

A Case Study on Ag/Co Co-Doped TiO₂ Nanoparticles: Green Synthesis, Doping Mechanisms, Photocatalysis, and Antibacterial Activity for Industrial Wastewater Remediation

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Abstract

The increasing threat of environmental pollution and microbial contamination has intensified research on multifunctional photocatalysis, particularly titanium dioxide (TiO₂), due to its stability, abundance, and oxidative potential. Although it has a wide band gap, rapid charge recombination limits visible-light activity. Recent advancements in green-synthesized doped TiO₂ nanostructures offer sustainable solutions by integrating plant-mediated synthesis and dopant engineering. This case study systematically examines the photocatalytic and antibacterial activities of green-synthesized Ag-Co-codoped TiO₂ NPs, emphasizing the combined roles of silver's plasmonic activity and cobalt's band-gap modulation. Individual Ag and Co doping studies show significant band-gap narrowing, from 3.3 eV to as low as 2.4 eV. Dye degradation efficiencies up to 97% under UV-light, attributed to enhanced charge separation and oxygen vacancy generation. Although direct Ag-Co co-doping reports remain limited, insights from similar co-doped systems (e.g., Ag-Cu, Co-Sr) demonstrate potential for improved charge carrier mobility and dual functionality in photocatalysis and antibacterial applications. The case study further discusses green synthesis parameters, structural and optical characterization, and environmental applications such as water purification and antimicrobial coatings. Finally, it highlights challenges in scalability and biosafety, urging future research toward mechanism-guided design and computational modelling of eco-friendly co-doped TiO₂ NPs for sustainable environmental remediation.

Keywords

Green Synthesis, Ag-Co co-doping, photocatalysis, dye degradation, antibacterial activity, waste water remediation.

1. Introduction

Titanium dioxide (TiO₂) is a cornerstone photocatalyst for environmental remediation and antimicrobial surface because of its chemical stability, low cost, abundance, and proven safety profile. Although these advantages exist, its application is hindered by two key challenges: it has a large band gap (anatase: 3.2 eV, almost), allowing it to absorb only solar UV light, and it rapidly loses holes and electrons, thereby becoming less active (Rahmawati et al., 2023). Addressing these challenges is critical for delivering solar-powered photocatalysis, excellent antibacterial activity, and durable self-cleaning surfaces for practical applications.

Green (bio-inspired) synthesis provides an eco-compatible approach to the preparation of TiO₂ NPs with controlled shape, surface chemistry, and defects by using plant extracts, microbes, or biomolecules as reducers, as well as cap agents (Kamble et al., 2022). By far, most such procedures give anatase-rich high-surface-area particles with functional groups aiding pollutant adsorption or aiding contact with bacteria, and low crystal sizes to boost charge separation at surfaces, all without the use of toxic chemicals or high-energy processing. Standardization of the extract preparation itself and post-synthesis heat treatment, however, is required for reproducible physicochemical properties (Mugundan et al., 2015; Uthiravel et al., 2024a).

Dopant engineering effectively extends TiO₂ activity into the visible region and manages charge carriers. Silver (Ag) offers two main advantages: (1) plasmonic sensitization via localized surface plasmon resonance (LSPR) for improved visible-light harvesting, and (2) Schottky junctions at Ag/TiO₂ interfaces that act as electron sinks, reducing recombination and enhancing photocatalytic degradation and antibacterial effects through ROS generation and Ag⁺ release. In contrast, cobalt (Co) adds 3d electronic states and promotes oxygen-vacancy formation, which narrows the band gap and facilitates mid-gap optimal transitions; when managed properly, Co-induced defects improve visible-light response without dominating recombination (Kamble et al., 2022; Njema & Kibet, 2024).

Co-doping TiO₂ with Ag and Co combine plasmonic absorption and electron trapping from Ag with Co's influence on defect chemistry and electronic states. This synergy aims to (i) extend light absorption into the visible range, (ii) offer multi-scale charge separation (surface Schottky trapping + bulk transport), and (iii) enable dual antibacterial effects (photocatalytic ROS + Ag ion toxicity). Early studies on related systems support these ideas, but green-synthesised Ag-Co co-doped TiO₂ is still underexplored (Rahmawati et al., 2023; Thakur et al., 2023; Uthiravel et al., 2024b).

Practical challenges for research and application include: (1) dopant state control; Co's multiple oxidation states and Ag's sintering/leaching; (2) phase stability; high-temperature calcination can cause anatase to rutile transformation and dopant segregation; (3) over-doping; excessive dopants create traps that lower photocatalytic activity, and (4) reproducibility; phytochemical variability affects nucleation and dopant incorporation (Uthiravel et al., 2024b). Strategies to mitigate these issues involve low-temperature bio-assisted synthesis or hydrothermal crystallisation to limit grain growth, atmosphere-programmed annealing for Co and Ag stabilization, optimised low-percentage dopants, and rigorous extract standardization (total phenolics/flavonoids characterization) (Kasithevar et al., 2017; Mugundan et al., 2015). Long-term stability should be assessed through leaching tests, recyclability trials, and spectroscopies to monitor distribution.

This review integrates green synthesis principles, morphology-defect-electronic structure relationships, and the roles of Ag and Co to create an experimental roadmap. By combining sustainable synthesis with dopant engineering and performance metrics, Ag-Co co-doped TiO₂ can evolve into a reproducible, high-performance material for visible-light photocatalysis, antibacterial surfaces, and self-cleaning technologies (Saeed et al., 2019; Uthiravel et al., 2024a).

2. Literature Review

The pursuit of sustainable and eco-friendly nanomaterial synthesis has drawn significant attention in recent years, and green synthesis has emerged as a promising route for fabricating functional photocatalysts (Rao et al., n.d.). Unlike conventional chemical methods, which often involve toxic solvents and harsh conditions, green synthesis utilises plant extracts rich in natural reducing and stabilizing agents, such as polyphenols, terpenoids, and flavonoids. These biomolecules facilitate the nucleation and growth of nanoparticles under mild conditions, enabling better control over surface chemistry while minimizing environmental impact (Kasithevar et al., 2017; Rao et al., n.d.). Within this framework, TiO₂ is widely used for its photocatalytic activity, chemical stability, and non-toxicity, but its wide band gap (3.2 eV) restricts activity mainly to the UV region (Kamble et al., 2022). To overcome this limitation, doping strategies are commonly employed. Noble metal doping with Ag can introduce surface plasmon resonance (SPR) effects that enhance visible-light absorption, while transition metal doping with Co can create defect states within the band gap, improving charge separation and reducing electron-hole recombination (Njema & Kibet, 2024; Uthiravel et al., 2024a).

Combining these two effects through Ag-Co co-doping is anticipated to yield synergistic benefits, simultaneously boosting visible-light harvesting and charge-carried dynamics. Before introducing the novel Ag-Co co-doping, it is

essential to understand the individual impacts of Ag doping, Co doping, and other reported co-doped TiO₂ systems synthesized via green routes (Table 1- Table 3).

Table 1. Silver-doped TiO₂ NPs and Photocatalytic Application

Dopant Metal in Titania	Plant Source	Band Gap/Optical Shifting	Functional Performance (MB dye degradation under UV light)	References
Ag	Lemongrass	3.3 eV to 0.9 eV	96.96%	(Uthiravel et al., 2024a)
Ag	Neem Leaf	3.2 eV to 2.6 eV	90%	(Saeed et al., 2019)
Ag	<i>Caesalpinia pulcherrima</i>	3.2 eV to 2.48 eV	94%	(Rathi et al., 2023)
Ag	Rambutan Peel	-	81.6%	(Kumar et al., 2016)
Ag	Turmeric extract	-	80%	(Rahmawati et al., 2023)

Table 2. Cobalt-doped TiO₂ NPs and Photocatalytic Application

Dopant Metal in Titania	Plant Source	Band Gap/Optical Shifting	Functional Performance (MB dye degradation under UV light)	References
Co	<i>Tinospora cordifolia</i>	3.54 eV for anatase and 3.47 eV for rutile	100% for anatase and 97% for rutile (MB dye degradation under UV light)	(Thakur et al., 2023)
Co	- (sol-gel method)	3.58 eV to 3.93 eV (4% to 16% doping)	-	(Mugundan et al., 2015)
Co	- (Hydrothermal method)	2.95 eV (1.61% doping)	82% removal of MG via COD analysis under sunlight	(Kamble et al., 2022)

Table 3. Co-Doping in TiO₂ with metallic/non-metallic dopants

Co-Dopant Metal in Titania	Plant Source	Band Gap/Optical Shifting	Functional Performance (MB dye degradation under UV light)	References
Ca+Sr	Croton macrostachyus leaves	3.21 eV to 2.31 eV (9% Ca+Sr)	96.62% MB degradation under visible light	(Tasisa et al., 2025)
N + Zr	- (aqueous sol-gel process)	-	-	(Benkhenouche-Bouchene et al., 2021)
Ag + Cu	Mulberry plant	-	98.55% MB dye degradation under sunlight	(Mali et al., 2025)

3. Fundamentals of Green Synthesis of Ag/Co-TiO₂ Nanoparticles

3.1 Principles of Green Synthesis

Green or biogenic synthesis of NPs harnesses biological materials, such as plant extracts, microbial metabolites, or biopolymers, as both reducing and capping agents. Plants rich in phenolics, flavonoids, and terpenoids can simultaneously reduce metal ions (e.g., Ag⁺, Co²⁺, Ti⁴⁺) and stabilize nascent nanoparticles by capping their surfaces, thereby controlling growth and preventing excessive aggregation (Rahman et al., 2022). For example, the review on plant-extract mediated metal and metal oxide nanoparticle synthesis emphasizes how green-synthesized TiO₂ exhibits enhanced antibacterial behavior under visible light, owing to clean surfaces and minimal chemical residues (Sofia et al., 2025).

When applied to the co-doping of TiO₂ with silver (Ag) and cobalt (Co), the green route offers distinct advantages:

- The phytochemical environment promotes uniform nucleation of TiO₂ and incorporation of dopant ions, reducing the formation of undesirable secondary phases (Rahman et al., 2022).
- Surface biomolecule capping stabilizes the NPs, limiting growth to nanoscale size and thus increasing active surface area, a key for photocatalysis and antibacterial activity.
- The combination of Ag and Co in a green-synthesized TiO₂ matrix is relatively underexplored; while single dopant Ag-TiO₂ or Co-TiO₂ have been reported, systematic green fabrication of Ag-Co co-doped TiO₂ is limited, offering a novel synthesis pathway with dual functional benefits (visible-light photocatalysis + enhanced antibacterial action). Additionally, green synthesis provides an eco-friendly, cost-effective route that aligns with the goals of sustainable nanomaterials for environmental remediation.

3.2 Parameters Affecting Green Synthesis

The successful fabrication of Ag-Co co-doped TiO₂ nanoparticles by green means critically depends on synthesis parameters, including pH, temperature, precursor and extract concentration, dopant loading, and reaction time, and each parameter has a direct effect on nanoparticle size, morphology, crystallinity, and dopant incorporation.

- **pH of reaction medium:** It influences hydrolysis/condensation of the titanium precursors, speciation of Ag⁺ and Co²⁺ ions, and the ion-binding behavior of phytochemicals (Liu et al., 2013). Alkaline pH often promotes faster reduction and smaller particles, but overly high pH may trigger rapid agglomeration or precipitation without dopant integration.
- **Temperature:** Elevated temperatures enhance reduction kinetics and crystallization of TiO₂ (anatase form), but may degrade the organic capping agents, reduce dopant uniformity, and promote dopant clustering or separate oxide phases (Kaveh & Alizadeh, 2025). In green routes, moderate hydrothermal or solvothermal temperatures (e.g., 80-150 °C) tend to strike a balance.

- **Concentrations (precursors, extract, dopants):** The Ti precursor to plant-extract ratio determines nucleation versus growth regime; the molar ratio of Ti: Ag: Co determines dopant loading. Excessive dopant can lead to segregated Ag or Co oxide phases rather than substitutional or interstitial doping (Görgülüer et al., 2021). Studies of other co-doped TiO₂ (Ca/Sr co-doped) indicate that optimum loading gives marked band-gap reduction and high visible light absorption.
- **Reaction time:** Longer durations allow better crystallinity, dopant diffusion, and removal of residual organics, yet extended time may cause growth of larger particles and reduce specific surface area.

3.3 Doping Mechanisms

TiO₂ is a wide-bandgap semiconductor (3.0-3.2 eV) that crystallizes mainly in anatase, rutile, and brookite phases, with anatase being the most photoactive due to its higher surface energy and reduced charge recombination. However, its UV-only activity (<4-5% of the solar spectrum) limits its efficiency in solar-driven applications, necessitating band structure engineering via doping (Ding et al., 2012; Rifat et al., 2025). Dopants can enter the lattice through:

- **Substitutional Doping:** Doping ions (e.g., Co²⁺) replace Ti⁴⁺ or O²⁻, introducing impurity states within the bandgap (Ding et al., 2012).
- **Interstitial Doping:** Dopants occupy vacant sites, often generating oxygen vacancies that enhance conductivity and light absorption, though excess vacancies act as recombination centers (Mali et al., 2025).

Co introduces mid-gap states via its mixed valence (Co²⁺/Co³⁺), effectively narrowing the bandgap and improving charge transfer (Naveenkumar et al., 2024). Ag NPs can resonate with the visible light through localized surface plasmon resonance (LSPR), creating “hot electrons” that transfer to TiO₂ and extend its response into the visible region. Also, Ag acts like an electron trap, reducing recombination and keeping charges available for reactions longer. Ag-Co co-doping can provide a better balance of charge separation and visible-light absorption than either dopant alone (Saeed et al., 2019). Some studies also suggest that co-doping stabilizes the crystal structure and prevents the crystal structure and prevents excessive formation of oxygen vacancies (Benkhenouche-Bouchene et al., 2021; Elbasiony et al., 2024; Naveenkumar et al., 2024).

3.4 Characterisation Techniques

(Ag/Co co-doping induces extremely great changes in TiO₂ through the introduction of defect states, oxygen vacancies, and localized surface plasmon resonance (LSPR) effects. Cobalt lowers the bandgap and creates oxygen vacancies that enhance visible-light absorption, and silver nanoparticles are electron sinks and plasmonic enhancers that inhibit charge recombination. The overall effect is a multifunctional photocatalyst with improved photocatalytic, antimicrobial, and energy-related activity (Mali et al., 2025).

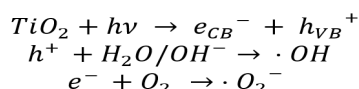
- **Structural & Morphological Analysis:** SEM analysis provides detailed insights into the surface morphology and particle size, shape, and dispersion of the synthesized nanoparticles (Rifat et al., 2025). EDS mapping confirms the presence of Ag, Co, Ti, and O (and possibly trace phytochemical elements), their elemental composition, verifying successful doping and overall material purity (Rifat et al., 2025). XRD identifies the TiO₂ polymorph (anatase, rutile), estimates crystallite size (via Scherrer equation), and reveals lattice shifts or peak broadening due to dopant substitution or strain. Dopants such as Co or Ag can cause small peak shifts or increased strain broadening, signifying lattice distortion and defect introduction. It shows mixed-phase TiO₂ (major anatase with rutile trace), impurities of silver oxide (Ag₂O/AgO). The crystallite sizes 40-64 nm depend on the calculation method (Scherrer, Williamson-Hall). Co and Ag addition introduces lattice distortion, tensile strain (0.000927), and increased dislocation density (0.00065 nm⁻²). SEM/TEM show 10-22 nm main particles agglomerated (up to 60 nm), porosity providing extra active sites. Ag nanoparticles are seen as dark, homogeneously dispersed spots, improving interfacial contact (Benkhenouche-Bouchene et al., 2021; Rifat et al., 2025).
- **Surface Composition & Chemistry:** FTIR confirms Ti-O, Ag-O, Co-O, -NH, -OH, -CO hydroxyl groups, and phytochemical residues. EDS/SEM mapping confirms that Ti, O, Co, and Ag are evenly distributed. Co

exists in mixed valence ($\text{Co}^{2+}/\text{Co}^{3+}$) form, and Ag in Ag^0 and Ag^+ form (Saeed et al., 2019). Electron donation by Ag to TiO_2 and Co doping enhances oxygen vacancies, which enhance reactivity.

- Optical and Electronic Properties:** UV-Vis DRS shows red-shift with a strong Ag LSPR peak. Bandgap is lowered to 2.90 eV (from 3.2 eV in pure TiO_2). PL spectra show emission suppression, indicating less electron-hole recombination. Peaks at visible ranges reflect oxygen vacancies and Ti^{3+} states. DFT confirms co-doping introduces mid-gap states, improving visible-light absorption (Mali et al., 2025; Rifat et al., 2025).

4. Photocatalytic Activities

Photocatalysis in TiO_2 begins when light energy equal to or greater than the band gap excites electrons (e^-) from the valence band (VB) to the conduction band (CB), generating holes (h^+) in the VB. The fundamental redox reactions can be summarized as:



Ag/Co- TiO_2 NPs have gained a lot of attention as photocatalysts, overcoming the limitations of standard TiO_2 . Pure TiO_2 is stable and non-toxic, but its wide bandgap (about 3.2 eV) restricts activation to UV light, which makes up only about 4% of solar energy. Cobalt doping adds mid-gap states that allow for visible-light absorption. Ag NPs improve plasmonic effects and act as electron sinks, which together increase efficiency (Benkhenouche-Bouchene et al., 2021).

Cobalt incorporation creates impurity levels (Figure 1). This narrows the bandgap and reduces electron-hole recombination through defect states and surface trapping. Ag also helps charge transfer by creating Schottky barriers while keeping the anatase structure stable at low loadings for better performance. The generation of reactive oxygen species ($\cdot\text{OH}$, $\text{O}_2\cdot^-$) allows for the breakdown of dyes, pharmaceuticals, and pesticides (Kamble et al., 2022; Rahmawati et al., 2023; Uthiravel et al., 2024a).

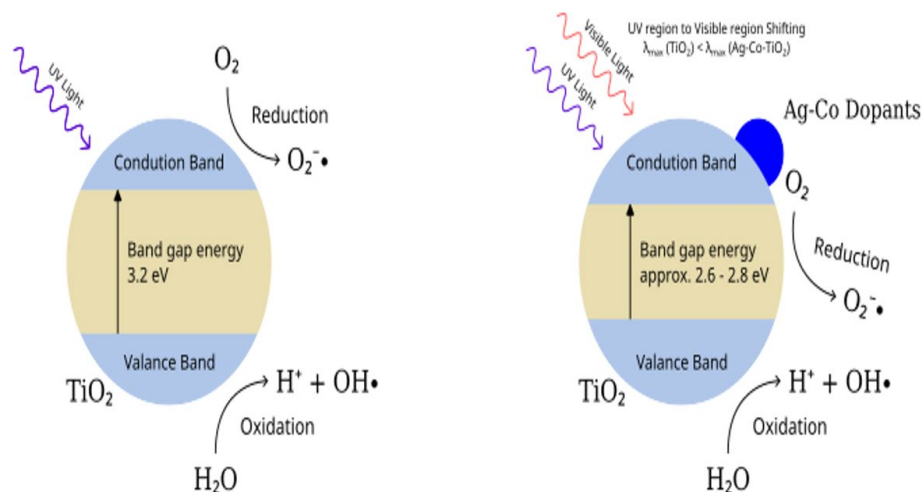


Figure 1. Photocatalytic mechanism of Ag-Co co-doping on TiO_2 (Naveenkumar et al., 2024)

5. Antimicrobial Applications

The antibacterial properties of TiO_2 -based NPs stem mainly from two combined routes: photocatalytic ROS generation and metal-ion-induced cell damage. Under light irradiation, TiO_2 generates ROS such as hydroxyl radicals ($\text{OH}\cdot$), superoxide ($\text{O}_2\cdot^-$), and hydrogen peroxide (H_2O_2), which oxidatively damage bacterial cell walls, lipids, and DNA, leading to loss of membrane integrity and cell death (Rahman et al., 2022).

A properly green-fabricated Ag/Co-TiO₂ could deliver antibacterial dual-function with improved stability and lower chemical footprint. Photocatalytic formation of membrane and DNA-damaging reactive oxygen species (\bullet OH and O₂ \bullet^-) and non-illuminated Co/Ag ions antagonizing microbes (Rahman et al., 2022). The improvement of the bandgap photoelectric effect is effective under visible light and overcomes the limitation of TiO₂, which relies on UV light alone. Although direct reports of green-synthesized Ag-Co-TiO₂ are still limited, analogies from other co-dopant systems (e.g., Ag/Zr-TiO₂ achieving a band gap of 2.66 eV and 93% MB degradation) show how combined engineering works (Mugundan et al., 2015; Uthiravel et al., 2024a).

Ag/Co-TiO₂ could also show activity against both Gram Positive (*S. aureus*) and Gram Negative (*E. coli* and *P. aeruginosa*) bacteria, as well as the pathogen *L. monocytogenes*. The Ag ion effect is enhanced by the synergistic effect of darkness. Also, in medicine, it could be effective in reducing the incidence of nosocomial infection through medical coatings, while in water treatment, it could provide safety. As an example of a biocompatible wound dressing, it is effective as an implantable biomedical device.

6. Future Outlook and Challenges

Ag/Co co-doping could enhance TiO₂, combining Ag's plasmonic electron generation and trapping with Co's bandgap narrowing, enabling efficient visible-light photocatalysis. However, challenges remain, including dopant segregation, formation of secondary phases, and long-term stability under operational conditions (Rifat et al., 2025). Also critical concern involves the toxicity and biosafety of metal-doped nanoparticles. The mechanistic understanding of co-doped TiO₂ remains incomplete. Few studies have systematically correlated dopant distribution, defect chemistry, and charge-carrier dynamics with observed photocatalytic or antibacterial performance. Future research should focus on controlled synthesis for uniform dopant distribution, optimization of doping levels to avoid recombination centres, and scalable green synthesis approaches to ensure environmental compatibility and reproducibility (Rao et al., n.d.).

7. Conclusion

Green synthesis of doped TiO₂ NPs provides an eco-friendly pathway to engineer with tunable optical and antibacterial properties. These reviewed studies confirm that Ag and Co dopants individually enhance TiO₂ performance, Ag through plasmonic charge trapping and Co through bandgap narrowing and oxygen vacancy creation. When integrated via green routes, their synergistic effects are expected to yield visible-light-active photocatalysis with high degradation efficiency, stability, and antibacterial potency. Beyond demonstrating superior activity in model dye degradation and microbial inactivation, such materials align with global trends toward sustainable and non-toxic nanotechnology. The coupling of green synthesis and co-doping strategies thus represents a promising frontier for developing next-generation TiO₂-based materials for environmental purification and biomedical protection.

References

- A. M. Elbasiony, A. A. Alamri, U. A. Soliman, H. G. Mohamedbagr, A. M. Wahba, and E. T. Helmy, "Green synthesis of N, B co-doped TiO₂ nanoparticles with enhanced photocatalytic and antioxidant activities," *J Taiwan Inst Chem Eng*, p. 105626, 2024, doi: 10.1016/J.JTICE.2024.105626.
- A. Rahman, M. A. Chowdhury, and N. Hossain, "Green synthesis of hybrid nanoparticles for biomedical applications: A review," 2022, *Elsevier B.V.* doi: 10.1016/j.apsadv.2022.100296.
- B. Kumar, K. Smita, Y. Angulo, and L. Cumbal, "Valorization of rambutan peel for the synthesis of silver-doped titanium dioxide (Ag/TiO₂) nanoparticles," *Green Processing and Synthesis*, vol. 5, no. 4, pp. 371–377, 2016, doi: 10.1515/GPS-2016-0003/MACHINEREADABLECITATION/RIS.
- D. G. Mali, S. P. Patil, G. H. Sonawane, B. S. Bhadane, and V. K. Mahajan, "Synthesis of TiO₂ and Ag/Cu doped TiO₂ nanoparticles in green approach and assess their structural, morphological, and photocatalytic applications," *Hybrid Advances*, vol. 10, p. 100468, 2025, doi: 10.1016/J.HYBADV.2025.100468.
- G. G. Njema and J. K. Kibet, "A review of novel materials for nano-photocatalytic and optoelectronic applications: Recent perspectives, water splitting and environmental remediation," *Progress in Engineering Science*, vol. 1, no. 4, p. 100018, 2024, doi: 10.1016/J.PES.2024.100018.
- G. Sofia, C. Koventhan, S. Kanmani, and A. Y. Lo, "Green synthesized rGO/TiO₂/g-C₃N₄ nanocomposites via *Plectranthus amboinicus* extract for efficient photocatalytic degradation of methylene blue: RSM optimization, antimicrobial and phytotoxicity assessment," *J Environ Chem Eng*, vol. 13, no. 1, 2025, doi: 10.1016/j.jece.2024.115267.

- H. Benkhenouche-Bouchene *et al.*, “Green Synthesis of N/Zr Co-Doped TiO₂ for Photocatalytic Degradation of p-Nitrophenol in Wastewater,” *Catalysts* 2021, Vol. 11, Page 235, vol. 11, no. 2, p. 235, 2021, doi: 10.3390/CATAL11020235.
- H. Görgülüer, B. Çakıroğlu, and M. Özacar, “Ag NPs deposited TiO₂ coating material for superhydrophobic, antimicrobial and self-cleaning surface fabrication on fabric,” *J Coat Technol Res*, vol. 18, no. 2, pp. 569–579, 2021, doi: 10.1007/S11998-020-00412-6.
- K. M. R. Rifat, M. R. Islam, M. F. Jakib, and S. M. N. Rokon, “Sphagneticola Trilobata leaves derived TiO₂ nanoparticles: Green synthesis, characterization and photocatalytic efficiency,” *AIP Conf Proc*, vol. 3307, no. 1, 2025, doi: 10.1063/5.0262505.
- K. Rao, C. Ashok, K. Rao, ... C. C.-P. of the, and undefined 2014, “Green synthesis of TiO₂ nanoparticles using hibiscus flower extract,” *researchgate.net* KG Rao, CH Ashok, KV Rao, CS Chakra, V Rajendar *Proceedings of the International Conference on Emerging Technologies, 2014* researchgate.net, Accessed: Jun. 24, 2025. [Online]. Available: https://www.researchgate.net/profile/Dr-Chinthakuntla/publication/303445315_Green_Synthesis_of_TiO_2_Nanoparticles_Using_Hibiscus_Flower_Extract/links/5743284508ae9ace841a94ad/Green-Synthesis-of-TiO-2-Nanoparticles-Using-Hibiscus-Flower-Extract.pdf
- M. Kasithevar *et al.*, “Green synthesis of silver nanoparticles using Alysicarpus monilifer leaf extract and its antibacterial activity against MRSA and CoNS isolates in HIV patients,” *J Interdiscip Nanomed*, vol. 2, no. 2, pp. 131–141, 2017, doi: 10.1002/JIN2.26.
- M. Saeed *et al.*, “Azadirachta indica leaves extract assisted green synthesis of Ag-TiO₂ for degradation of Methylene blue and Rhodamine B dyes in aqueous medium,” *Green Processing and Synthesis*, vol. 8, no. 1, pp. 659–666, 2019, doi: 10.1515/GPS-2019-0036/MACHINEREREADABLECITATION/RIS.
- N. Thakur, N. Thakur, K. Kumar, and A. Kumar, “Tinospora cordifolia mediated eco-friendly synthesis of Cobalt doped TiO₂ NPs for degradation of organic methylene blue dye,” *Mater Today Proc*, 2023, doi: 10.1016/J.MATPR.2023.01.253.
- R. J. Kamble, P. V. Gaikwad, K. M. Garadkar, S. R. Sabale, V. R. Puri, and S. S. Mahajan, “Photocatalytic degradation of malachite green using hydrothermally synthesized cobalt-doped TiO₂ nanoparticles,” *Journal of the Iranian Chemical Society*, vol. 19, no. 1, pp. 303–312, 2022, doi: 10.1007/S13738-021-02303-Y/METRICS.
- R. Kaveh and Z. Alizadeh, “Fabrication and characterization of a transparent, hydrophilic, and self-cleaning polyurethane coating on glass with a silica buffer layer and Ag₃PO₄/TiO₂ nanocomposite,” *Prog Org Coat*, vol. 207, 2025, doi: 10.1016/j.porgcoat.2025.109382.
- R. Naveenkumar, B. Karthikeyan, and S. Senthilvelan, “Facile Green Synthesis of Activated Biocarbon-Cobalt-Doped TiO₂ Nanocomposite for Enhanced Antibacterial Effect and Efficient Photocatalytic for Dye Degradation,” *Brazilian Journal of Physics*, vol. 54, no. 5, pp. 1–22, 2024, doi: 10.1007/S13538-024-01543-6/METRICS.
- R. Sharma, A. Sarkar, R. Jha, A. Kumar Sharma, and D. Sharma, “Sol-gel-mediated synthesis of TiO₂ nanocrystals: Structural, optical, and electrochemical properties,” *Int J Appl Ceram Technol*, vol. 17, no. 3, pp. 1400–1409, 2020, doi: 10.1111/IJAC.13439.
- S. Liu, H. Sun, S. Liu, and S. Wang, “Graphene facilitated visible light photodegradation of methylene blue over titanium dioxide photocatalysts,” *Chemical Engineering Journal*, vol. 214, pp. 298–303, 2013, doi: 10.1016/J.CEJ.2012.10.058.
- S. Mugundan, B. Rajamannan, G. Viruthagiri, N. Shanmugam, R. Gobi, and P. Praveen, “Synthesis and characterization of undoped and cobalt-doped TiO₂ nanoparticles via sol-gel technique,” *Applied Nanoscience (Switzerland)*, vol. 5, no. 4, pp. 449–456, 2015, doi: 10.1007/S13204-014-0337-Y/TABLES/3.
- T. Rahmawati *et al.*, “Green synthesis of Ag-TiO₂ nanoparticles using turmeric extract and its enhanced photocatalytic activity under visible light,” *Colloids Surf A Physicochem Eng Asp*, vol. 665, p. 131206, 2023, doi: 10.1016/J.COLSURFA.2023.131206.
- V. H. Rathi, A. R. Jeice, and K. Jayakumar, “Green synthesis of Ag/CuO and Ag/ TiO₂ nanoparticles for enhanced photocatalytic dye degradation, antibacterial, and antifungal properties,” *Applied Surface Science Advances*, vol. 18, p. 100476, 2023, doi: 10.1016/J.APSADV.2023.100476.
- V. Uthiravel, K. Narayanamurthi, V. Raja, S. Anandhabasker, and K. Kuppasamy, “Green synthesis and characterization of TiO₂ and Ag-doped TiO₂ nanoparticles for photocatalytic and antimicrobial applications,” *Inorg Chem Commun*, vol. 170, p. 113327, 2024, doi: 10.1016/J.INOCHE.2024.113327.
- V. Uthiravel, K. Narayanamurthi, V. Raja, S. Anandhabasker, and K. Kuppasamy, “Green synthesis and characterization of TiO₂ and Ag-doped TiO₂ nanoparticles for photocatalytic and antimicrobial applications,” *Inorg Chem Commun*, vol. 170, p. 113327, 2024, doi: 10.1016/J.INOCHE.2024.113327.
- Y. Ding, X. J. Xu, Z. H. Gan, R. Xiong, and H. L. Liu, “Extension of the Optical Absorption of TiO₂ Nanoparticles to Visible Light Region by Doping with Cobalt,” *Solid State Phenomena*, vol. 181–182, pp. 348–351, 2012, doi: 10.4028/WWW.SCIENTIFIC.NET/SSP.181-182.348.
- Y. E. Tasisa, M. Gunasekaran, and R. Krishnaraj, “Green synthesis of Ca/Sr co-doped TiO₂ nanoparticles: impact on morphology, band gap reduction, supercapacitor, and visible-light photocatalytic efficiency,” *Discover Applied Sciences*, vol. 7, no. 9, pp. 1–22, 2025, doi: 10.1007/S42452-025-06976-5/TABLES/3.