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Emerging Role of Calcium Oxide Nanoparticles in the Photocatalytic Breakdown of Organic Contaminants from Industrial Effluents

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Abstract: The aim of this study is to critically evaluate the potential of calcium oxide nanoparticles (CaO-NPs) as effective photocatalysts for the degradation of organic contaminants in industrial wastewater, by examining their synthesis methods, physicochemical characterization, photocatalytic performance, and comparative efficiency with other photocatalysts, while also highlighting current treatment approaches and regulatory considerations to support the development of sustainable wastewater remediation technologies. The increasing prevalence of organic contaminants in industrial wastewater poses severe ecological and health challenges, necessitating the development of effective and sustainable remediation technologies. Calcium oxide nanoparticles (CaO-NPs) have garnered significant attention due to their unique physicochemical properties, cost-effectiveness, and environmental compatibility. This review provides a detailed evaluation of CaO-NPs, focusing on synthesis techniques, characterization methods, and photocatalytic performance in degrading organic pollutants, including dyes, pharmaceuticals, pesticides, and petrochemical derivatives. The paper also compares CaO with other well-established photocatalysts and discusses the current treatment methods and regulatory frameworks governing industrial effluent management. The insights provided aim to support the advancement of CaO-NP-based technologies for enhanced wastewater treatment.

1. Introduction

Water is a critical resource for life and a key component in numerous industrial processes. However, rapid industrialization and agricultural expansion have significantly deteriorated water quality, primarily through the discharge of untreated or inadequately treated wastewater. Industrial wastewater often contains a complex matrix of organic and inorganic pollutants, many of which are persistent, toxic, and difficult to degrade using conventional methods (Akartasse *et al*., 2022; Sedlak, 2014; Owa, 2013; Khachani *et al*., 2014). Various industrial sectors, including chemical manufacturing, pharmaceuticals, textiles, food processing, and petrochemicals, are significant sources of organic contaminants in wastewater (Akartasse *et al*., 2022b). For instance, the chemical industry discharges a diverse range of solvents, aldehydes, ketones, and chlorinated hydrocarbons (Aaddouz *et al*., 2023; Wittcoff *et al*., 2012; Mellouki *et al*., 2015; Ozoemena *et al*., 2023).

These compounds are not only recalcitrant but also pose serious ecological and human health risks (Kong *et al*., 2019; Jungclaus, 1978). The pharmaceutical sector is particularly concerning due to the release of active pharmaceutical ingredients (APIs) that may persist in the environment, accumulate in aquatic organisms, and contribute to the development of antibiotic-resistant bacteria (Focazio *et* *al*., 2008; Dsikowitzky and Schwarzbauer, 2014; Kumar *et al*., 2022). Similarly, wastewater from the textile industry contains dyes like azo compounds, which are both mutagenic and resistant to biodegradation (Nayyar *et al*., 2021; Essien *et al*., 2024; Essien *et al*., 2022). In food processing and meat industries, high loads of fats, oils, proteins, sugars, and organic acids add to the complexity of treatment (Sabbahi *et al*., 2022; Asgharnejad *et al*., 2021). The petrochemical sector further complicates this scenario with hydrocarbon-rich effluents, including BTEX compounds (benzene, toluene, ethylbenzene, and xylene), which are highly toxic and environmentally persistent (Singh and Shikha, 2019; Ukoha *et al*., 2015).

Nanoparticles, typically ranging between 1–100 nm, possess unique size-dependent properties—physical, chemical, optical, electrical, and catalytic, that set them apart from bulk materials (Joudeh and Linke, 2022; Khan *et al*., 2022; Asha and Narain, 2020). Their high surface-area-to-volume ratio, tunable morphology, and enhanced reactivity make them versatile building blocks for advanced functional materials (Hwang *et al*., 2020; Caldwell *et al*., 2020). They serve as catalysts, carriers, sensors, and protective agents, effectively bridging the gap between fundamental nanoscience and practical applications (Sharma *et al*., 2015; Tao *et al*., 2024).

In medicine, nanoparticles are widely used in targeted drug delivery systems, diagnostic imaging, antimicrobial coatings, and cancer therapies such as photothermal and photodynamic treatments (Nasseri *et al*., 2022). In energy and environmental sectors, nanomaterials like TiO_2 and CaO enable photocatalytic wastewater treatment, while nanostructured electrodes enhance fuel cells, batteries, and supercapacitors (Ge *et al*., 2016; Thangadurai *et al*., 2019). Quantum dots improve solar energy conversion, and nanoadsorbents contribute to pollution control (Sahai *et al*., 2024). In electronics and ICT, nanoparticles are applied in nanoelectronics, semiconductors, transparent conductive films, high-density storage devices, and advanced sensors for gases, biomolecules, and environmental monitoring (Nazir *et al*., 2024; Fritea *et al*., 2021; Labiadh *et al*., 2016).

Agriculture benefits from nanoparticle-based fertilizers, controlled-release pesticides, biosensors for detecting pathogens, and food packaging with antimicrobial coatings (Singh *et al*., 2024; Sekhon, 2014). In materials and engineering, nanocomposites improve corrosion protection, durability, and mechanical strength of structures, while enabling self-cleaning coatings, wear-resistant lubricants, and lightweight construction materials (Singh *et al*., 2022). Consumer products also exploit nanoparticles in sunscreens (TiO_2, ZnO), skin-care formulations, and smart textiles with antibacterial and stain-resistant properties, underscoring their growing influence across industries (Zwanenberg, 2008).

Environmental consequences of untreated or poorly treated wastewater include oxygen depletion in aquatic ecosystems, bioaccumulation of toxins, groundwater contamination, and increased risks of diseases such as dermatitis, respiratory infections, and cancer (Zheng *et al*., 2013; Karri *et al*., 2021; Okoro *et al*., 2023). These challenges necessitate the development of advanced and efficient remediation technologies.

2. Relevance of Calcium Oxide Nanoparticles

Calcium, an essential biogenic element, plays a vital role in metabolic and physiological processes (Weaver and Peacock, 2011). Its oxide form, calcium oxide (CaO), exhibits exceptional antimicrobial properties and biocompatibility, making it suitable for various biomedical and environmental applications. CaO nanoparticles (CaO-NPs) exhibit enhanced physicochemical reactivity due to their nanoscale size (1–100 nm), high surface area, UV absorption ability, and tunable band gap, making them promising candidates for photocatalytic degradation of pollutants (Jayaraj *et al.*, 2024; Scholes, 2008).

Beyond their role in bone regeneration and antimicrobial polymer composites (Bae *et al.*, 2006; Silva *et al.*, 2020), CaO-NPs show high efficacy in degrading organic contaminants due to their alkaline nature, surface reactivity, and catalytic potential under UV or visible light. These properties are especially valuable in treating wastewater containing persistent organics such as dyes, pesticides, and pharmaceuticals.

3. Characterization Techniques for CaO Nanoparticles

Thorough characterization of CaO-NPs is vital for correlating structural features with photocatalytic performance. The techniques commonly employed are shown in Table 1.

Table 1. Techniques for CaO Nanoparticles

Technique	Purpose	Key Features
X-ray Diffraction (XRD)	Determines crystal structure and phase purity	Identifies lattice parameters and crystallinity (Roy *et al.*, 2013)
Transmission Electron Microscopy (TEM)	Visualizes particle size and morphology at the nanoscale	SAED can also assess crystallinity (Muller, 2009)
Scanning Electron Microscopy (SEM)	Examines surface topography and agglomeration behavior	Often used with EDX for compositional analysis (Zhou *et al.*, 2007)
Dynamic Light Scattering (DLS)	Measures hydrodynamic size and size distribution in suspension	Suitable for assessing colloidal stability (Hassan *et al.*, 2015)
BET Surface Area Analysis	Quantifies specific surface area and porosity	Crucial for adsorption and catalytic studies (Mohan *et al.*, 2020)
Fourier Transform Infrared Spectroscopy (FTIR)	Identifies surface functional groups and bonding	Useful for determining surface reactivity (Chen *et al.*, 2015)
X-ray Photoelectron Spectroscopy (XPS)	Assesses surface elemental composition and chemical states	Provides oxidation state data (Andrade, 1985)
Raman Spectroscopy	Detects molecular vibrations and chemical structure	Complements FTIR analysis (Lyon *et al.*, 1998)
Atomic Force Microscopy (AFM)	Analyzes surface roughness and mechanical properties	Offers 3D imaging at nanometer resolution (Salapaka & Salapaka, 2008)
Energy-Dispersive X-ray Spectroscopy (EDS/EDX)	Determines elemental composition	Often integrated with SEM/TEM (Mishra *et al.*, 2017)

4. Current Treatment Technologies

The treatment of industrial wastewater involves a range of technologies designed to remove, degrade, or neutralize contaminants before discharge or reuse. Existing treatment methods are generally classified into three main categories—physical, chemical, and biological processes—which are summarized in **Tables 2, 3, and 4**, respectively. Each category offers unique advantages and limitations depending on the type and concentration of pollutants present in the wastewater. Advanced methods for solid-liquid separation in water and wastewater treatment are summarized in **Table 5**.

Table 2. Physical Methods for Solid-Liquid Separation in Water and Wastewater Treatment

S/N	Method	Mechanism	Applications	Reference(s)
1	Screening	Physical barriers (screens) remove large debris and solids	(i) Removes sticks, plastics, etc. (ii) Protects downstream units	Metcalf & Eddy (2014); Spellman (2008)
2	Straining	Finer mesh than screening; removes smaller particles	Protects pumps and sensitive equipment	Asano *et al*. (2007)
3	Filtration	Water passes through porous media to trap solids	(i) Removes turbidity (ii) Prevents fouling (iii) Pre-treatment	Edzwald (2011); Tchobanoglous *et al*. (2014)
4	Granular Media Filtration	Uses sand/anthracite beds to filter particles	(i) Dual Media Filters (ii) Rapid sand filters	Rajasulochana and Preethy (2016)
5	Microscreening	Uses fine mesh screens for small particles	Post-biological treatment polishing	Wang *et al*. (2007)
6	Sedimentation	Gravity settles heavy suspended solids	(i) Primary settling (ii) Biomass separation	Metcalf & Eddy (2014)
7	Clarification	Combines sedimentation with coagulation/flocculation	(i) Raw water clarification (ii) Pre-filtration	Spellman (2008); Tchobanoglous *et al*. (2014)
8	Flotation	Air bubbles attach to particles and float them	(i) Removes FOG and metals (ii) Textile and petrochemical wastewater	Rajasulochana and Preethy (2016); Qu *et al*. (2013)
9	Centrifugation	Centrifugal force separates solids by density	(i) Sludge thickening (ii) Fine particle removal	Spellman (2008); Wang *et al*. (2005)
10	Magnetic Separation	Magnetic field removes magnetic materials	Removes Fe and other ferromagnetic pollutants	Wang *et al*. (2005)

Table 3. Chemical Methods for Solid-Liquid Separation in Water and Wastewater Treatment

S/N	Method	Mechanism	Applications	Reference(s)
1	Coagulation	Coagulants destabilize fine particles and colloids	Removes turbidity, NOM, and heavy metals	Edzwald (2011); Tchobanoglous *et al*. (2014)
2	Flocculation	Gentle mixing encourages floc growth	Improves sedimentation and turbidity removal	Metcalf & Eddy (2014); Binnie & Kimber (2013)
3	Chemical Precipitation	Forms insoluble compounds for removal	Removes Ca^{2+}, Mg^{2+}, phosphates, and metals	Spellman (2008); Wang *et al*. (2005)
4	Disinfection	Chemicals like chlorine or ozone kill pathogens	Ensures safe drinking/recreational water	Lazarova *et al*. (1999)
5	pH Adjustment	Controls pH using acids/bases	Enhances coagulant performance, corrosion control	Tchobanoglous *et al*. (2014)
6	Oxidation and Reduction	Redox reactions neutralize contaminants	Removes Fe, Mn, color, odor, and organics	Qu *et al*. (2013); Ray *et al*. (2016)
7	Ion Exchange	Resins swap undesirable ions	Removes hardness, nitrates, metals	Metcalf & Eddy (2014); Rajasulochana and Preethy (2016)

Table 4. Biological Methods for Solid-Liquid Separation in Water and Wastewater Treatment

S/N	Method	Mechanism	Applications	Reference(s)
1	Aerobic Treatment	Oxygen-driven microbial degradation	Reduces BOD, COD; used in municipal and industrial plants	Judd (2010); Tchobanoglous *et al.* (2014)
2	Anaerobic Treatment	Microbial degradation without oxygen; produces biogas	Treats high-strength wastewater and sludge	Wang *et al.* (2007); Metcalf & Eddy (2014)
3	Combined Systems	Uses both aerobic and anaerobic steps	Improves treatment range for complex wastes	Tchobanoglous *et al.* (2014)
4	Biofilm Processes	Microbial growth on surfaces enhances stability	High-rate treatment; suitable for retrofits	Spellman (2008); Judd (2010)
5	Constructed Wetlands	Mimics natural wetlands using vegetation and microbes	Decentralized systems; removes nutrients and solids	Rajasulochana and Preethy (2016); Tchobanoglous *et al.* (2014)
6	Composting & Vermicomposting	Aerobic decomposition; worms enhance process	Treats solid waste, sludge; creates compost	Wang *et al.* (2007); Spellman (2008)

Table 5. Advanced Methods for Solid-Liquid Separation in Water and Wastewater Treatment

S/N	Method	Mechanism	Applications	Reference(s)
1	Adsorption	Pollutants adhere to adsorbent surfaces	Removes organics, dyes, VOCs, heavy metals	Qu *et al.* (2013); Rajasulochana and Preethy (2016)
2	AOPs	Hydroxyl radicals oxidize pollutants	Treats pharmaceuticals, EDCs, dyes, pesticides	Qu *et al.* (2013); Ray *et al.* (2019)
3	Membrane Filtration	Semi-permeable membranes filter pollutants	Used for desalination, reuse, ultrapure water	Judd (2010); Ray *et al.* (2019)
4	AOP + Membrane	Combines degradation and filtration	Enhances micropollutant removal	Qu *et al.* (2013); Ray *et al.* (2016)
5	Membrane Bioreactors	Biological + membrane filtration	Produces reuse-quality water; decentralized use	Judd (2010); Tchobanoglous *et al.* (2014)
6	Adsorption + Bio	Adsorption enhances biological efficiency	Used for polishing and complex effluents	Rajasulochana and Preethy (2016); Spellman (2008)

The synthesis of CaO nanoparticles is a critical step that directly influences their morphology, crystallinity, particle size, and overall performance in specific applications. Various synthesis approaches are summarized in **Table 6.** The applications of calcium oxide (CaO) nanoparticles in the photocatalytic degradation of organic contaminants are summarized in **Table 7.** This table highlights the diverse range of organic pollutants that have been effectively degraded using CaO nanoparticles, including dyes, phenolic compounds, pharmaceutical residues, and industrial effluents.

Table 6. Synthesis Methods of CaO Nanoparticles

S/N	Method	Process	Advantages	Challenges	Reference(s)
1	Chemical Precipitation	Involves mixing calcium salts (e.g., $CaCl_2$ or $Ca(NO_3)_2$) with a precipitating agent (e.g., NaOH or NH_4OH). The precipitate is filtered, washed, dried, and calcined.	Simple, cost-effective, and scalable; allows control over particle size and purity through reaction condition adjustments.	Requires precise control of pH, temperature, and concentration to avoid agglomeration and ensure uniformity.	AbuKhadra *et al.* (2020);
2	Sol-Gel Method	Involves hydrolysis and condensation of metal alkoxides or salts to form a gel, then dried and calcined to yield CaO nanoparticles.	Excellent control over size, morphology, and purity; produces homogeneous nanoparticles.	Time-consuming; requires strict synthesis control; post-treatment may be needed.	Jayaraj *et al.* (2024); Zhang *et al.* (2021)
3	Hydrothermal Synthesis	Reactions occur in an autoclave under high T and P using calcium salts and a base in aqueous media.	Produces highly crystalline nanoparticles with good morphology control.	Requires specialized equipment and careful scale-up.	Wang *et al.* (2019); Zhang *et al.* (2013)
4	Microemulsion Method	Utilizes microemulsions (water/oil/surfactant) to create nanoreactors for controlled CaO NP formation.	Uniform, narrow particle distribution; precise size/morphology control.	Complex; expensive surfactants; requires stability optimization.	Inbaraj *et al.* (2019)
5	Co-precipitation	Simultaneous precipitation of calcium and oxide precursors; followed by separation, drying, and calcination.	Simple, economical; produces high-purity nanoparticles.	Susceptible to unwanted phases if stoichiometry/process is off.	Zhang *et al.* (2013)
6	Solid-State Synthesis	Involves grinding solid precursors (e.g., $CaCO_3$ or $Ca(OH)_2$), then calcining to decompose them to CaO.	Simple, low-cost, scalable using abundant raw materials.	May yield lower purity; control over size/morphology is limited.	Jayaraj *et al.* (2024)

Table 7. Applications of CaO Nanoparticles in Photocatalytic Degradation of Organic Contaminants

S/N	Contaminant Type	Specific Pollutant	Reference	Material/System	Synthesis Method	Key Findings	Model/Fit	Performance
1	Dyes	Methylene Blue (MB)	Eddy *et al.* (2023a)	CaO NPs from oyster shells	Sol-gel	Up to 98% degradation; degradation efficiency influenced by operational factors; quantum chemical analysis confirms chloride group interaction with Ca sites	Langmuir-Hinshelwood, First-order, Pseudo-first-order	98% removal
2	Dyes	Methylene Blue (MB)	Emara *et al.* (2020)	AC/CaO core-shell composite from *Ficus nitida* leaves + CaCO3	Chemical activation	1255.5 m^2/g total surface area; adsorption favorable, spontaneous, and exothermic	Freundlich, Pseudo-second-order	356 mg/g
3	Dyes	Methylene Blue (MB)	Obayomi *et al.* (2023)	GO@CaONPs-ES/DSAC, GO@CaONPs-FB/DSAC	Green synthesis using MES	Enhanced surface area; optimized via CCD; stable across reuse cycles	Pseudo-second-order	1274.5 mg/g (ES), 689.7 mg/g (FB)
4	Dyes	Rhodamine B	Vijayakumar *et al.* (2023)	CaO, CaTiO3, MgO, MgTiO3	Calcination and solution combustion	CaO and CaTiO3 achieved 63% and 72% degradation; MgO and MgTiO3 lower; mixed titanates 64.63%	Not specified	Up to 72% degradation
5	Dyes	Rhodamine B	Kornprobst & Plank (2012)	CaO and NiO-CaO catalysts	Calcination of hydroxides	CaO better under UV; NiO-CaO better under visible light; surface area not determinant	Nonconventional photocatalysis	Incomplete degradation
6	Dyes	Congo Red	Xia *et al.* (2013)	Nano-CaO vs commercial CaO	Not specified	Nano-CaO superior; 357.14 mg/g in 10 min vs 238.66 mg/g in 30 min; influenced by pH, salt, temp	Not specified	357.14 mg/g
7	Pharmaceuticals	Drug delivery (DOX/PTX)	Wu *et al.* (2014)	Alginate/CaCO3 hybrid NPs	Co-precipitation	Dual-drug delivery; <200 nm; improved tumor inhibition and cell uptake	Sustained release model	Effective on drug-resistant cells
8	Pharmaceuticals	Levofloxacin	AbuKhadra *et*	MgO/CaO	Hydrothermal	BET: 112.8 m^2/g; monolayer	Langmuir	106.7 mg/g

		(LVX)	*al.* (2020)	nanorods	with microwave	adsorption; physisorption; recyclable		
9	Pharmaceuticals	MB, Toluidine Blue	Sree *et al.* (2020)	CaO NPs from eggshells	Calcination	MB degraded in 15 min, TB in 10 min; pH 7, 20 ppm, 50 mg catalyst optimal	Pseudo-first-order	COD removal confirmed; reused 7 cycles
10	Pharmaceuticals	Procaine penicillin	Eddy *et al.* (2023b)	CaO NPs from mangrove oyster shells	Calcination	93% degradation under sunlight; 0.125 M catalyst, pH 2; band gap 4.42 eV	Langmuir-Hinshelwood, Mod. Freundlich, Pseudo-2nd-order	93% removal
11	Pharmaceuticals	Antibacterial agents	Roy *et al.* (2013)	Microwave-irradiated CaO NPs	Microwave synthesis	Effective vs P. aeruginosa, S. epidermidis, and C. tropicalis; MIC 2–8 mM; biofilm inhibition	Not specified	Antimicrobial activity confirmed
12	Pharmaceuticals	Antibacterial (L. plantarum)	Tang *et al.* (2013)	CaO NPs	Varying calcination	Size ~20 nm; lethal effect increases with time; significant log reductions	Not specified	5.97 log reduction at 100 ppm
13	Pesticides	Au-O dye	Vatchalan *et al.* (2023)	C NPs, C-CaO NCs from neem leaves	XRD, SEM characterization	C-CaO NCs: 88.39% as photocatalysts; eco-friendly and effective	Not specified	91.56% (adsorbent), 88.39% (photocatalyst)
14	Petrochemicals	Heating oil, LCO, ILCO	Karakasi & Moutsatsou (2010)	HCFA from fly ash (AD & M types)	Hydrothermal w/ sodium oleate	Ca-rich HCFA (AD) formed semi-solid for oil removal; improved floatation; complete oil removal at low ratios	Not applicable	0.7–0.9 g/g (AD); full removal at 1:0.004 HCFA ratio

Note: ES = Eggshell, FB = Fish Bone, DSAC = Durian Shell Activated Carbon, MES = Maize Extract Solution, CCD = Central Composite Design, NPs = Nanoparticles, NCs = Nanocomposites, HCFA = Hazardous and Contaminated Fly Ash.

A comparative analysis of CaO nanoparticles with other commonly used photocatalysts is presented in **Table 8**, highlighting differences in photocatalytic efficiency, reaction conditions, and suitability for the degradation of various organic contaminants.

Table 8. Comparative Analysis of CaO with Other Photocatalysts

S/N	Photocatalyst	Applications	Photocatalytic Activity	Band Gap (eV)	Limitations	References
1	**Calcium Oxide (CaO)**	Pollutant degradation, CO_2 capture, support material in hybrid catalysts	Limited in pure form; enhanced when doped or composited; high adsorption aids degradation	~7.0 (pure), lower when doped	Wide band gap limits visible light use; requires modification	Jayaraj *et al.* (2024); AbuKhadra *et al.* (2020)
2	**Titanium Dioxide (TiO_2)**	Environmental cleanup, self-cleaning, H_2 generation	Benchmark photocatalyst under UV; stable, efficient, non-toxic	3.0–3.2	Ineffective under visible light	Fujishima and Honda (1972); Chen & Mao (2007)
3	**Zinc Oxide (ZnO)**	Wastewater treatment, air purification, antibacterial	High UV quantum efficiency; antimicrobial; dye degradation	~3.37	Prone to photocorrosion under UV	Zhang *et al.* (2014); Kołodziejczak-Radzimska & Jesionowski (2014)
4	**Bismuth Oxyhalides (BiOX)**	Dye degradation, remediation	Visible-light active; internal field aids charge separation	2.5–3.0 (X = Cl, Br, I)	Costly synthesis; moderate stability	Zhang *et al.* (2021)
5	**g-C_3N_4 (Graphitic Carbon Nitride)**	H_2 generation, pollutant degradation, CO_2 reduction	Metal-free; visible light responsive; chemically stable	~2.7	Lower efficiency than TiO_2, ZnO	Wang *et al.* (2009)
6	**Zirconium Dioxide (ZrO_2)**	Dye degradation, photocatalyst support	Chemically stable; often used as a support	~5.0–5.8	UV-only active; needs modification for visible light	Servin *et al.* (2015)
7	**Silver Phosphate (Ag_3PO_4)**	Visible-light photocatalysis, water splitting	High visible-light activity; efficient charge separation	~2.4	Prone to photocorrosion; unstable over time	Yi *et al.* (2010); Zhang *et al.* (2013)
8	**Tungsten Oxide (WO_3)**	NOx removal, dye degradation, electrochromics	Absorbs visible light; strong oxidation ability	2.4–2.8	Requires acidic pH; weak reducing ability	Zhang *et al.* (2013); Wang *et al.* (2018)
9	**Cadmium Sulfide (CdS)**	H_2 generation, dye degradation	Narrow band gap; visible light responsive	~2.4	Toxicity, photo-instability; Cd^{2+} leaching	Kamat (2007)
10	**Copper Oxides (CuO/Cu_2O)**	Organic degradation, CO_2 reduction, antimicrobials	Strong visible light absorption; low-cost	CuO: ~1.2–1.9, Cu_2O: ~2.0–2.2	Unstable; photocorrosion risk	Wang *et al.* (2019)

5. Challenges and Limitations of CaO Nanoparticles

Calcium oxide (CaO) nanoparticles offer promise in fields like environmental remediation and catalysis due to their high surface area and cost-effectiveness. However, several limitations hinder their widespread application (Jayaraj *et al*., 2024):

i. Wide Band Gap (~7.0 eV): Limits visible light absorption, reducing photocatalytic efficiency. Enhancements require doping or coupling with other photocatalysts, increasing complexity.
ii. Agglomeration: CaO nanoparticles easily clump together due to high surface energy, reducing active surface area and performance.
iii. Hygroscopic and Chemically Reactive: Readily forms $Ca(OH)_2$ upon exposure to moisture, affecting stability, storage, and application.
iv. Limited Photocatalytic Standalone Use: Due to poor light absorption, CaO must be modified or combined with more effective photocatalysts.
v. Environmental and Health Concerns: Nanoparticle inhalation may pose respiratory risks. Moisture-induced reactions can release heat and caustic byproducts, requiring strict safety protocols.
vi. Synthesis and Scalability: Achieving controlled nanoparticle properties at industrial scale is difficult and costly.
vii. Surface Functionalization: High reactivity complicates surface modification, impacting compatibility and performance in hybrid systems.
viii. Biomedical Limitations: Potential cytotoxicity and pH changes in biological environments restrict applications in drug delivery and tissue engineering.

6. Implications for Industrial Wastewater Treatment

CaO nanoparticles have demonstrated potential in treating industrial wastewater (Kesari *et al*., 2021; Iloms *et al*., 2020):

i. Efficient Contaminant Removal: Adsorbs heavy metals and organic pollutants, particularly effective in textile, mining, and chemical industries.
ii. pH Neutralization: Converts acidic wastewater to neutral pH and helps precipitate metals through $Ca(OH)_2$ formation.
iii. Enhanced Degradation: Promotes advanced oxidation of persistent organic contaminants.
iv. Economic Viability: Offers a low-cost treatment option due to material abundance and catalytic activity.
v. Stability Issues: Agglomeration and moisture sensitivity can limit efficiency; surface modification is necessary.
vi. Safety and Environmental Risk: Requires careful handling and monitoring to avoid unintended ecological impacts.
vii. Scalability Needs: Practical deployment demands robust synthesis methods and integration with existing infrastructure.

Conclusion

This comprehensive review underscores the promising potential of calcium oxide (CaO) nanoparticles as an effective and sustainable material for the photocatalytic degradation of organic contaminants in industrial wastewater. Owing to their high surface area, strong basicity, and cost-effectiveness, CaO nanoparticles exhibit notable catalytic activity, making them attractive for various environmental remediation applications. Despite these advantages, their practical deployment faces several significant challenges. The inherently wide band gap of CaO limits its photocatalytic activity under visible light, while its tendency to agglomerate and hygroscopic nature reduce its stability and operational efficiency. These limitations necessitate strategic modifications—such as doping with transition metals, hybridization with complementary photocatalysts, and surface engineering—to enhance light absorption, dispersion, and resistance to moisture-induced degradation.

Notwithstanding these challenges, CaO nanoparticles have demonstrated efficacy in neutralizing acidic wastewater, degrading persistent organic pollutants, and improving overall water quality. Their role in advanced oxidation processes (AOPs), particularly in the breakdown of recalcitrant organic molecules, further emphasizes their value in addressing contaminants that resist conventional treatment methods.

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