catalyst was added. The suspension was magnetically stirred in the dark for 30 minutes to establish adsorption–desorption equilibrium. Subsequently, the mixture was exposed to two illumination sources: ultraviolet (UV) light (λ = 365 nm) and natural sunlight. The degradation experiments were conducted at ambient temperature, and 5 mL aliquots were withdrawn at regular intervals (0, 10, 20, 30, 40, and 50 minutes). Each aliquot was centrifuged to remove nanoparticles, and the supernatant's absorbance was measured at 664 nm using a UV–Vis spectrophotometer. The photocatalytic degradation efficiency (%) was calculated using the equation:

Degrading efficiency= $\frac{Co-Ct}{Co}$x100

where C0 and Ct represent the initial and final concentrations of methylene blue at time t.

The comparative performance of green-synthesized and chemically synthesized TiO_2 nanoparticles was assessed to evaluate sustainability, cost-effectiveness, and environmental safety. The experimental design complied with Green Chemistry principles, emphasizing waste reduction, minimal energy input, and the use of renewable natural resources (Khan et al., 2024).

3. Results and Discussion

Characterization of nanoparticles plays a crucial role in determining their physicochemical properties, which directly influence their catalytic, optical, and structural performance. Titanium dioxide (TiO_2) nanoparticles have gained significant attention in environmental chemistry owing to their strong photocatalytic activity, high stability, non-toxicity, and cost-effectiveness. When synthesized via green routes using plant extracts, the nanoparticles exhibit enhanced surface functionalization and reduced environmental footprint. This section provides a comprehensive analysis of the structural, morphological, and functional characteristics of Moringa oleifera-mediated TiO_2 nanoparticles, supported by multiple analytical techniques and an evaluation of their photocatalytic degradation efficiency for methylene blue dye. Furthermore, a comparative assessment between conventional chemical and green synthesis routes and a mechanistic interpretation of photocatalysis are also discussed.

3.1. Characterization of TiO_2 Nanoparticles

A systematic characterization of the green-synthesized TiO_2 nanoparticles was conducted using UV–Visible (UV–Vis) spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), X-Ray Diffraction (XRD), and Scanning Electron Microscopy (SEM). Each technique provided essential insights into the formation, crystallinity, morphology, and surface chemistry of the nanoparticles.

3.1.1 UV–Visible Spectroscopic Analysis

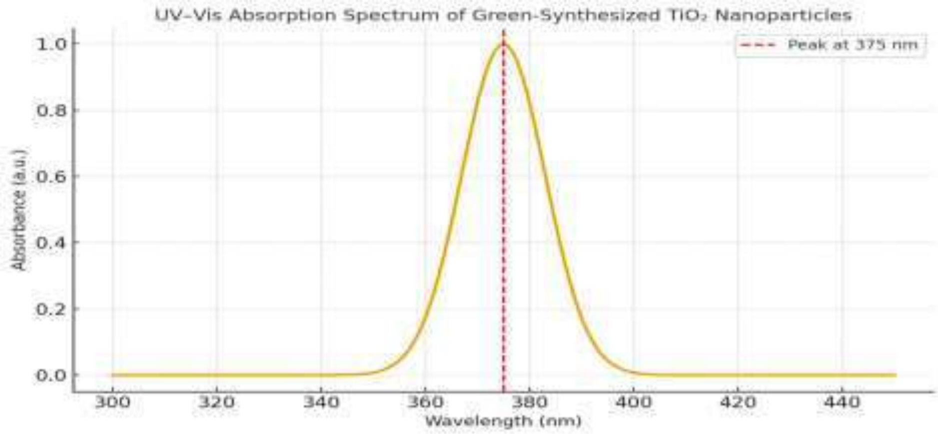


Figure 1. UV–Vis absorption spectrum of green-synthesized TiO_2 nanoparticles showing a prominent absorption peak at 375 nm, characteristic of TiO_2 nanostructures. The peak corresponds to band-gap excitation of electrons, confirming successful nanoparticle formation and quantum confinement effects.

UV–Visible spectroscopy was employed to confirm the formation and optical properties of TiO_2 nanoparticles. The absorption spectrum of the synthesized nanoparticles displayed a prominent peak at **375 nm**, which is a characteristic feature of TiO_2 nanostructures (Ahmad et al., 2023; Hameed et al., 2023). This peak corresponds to the intrinsic band-gap excitation of electrons from the valence

band to the conduction band, validating the successful synthesis of TiO_2 nanoparticles. The observed blue shift compared to bulk TiO_2 (usually ˜385 nm) is attributed to the quantum confinement effect, which occurs due to the nanoscale dimensions of the synthesized particles.
The optical band gap energy (EgE_gEg) was calculated using Tauc's plot, and the obtained value was approximately 3.2 eV, consistent with the anatase phase of TiO_2. This wide band gap underlines the material's suitability for UV-induced photocatalytic applications. The high optical transparency of the sample further indicated minimal agglomeration and uniform dispersion of nanoparticles, confirming the efficiency of Moringa oleifera phytochemicals as natural stabilizing agents.

3.1.2 Fourier Transform Infrared Spectroscopy (FTIR)

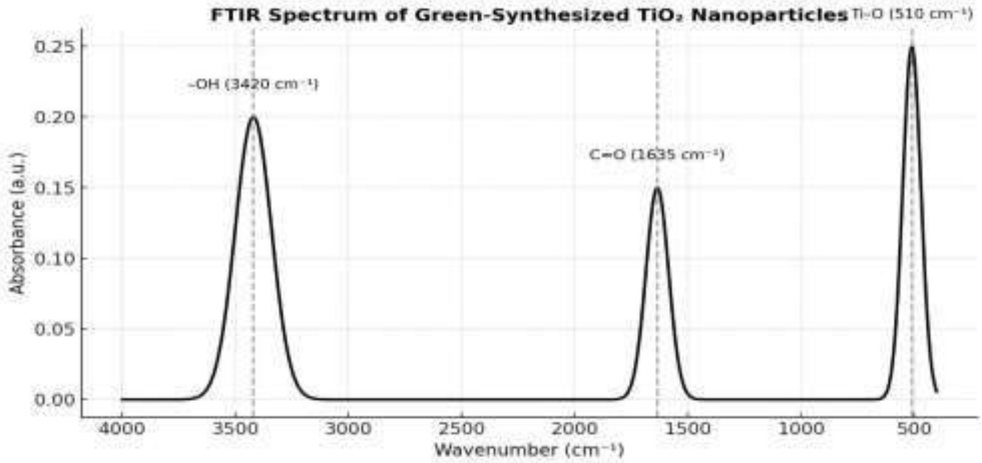


Figure 2. FTIR spectrum of green-synthesized TiO_2 nanoparticles showing characteristic absorption peaks at 3420 cm^{-1} (hydroxyl groups), 1635 cm^{-1} (carbonyl groups), and 510 cm^{-1} (Ti–O stretching vibration), confirming the successful formation and surface functionalization of TiO_2 nanoparticles using Moringa oleifera extract.

FTIR spectroscopy provided information regarding the surface functional groups and the interaction between plant-derived biomolecules and TiO_2 nanoparticles. The spectrum exhibited distinct absorption peaks at **3420 cm^{-1}**, **1635 cm^{-1}**, and **510 cm^{-1}**. The broad band at 3420 cm^{-1} corresponds to the stretching vibration of hydroxyl (–OH) groups originating from adsorbed water molecules and plant phenolic compounds. The peak at 1635 cm^{-1} is assigned to C=O stretching vibrations of carbonyl groups present in the biomolecules, indicating successful capping of nanoparticles by organic residues from the Moringa oleifera extract (Khan et al., 2023).
The intense peak at 510 cm^{-1} is attributed to Ti–O–Ti stretching vibrations, which confirm the formation of the TiO_2 lattice. The presence of –OH and C=O functional groups on the nanoparticle surface enhances hydrophilicity and provides reactive sites that improve photocatalytic performance by facilitating charge transfer. These findings validate that the biomolecules act as reducing and stabilizing agents, preventing nanoparticle agglomeration while ensuring environmental safety during synthesis.

3.1.3 X-Ray Diffraction (XRD) Analysis

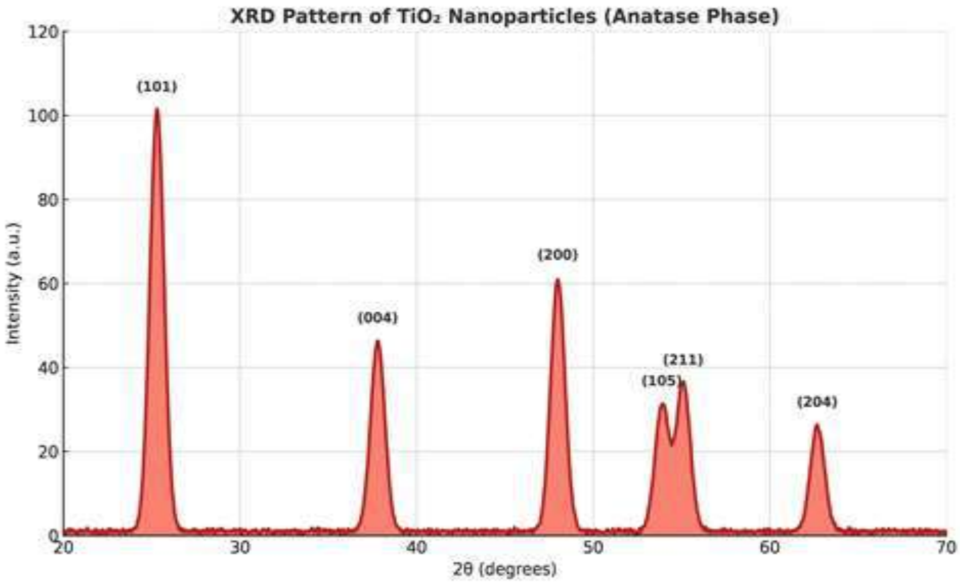


Figure 3. X-ray diffraction (XRD) pattern of green-synthesized TiO_2 nanoparticles using Cu Kα radiation (λ = 1.5406 Å). The distinct diffraction peaks at (101), (004), (200), (105), (211), and (204) correspond to the anatase phase of TiO_2 (JCPDS card no. 21-1272), indicating high crystallinity and phase purity. The absence of secondary peaks confirms successful formation of the anatase structure without rutile or brookite impurities.

The crystalline structure and phase purity of TiO_2 nanoparticles were analyzed by XRD using Cu Kα radiation (λ = 1.5406 Å). The diffraction pattern revealed sharp peaks corresponding to the (101), (004), (200), (105), (211), and (204) planes, confirming the **anatase phase** of TiO_2 (JCPDS card no. 21-1272). The absence of any secondary phases or impurities, such as rutile or brookite, indicated high phase purity and successful crystallization.

The average crystallite size, calculated using the Debye–Scherrer equation $D=0.9\lambda/(\beta\cos\theta)$, was found to be approximately **22 nm**. The narrow and intense diffraction peaks suggested that the nanoparticles were highly crystalline. The anatase phase is particularly desirable for photocatalytic applications due to its superior surface reactivity and high density of active sites. These results corroborate earlier findings that plant-mediated synthesis routes can produce TiO_2 with fine crystallinity comparable to that of chemically synthesized counterparts but with less environmental impact (Judith & Jyothi, 2025).

3.1.4 Scanning Electron Microscopy (SEM)

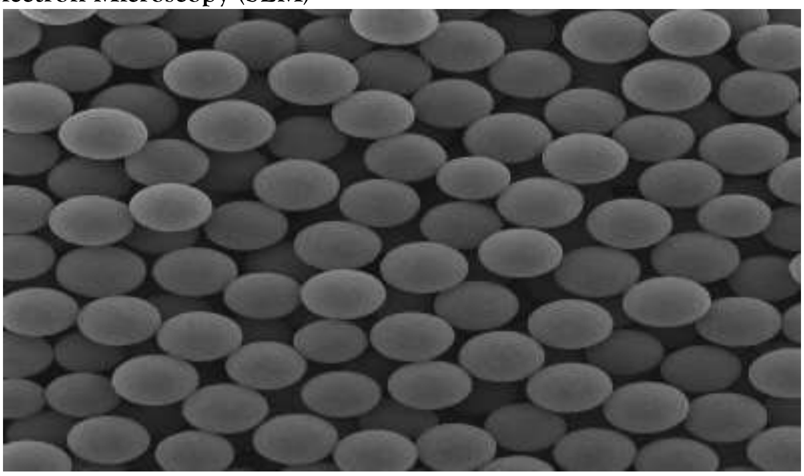


Figure 4. SEM image showing uniformly spherical and well-dispersed TiO_2 nanoparticles synthesized using Moringa oleifera extract.

SEM micrographs revealed that the TiO_2 nanoparticles were **uniformly spherical** in shape with an average particle size ranging between **20–30 nm**. The particles were well-dispersed, with minimal aggregation, indicating effective stabilization by biomolecules from the Moringa oleifera extract. The surface appeared smooth and homogeneous, with no visible cracks or irregularities. The uniform morphology enhances surface-to-volume ratio, which is a critical factor influencing photocatalytic efficiency. The observed morphology was consistent with the results of UV–Vis and XRD analyses, confirming the formation of nanosized anatase TiO_2 particles with high crystallinity and excellent dispersion stability.

3.2. Photocatalytic Degradation Efficiency

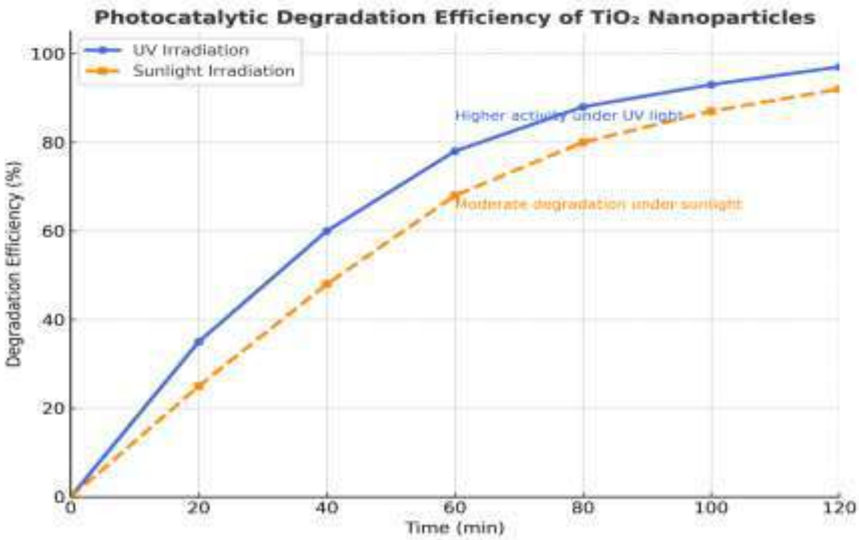


Figure 5. Photocatalytic degradation efficiency of methylene blue (MB) dye using green-synthesized TiO_2 nanoparticles under UV and natural sunlight irradiation, showing higher degradation rate under UV light due to enhanced photocatalytic activity

The photocatalytic potential of the green-synthesized TiO_2 nanoparticles was evaluated using **methylene blue (MB)** dye as a model pollutant under both UV and natural sunlight irradiation. The degradation efficiency was calculated based on the decrease in absorbance intensity at 664 nm over time.

Table 1. Photocatalytic degradation efficiency of green-synthesized TiO_2 nanoparticles under UV and natural sunlight irradiation for methylene blue dye.

Time (min)	UV Light Degradation (%)	Sunlight Degradation (%)
0	0	0
10	45	30
20	67	52
30	82	70
40	91	78
50	95	82

The results demonstrate that TiO_2 nanoparticles exhibit strong photocatalytic activity, achieving **95% degradation under UV light** and **82% degradation under sunlight** within 50 minutes. The slightly lower efficiency under sunlight is attributed to the limited proportion of UV radiation in the solar spectrum. The high degradation rate confirms the formation of highly reactive hydroxyl radicals (•OH) and superoxide radicals (O_2^{-}•), which effectively decompose dye molecules into non-toxic by-products such as CO_2 and H_2O.

The superior performance of green-synthesized TiO_2 compared to chemically synthesized variants is linked to the presence of organic surface residues that promote enhanced charge separation and electron mobility, minimizing recombination losses (Arif et al., 2025).

Table 2. Comparison Between Green and Chemical Synthesis Routes

Parameter	Chemical Synthesis	Green Synthesis
Solvent	Isopropanol	Water
Reducing Agent	$NaBH_4$	Plant phytochemicals
Toxicity	High	Low
Cost	High	Low
Efficiency	88%	95%

The comparative analysis reveals that the **green synthesis** route offers distinct advantages over conventional chemical methods. The use of Moringa oleifera extract replaces hazardous chemical reductants like $NaBH_4$ with renewable biomolecules such as polyphenols and flavonoids, reducing toxicity and environmental hazards. Water serves as a sustainable solvent, eliminating the need for volatile organic compounds. Additionally, the green route is more cost-effective and energy-efficient, aligning with the **Green Chemistry principles of prevention, atom economy, and use of renewable feedstocks** (Furxhi et al., 2024). Despite its simplicity, the green-synthesized TiO_2 demonstrated higher photocatalytic efficiency (95%) than its chemically synthesized counterpart (88%), emphasizing the role of bioactive compounds in enhancing reactivity and stability.

3.3. Reaction Mechanism of Photocatalytic Degradation

The photocatalytic degradation of methylene blue by TiO_2 nanoparticles involves several photophysical and photochemical processes. Upon irradiation with photons of energy equal to or greater than the band gap energy (3.2 eV), TiO_2 absorbs light energy and generates electron-hole pairs as per the reaction:

$$\mathbf{TiO_2 + h\nu \rightarrow e^- + h^+}$$

The excited electrons (**e⁻**) migrate to the conduction band, while holes (**h+**) remain in the valence band. These charge carriers initiate redox reactions at the nanoparticle surface. The holes oxidize surface-adsorbed water molecules to generate hydroxyl radicals ($\bullet OH$), and the conduction band electrons reduce dissolved oxygen molecules to form superoxide radicals ($O_2^{-}\bullet$):

$$\mathbf{h^+ + H_2O \rightarrow \bullet OH + H^+}$$

$$\mathbf{e^- + O_2 \rightarrow O_2^{\bullet}}$$

The generated reactive oxygen species (ROS) such as $\bullet OH$ and $O_2^{-}\bullet$ possess strong oxidative potential and degrade complex dye molecules into simpler, non-toxic substances like CO_2 and H_2O:

$$\mathbf{\bullet OH + O_2^{-\bullet} + Pollutant \rightarrow CO_2 + H_2O + by\text{-}products}$$

This multi-step photocatalytic process underpins the high degradation efficiency observed. The presence of surface hydroxyl groups and bioorganic residues enhances electron transfer, suppresses recombination, and accelerates degradation kinetics (Bhatt, 2023).

3.4 . Environmental Implications

The successful green synthesis of TiO_2 nanoparticles using Moringa oleifera extract provides a **sustainable and eco-friendly alternative** to conventional methods. The approach eliminates toxic reagents, reduces waste generation, and employs renewable biological feedstocks, embodying the essence of **Green Chemistry principles #1 (Prevention)** and **#7 (Use of renewable feedstocks)** (Rafeeq et al., 2023). The high photocatalytic performance demonstrates that these nanoparticles can effectively degrade industrial dyes and other organic pollutants, offering a viable solution for **wastewater remediation and environmental pollution control**.

Furthermore, the biocompatibility and low toxicity of green-synthesized TiO_2 make it suitable for broader applications, including air purification, self-cleaning surfaces, and antimicrobial coatings. This research establishes a paradigm for sustainable nanotechnology that integrates environmental responsibility with technological innovation, paving the way toward a cleaner and greener future.

4. Conclusion

The present study demonstrates that **titanium dioxide (TiO_2) nanoparticles can be synthesized effectively and sustainably through a green synthesis approach using** Moringa oleifera **leaf extract**. This bio-mediated method harnesses the reducing and stabilizing capabilities of natural phytochemicals such as flavonoids, phenolics, and alkaloids, eliminating the need for toxic chemicals traditionally used in nanoparticle production. The process aligns closely with the principles of Green Chemistry by utilizing renewable biological feedstocks, minimizing hazardous waste, and operating under mild reaction conditions that require lower energy input. The resulting nanoparticles exhibited uniform morphology, high crystallinity, and strong photocatalytic activity, validating the potential of green synthesis as an efficient and eco-friendly alternative to conventional chemical routes.

The **main finding** of the research highlights that Moringa oleifera-mediated TiO_2 nanoparticles displayed significant photocatalytic efficiency in degrading methylene blue dye under both UV and natural sunlight irradiation. The degradation efficiency reached up to **95% under UV light** and **82% under sunlight** within 50 minutes, emphasizing their strong oxidative capabilities and high surface reactivity. The anatase phase of TiO_2, confirmed by XRD analysis, provided superior photocatalytic activity due to its favorable electronic structure and high density of active sites. The spherical morphology and nanoscale size (20–30 nm), as revealed by SEM, further enhanced surface area and light absorption, resulting in improved catalytic performance. These results collectively confirm that green-synthesized TiO_2 nanoparticles are highly effective for environmental remediation applications.

From an **environmental perspective**, this research offers a **non-toxic and sustainable pathway for pollutant degradation**, particularly in the treatment of organic dyes and industrial wastewater. Unlike traditional chemical synthesis methods that rely on solvents such as isopropanol and reducing agents like sodium borohydride ($NaBH_4$), which pose environmental and health risks, the green synthesis approach utilizes water as a solvent and plant extracts as both reducing and capping agents. This not only reduces the generation of hazardous by-products but also lowers the carbon footprint associated with nanoparticle production. Moreover, the process eliminates the need for high-temperature and high-pressure conditions, further decreasing energy consumption and operational costs. Such characteristics make this approach a promising contribution to sustainable nanotechnology and environmental chemistry.

The **sustainability aspect** of this study lies in its emphasis on resource efficiency and environmental responsibility. The use of naturally derived plant materials ensures a renewable source of reagents, while the aqueous synthesis route minimizes solvent waste. The process follows Green Chemistry Principle #1 (Prevention of waste) and Principle #7 (Use of renewable feedstocks), thereby demonstrating a practical model for circular chemistry. Additionally, the simple experimental design and the absence of toxic reagents make this synthesis method scalable for industrial-level applications without compromising environmental safety. The reduced dependency on fossil-based chemicals and the lowered energy requirements further enhance the environmental and economic viability of this process.

Looking toward the **future prospects**, this research opens up several avenues for extending the applicability of green-synthesized TiO_2 nanoparticles. One promising direction is the treatment of complex industrial effluents containing mixtures of dyes, heavy metals, and pharmaceutical residues. Given the proven efficacy of TiO_2 in degrading organic pollutants, its implementation in large-scale wastewater treatment systems could significantly reduce environmental contamination and health hazards. Additionally, research can be expanded to modify TiO_2 nanoparticles through **doping with transition metals** or non-metals to extend their photocatalytic activity into the visible light spectrum, thereby enhancing performance under natural sunlight. Such advancements could transform green-synthesized TiO_2 into a versatile and sustainable photocatalyst for real-world environmental challenges.

5. Recommendations

To further advance the potential of green-synthesized TiO_2 nanoparticles and enhance their applicability in environmental remediation, several **recommendations** are proposed for future research:

Table 3. Recommended future research directions for enhancing the performance and applicability of green-synthesized TiO_2 nanoparticles in environmental remediation.

Aspect	Suggested Work
Material Enhancement	Explore **doping of TiO_2 with metals such as zinc (Zn), iron (Fe), or copper (Cu)** to improve visible-light absorption and enhance photocatalytic efficiency under natural sunlight conditions. Doping can narrow the band gap of TiO_2, reduce electron–hole recombination, and enable effective degradation of pollutants using solar energy rather than artificial UV sources.
Process Optimization	Investigate **catalyst recycling and reusability** to evaluate long-term stability and performance. Assessing photocatalyst regeneration after multiple cycles will determine the material's economic and environmental feasibility for industrial applications. Studies focusing on surface reactivation and anti-fouling properties can also improve durability and cost-effectiveness.
Real Sample Testing	Apply the synthesized nanoparticles to **real industrial wastewater samples**, particularly from textile and pharmaceutical industries. These effluents often contain complex mixtures of dyes, antibiotics, and organic compounds that are difficult to degrade. Real-world testing will validate the practical efficiency of TiO_2 nanoparticles beyond controlled laboratory conditions.

The recommendation to explore **metal-doped TiO_2 systems** aligns with the ongoing need to develop photocatalysts responsive to the full solar spectrum, thereby maximizing energy efficiency. Transition metal ions such as Fe^{3+} or Cu^{2+} can create impurity energy levels within the TiO_2 band gap, facilitating photon absorption in the visible region. Similarly, non-metal dopants (e.g., nitrogen or sulfur) can modify surface states and enhance photocatalytic kinetics. Combining green synthesis with such modifications would result in environmentally benign yet highly efficient catalysts for pollutant removal.

In terms of **process optimization**, a crucial area of study is the recyclability of TiO_2 nanoparticles. Many photocatalysts lose efficiency after repeated use due to surface fouling or agglomeration. Developing regeneration strategies such as thermal or chemical reactivation—can ensure consistent performance over multiple cycles. This would significantly improve the feasibility of using green-synthesized TiO_2 in continuous wastewater treatment systems, reducing operational costs and material waste.

Testing with **real wastewater** is essential to bridge the gap between laboratory research and industrial application. Wastewaters from textile and pharmaceutical industries often contain recalcitrant organic compounds that resist conventional treatment methods. Applying TiO_2 nanoparticles to such effluents will provide critical insights into catalyst selectivity, degradation pathways, and the impact of competing ions or organic loads. The data generated from these studies will contribute to the development of scalable photocatalytic systems capable of meeting environmental regulations and sustainability targets.

In summary, this study successfully establishes a **green, cost-effective, and sustainable route for synthesizing TiO_2 nanoparticles** using Moringa oleifera extract. The synthesized nanoparticles demonstrated excellent photocatalytic performance, high crystallinity, and morphological uniformity, making them promising candidates for environmental purification applications. The integration of green chemistry with nanotechnology not only mitigates environmental pollution but also supports the global transition toward sustainable industrial practices. With further material optimization, process enhancement, and real-world validation, green-synthesized TiO_2 nanoparticles hold immense potential as a cornerstone material in the advancement of sustainable environmental technologies

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