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Advances in TiO_2 nanoparticles for rhodamine B degradation

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Abstract

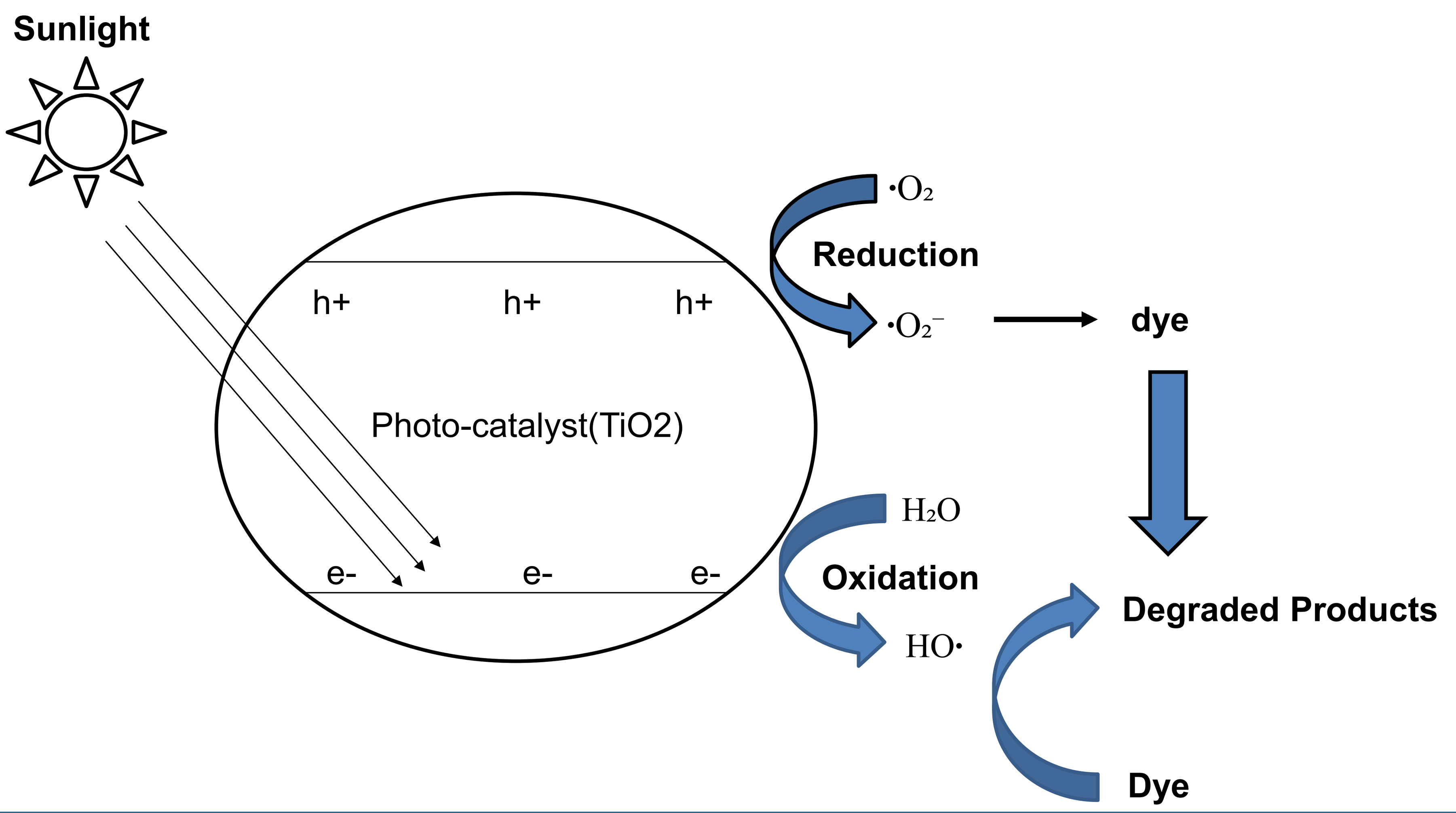
Titanium dioxide (TiO_2) nanoparticles have garnered significant attention as a photocatalyst for degrading organic pollutants, particularly synthetic dyes such as rhodamine B (RhB), methylene blue, methyl orange, and others. The impact of several synthesis methods, including sol–gel, hydrothermal, and CVD techniques, on the electrical and morphological properties of TiO_2 nanoparticles has been studied, emphasizing the distinctive physicochemical properties of TiO_2 nanoparticles, including their extensive surface area, significant oxidative capacity, and remarkable chemical stability, which are important in addressing recent advancements in their use for RhB degradation. A detailed examination of TiO_2's photocatalytic mechanism is based on the generation of reactive oxygen species (ROS) by photoinduced electron–hole pair formation under ultraviolet (UV) light exposure. In wastewater treatment, TiO_2 degrades RhB into less harmful byproducts by the generation of electron–hole pairs that initiate redox reactions under sunlight. This study includes a thorough overview of significant factors influencing photocatalytic efficacy. The parameters include particle size, crystal phase (anatase, rutile, and brookite), surface changes, and the incorporation of metal or non-metal dopants to enhance visible light absorption. Researchers continually seek methods to overcome challenges, including restricted visible light responsiveness and rapid electron–hole recombination. The investigated approaches include heterojunction generation, composite development, and co-catalyst insertion. The primary objective of this work is to address the deficiencies in our understanding of TiO_2-based photocatalysis for the degradation of RhB and to propose enhancements for these systems to enable more efficient and sustainable wastewater treatment in the future.

Introduction

Dye wastewater from industries is a significant source of water pollution because dyes are specifically designed to resist breakdown under light, water, and other environmental conditions, and many are carcinogenic or hazardous to human health. Several treatment techniques, including chemical oxidation ,electrochemical degradation, nanoscale zerovalent iron (NZVI) reduction, biodegradation, and adsorption on activated carbon, have been studied. However, each method has limitations such as high cost, secondary pollution, or low efficiency. Titanium dioxide (TiO_2) has emerged as an effective photocatalyst due to its low cost, non-toxicity, chemical stability, and high catalytic activity. Since the discovery of its photovoltaic properties, TiO_2 has been widely studied for environmental purification and photocatalytic degradation of organic pollutants including phenolic compounds, dyes, and other hazardous chemicals. Anatase, rutile, and brookite are the three crystalline phases of TiO_2, with anatase generally exhibiting the highest photocatalytic activity.The photocatalytic behavior is influenced by particle size, crystallinity, surface morphology, and preparation methods.

Mechanism

Excitation:
TiO_2 absorbs UV light; electrons (e^-) are promoted from the valence band (VB) to the conduction band (CB), leaving holes (h^+) in the VB.
Reactive Species Generation:
h^+ oxidizes H_2O → hydroxyl radicals (·OH).
e^- reduces O_2 → superoxide radicals ($O_2^{\cdot -}$).
Pollutant Attack:
·OH and $O_2^{\cdot -}$ attack Rhodamine B (RB), causing stepwise deethylation, ring opening, and formation of small intermediates.



Synthesis Methods

Sol-gel:easy, low cost, good for size control.
Hydrothermal:uniform, crystalline anatase at low temperature.
CVD: precise but expensive

Key Factors Influencing Photocatalysis

1. Particle Size
Smaller particles → larger surface area → more active sites.
Quantum size effect changes band gap.
Optimum size often between **7–25 nm.**

2. Crystal Phase
Anatase: highest activity (band gap ~3.2 eV).
Rutile: stable, less active, useful in mixtures.
Brookite: less studied, difficult to synthesize.

3. Surface Properties
High surface area improves dye adsorption.
Surface modification/doping (C, N, S, Fe) extends activity into visible light.
Large surface area + high crystallinity → enhanced charge separation.

Challenges & Strategies

Challenges:
1.Fast electron-hole recombination
2.Poor visible light responsiveness

Strategies:
1.Doping with metals/non-metals
2.Forming heterojunctions
3.Using co-catalysts

Applications

1.Efficient degradation of dyes: Rhodamin B, Methalene Blue, Methyl Orange.
2.Potential in sustainable wastewater treatment.

CONCLUSION

The mineralization rates of total organic carbon disappearance were consistent with the RB5 decolorization kinetic trend, demonstrating the potential of TiO2 nanoparticles for photodegradation treatments in wastewater.TiO2 samples modified under different hydrothermal times exhibited variations in crystallite size, crystallinity, and surface defects, with TiO2-24 showing improved photocatalytic degradation under visible light due to the combined effects of size and oxygen vacancies. Furthermore, pure anatase TiO2 with an 8 nm crystallite size, synthesized hydrothermally, proved to be highly efficient in the rapid degradation of Rhodamine B under UV irradiation. Together, these findings highlight the importance of crystalline size, surface oxygen defects, and phase purity in optimizing TiO2-based photocatalysts for wastewater purification.

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