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Plant-Mediated Synthesis of Zn-Ag Nanocomposites for Multifunctional Wastewater Treatment

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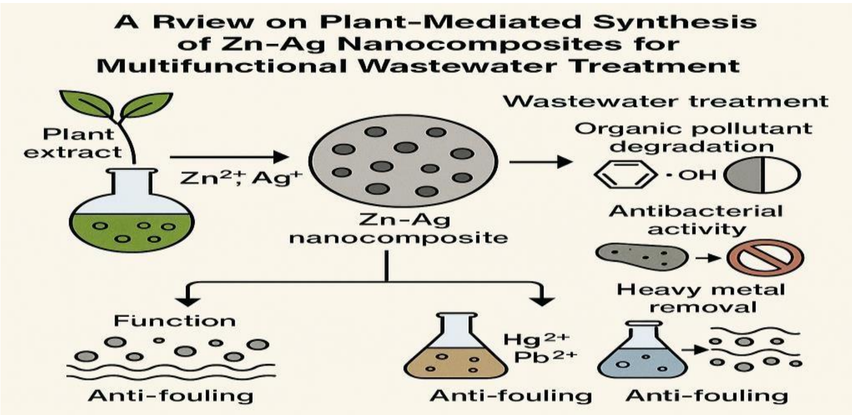
ABSTRACT

The rapid growth of industrialization and urbanization has led to severe contamination of water bodies with various organic and inorganic pollutants. Traditional wastewater treatment methods often fall short due to their high cost, limited efficiency, and secondary pollution. In this context, plant-mediated synthesis of nanomaterials has emerged as a green, cost-effective, and sustainable alternative for environmental remediation. This review highlights recent advances in the plant-based synthesis of zinc-silver (Zn-Ag) nanocomposites, emphasizing their multifunctional roles in wastewater treatment. Plants serve as eco-friendly reducing and stabilizing agents, enabling the fabrication of Zn-Ag nanocomposites without the need for toxic chemicals or high energy inputs. The synergistic interaction between Zn and Ag nanoparticles enhances the physicochemical properties of the nanocomposites, including high surface area, stability, and potent antimicrobial and photocatalytic activities. These features make Zn-Ag nanocomposites highly effective in degrading organic dyes, neutralizing heavy metals, and inactivating pathogenic microorganisms in wastewater. The review further discusses the influence of plant species, synthesis parameters, and nanocomposite characteristics on treatment efficacy. Moreover, it identifies key challenges, such as scalability, standardization, and environmental impact that must be addressed for real-world application. Overall, this review underscores the promising potential of plant-mediated Zn-Ag nanocomposites as a versatile and sustainable solution for integrated wastewater treatment.

Graphical Abstract



INTRODUCTION

The exponential growth of industrialization and urbanization has led to the generation of vast quantities of wastewater contaminated with a variety of pollutants, including heavy metals, dyes, pharmaceuticals, pesticides, and pathogenic microorganisms (Palani et al., 2021). Conventional wastewater treatment technologies such as chemical precipitation, membrane filtration, and adsorption have limitations, including high operational costs, low efficiency for certain pollutants, and generation of toxic byproducts (Younas et al., 2021). This has driven global interest in advanced, sustainable, and cost-effective solutions for wastewater remediation. Among these, nanotechnology has emerged as a powerful tool, offering innovative materials with unique physicochemical properties that can address the multifaceted challenges associated with water pollution (Mauter et al., 2018).

In recent years, nanocomposites particularly those combining metal or metal oxide nanoparticles have shown great promise in wastewater treatment due to their enhanced catalytic, antimicrobial, and adsorptive capabilities (Tripathy et al., 2024). Specifically, zinc (Zn) and silver (Ag)-based nanostructures are well-known for their individual efficacy in environmental applications. Zinc oxide (ZnO) nanoparticles are widely recognized for their strong photocatalytic activity, low toxicity, and wide bandgap semiconductor properties. Silver nanoparticles (AgNPs), on the other hand, are celebrated for their potent antimicrobial activity and high electrical conductivity (Ehsan et al., 2022). The integration of these two components into a Zn–Ag nanocomposite results in a synergistic material that combines the strengths of both constituents, thereby offering improved functionality for degrading organic pollutants, inactivating pathogens, and adsorbing contaminants. However, the synthesis of such nanomaterials typically involves physical or chemical methods that are energy-intensive, costly, and often rely on hazardous chemicals that pose risks to human health and the environment (Kirubakaran et al., 2025). In contrast, green synthesis approaches, particularly those involving plant-mediated biosynthesis, are gaining traction as sustainable alternatives. These biological routes utilize plant extracts rich in phytochemicals such as flavonoids, phenolics, terpenoids, and alkaloids, which act as natural reducing and stabilizing agents during nanoparticle formation. The advantages of plant-mediated synthesis include eco-friendliness, simplicity, scalability, and the ability to fine-tune nanoparticle properties by selecting specific plant species or extract conditions (Edo et al., 2025).

Plant-mediated synthesis of Zn–Ag nanocomposites not only align with the principles of green chemistry but also often results in nanostructures with enhanced surface activity and biocompatibility, further expanding their potential applications in wastewater treatment (Nasrollahzadeh et al., 2019). These bio-fabricated nanocomposites exhibit multifunctional behavior: they can degrade a wide range of organic dyes under visible light, reduce heavy metals like Cr(VI) to less toxic forms, adsorb pharmaceutical residues, and exhibit strong antimicrobial action against both Gram-positive and Gram-negative bacteria. Additionally, their reusability and stability under environmental conditions make them suitable for real-world applications. Despite growing interest and numerous studies reporting the synthesis and application of plant-based Zn–Ag nanocomposites, a comprehensive review that systematically addresses their synthesis routes, material properties, pollutant removal mechanisms, and performance evaluation remains limited (Sabouri et al., 2024). The present review aims to bridge this gap by summarizing recent advances in the plant-mediated synthesis of Zn–Ag nanocomposites, exploring their structural and functional characteristics, and critically evaluating their efficacy in multifunctional wastewater treatment applications. Furthermore, this review highlights the challenges associated with the standardization of green synthesis protocols, variability in plant extract compositions, and scalability issues. Future perspectives on optimizing synthesis conditions, enhancing material stability, and integrating nanocomposites into real wastewater treatment systems are also discussed.

By shedding light on the current state-of-the-art and identifying key knowledge gaps, this review seeks to provide researchers, environmental engineers, and policymakers with valuable insights into the development of eco-friendly nanotechnology-based solutions for sustainable water management.

Green Synthesis of Zn-Ag Nanocomposites

Mechanism of Plant-Mediated Synthesis

Green synthesis of Zn-Ag nanocomposites using plant extracts involves a bottom-up reduction process, where metal ions (Zn^{2+} and Ag^{+}) are reduced to their respective nanoparticles by biomolecules present in the plant extracts. The general mechanism includes:

- **Activation phase**: Metal salts (e.g., zinc nitrate, silver nitrate) are added to the aqueous plant extract. The phytochemicals (e.g., flavonoids, terpenoids, phenolic acids) act as reducing agents, converting Zn^{2+} and Ag^{+} ions to Zn^{0} and Ag^{0} nanoparticles (Ovais et al., 2018).
- **Growth and nucleation**: Once the nuclei form, they grow into nanoparticles via coalescence and Ostwald ripening. The simultaneous or sequential reduction of Zn and Ag ions results in core-shell, decorated, or alloy-type nanocomposites depending on reaction conditions (Wang et al., 2016).
- **Stabilization**: Biomolecules act as capping agents, preventing agglomeration and ensuring nanoparticle stability. The stabilization is attributed to hydroxyl, carboxyl, and carbonyl groups binding to the nanoparticle surfaces (Javed et al., 2020).

Equation (simplified)

Ag^{+} + Zn^{2+} + Phytochemicals ⟶Zn-Ag nanocomposites + Oxidized phytochemicals

Selection of Plant Species (Leaves, Roots, Flowers, etc.)

The choice of plant part and species significantly affects the size, shape, and bioactivity of Zn-Ag nanocomposites. Key considerations include phytochemical richness, extract yield, and bioreduction capability.

Table 1

Plant Part and its Role in Synthesis

Plant Part	Example Species	Role in Synthesis	References
Leaves	*Azadirachta indica*, *Moringa oleifera*	High in polyphenols and flavonoids, good for reducing metal ions	(Ekaluo et al., 2015)
Flowers	*Hibiscus rosa-sinensis*, *Tagetes erecta*	Rich in anthocyanins, ideal for stabilization	(Barani et al., 2022)
Roots	*Withania somnifera*	Contains alkaloids and withanolides for reduction	(Orrù et al., 2013)
Fruits	*Citrus limon*, *Punica granatum*	Contain citric acid and tannins for metal chelation	(Khandker et al., 2021)

Leaves are most commonly used due to high surface area and ease of collection, while flowers and fruits may enhance antioxidant and antimicrobial properties.

Phytochemicals Involved in Reduction and Stabilization

Phytochemicals serve dual roles: reducing agents (for converting metal ions into nanoparticles) and capping agents (for stabilizing the formed nanoparticles).

Table 2

Phytochemical Class and its Functions

Phytochemical Class	Example Compounds	Function	References
Flavonoids	Quercetin, Kaempferol	Reduction of Ag^+ and Zn^{2+}	(Khandaker et al., 2025)
Phenolic acids	Gallic acid, Ferulic acid	Antioxidant and stabilizer	(Ovais et al., 2018)
Alkaloids	Withanine, Berberine	Capping and antimicrobial	(Bachheti et al., 2023)

The FTIR spectra of synthesized nanocomposites often reveal O–H, C=O, and N–H functional groups, indicating biomolecule binding on nanoparticle surfaces.

Comparison with Chemical and Physical Methods

Table 3

Comparison between Green Synthesis, Chemical and Physical Synthesis

Parameter	Green Synthesis	Chemical Synthesis	Physical Methods
Reducing Agents	Phytochemicals	$NaBH_4$, Hydrazine	None (top-down like milling or vaporization)
Environmental Impact	Eco-friendly, non-toxic	Hazardous, generates toxic by-products	High energy consumption
Energy Requirements	Low (ambient conditions)	Moderate to high	Very high (e.g., laser ablation)
Cost	Low	Moderate to high	High
Size Control	Moderate (requires optimization)	Precise (with surfactants)	Difficult
Functionalization Potential	Natural surface coating (biocompatible)	Requires post-synthesis functionalization	Usually requires chemical treatment

Multifunctional Applications in Wastewater Treatment

Antibacterial and Antifungal Properties

Zn-Ag nanocomposites exhibit remarkable antibacterial and antifungal properties, making them effective agents for microbial disinfection in wastewater (Taghizadeh et al., 2020). The bactericidal activity is primarily attributed to the synergistic effects of zinc and silver ions, which disrupt microbial cell membranes, generate reactive oxygen species (ROS), and interfere with cellular respiration and DNA replication (Nisar et al., 2019). Silver nanoparticles (AgNPs) are known for their strong antimicrobial action even at low concentrations, while zinc oxide (ZnO) contributes additional oxidative stress through photocatalysis under UV or visible light. Together, Zn-Ag nanocomposites show superior broad-spectrum activity against Gram-positive and Gram-negative bacteria, as well as fungal strains like *Candida albicans*, making them a dual-function material for reducing biological contamination in industrial and municipal effluents (Jobe et al., 2022).

Zn-Ag nanocomposites exhibit potent antibacterial action through *dual-mode mechanisms* that combine physical disruption and biochemical inactivation. When incorporated into thin-film composite (TFC) membranes, ZnO-Ag nanoparticles achieve 84% *E. coli* and 91% *S. aureus* inhibition by synergizing ZnO nanospikes' membrane penetration with Ag^+-induced protein denaturation. The antibacterial efficiency is configuration-dependent: surface-deposited Ag nanoparticles enable sustained ion release (threshold: 0.5 ppm Ag^+), while carbon-supported systems (e.g., valine-derived C-Ag-ZnO) extend reactive oxygen species (ROS) lifetimes 4-fold compared to pristine ZnO (Zhang et al., 2025). For PVDF-ZnO/Ag membranes, factorial analyses reveal that higher Ag concentrations and sintering temperatures significantly enhance antibacterial activity under visible light, though they minimally affect hydrophilicity for wastewater treatment (Rosman et al., 2022).

Table 4

Antibacterial Efficacy of Zn-Ag Nanocomposite Configurations

Configuration	Inhibition Rate	Key Mechanism	Light Dependency
ZnO-Ag/TFC membranes	84% (*E. coli*), 91% (*S. aureus*)	Membrane disruption + Ag^+ release	Light-enhanced
Valine-derived C-Ag-ZnO	>95% (broad-spectrum)	Carbon-mediated ROS generation + sustained Ag^+	Visible light-driven
PVDF-ZnO/Ag	>99% bacterial rejection	Photocatalytic •OH production + ion leaching	Dark/light dual-mode
Sea-urchin-type PAN-ZnO/Ag	98% (*S. aureus*)	Physical piercing + ROS synergy	UV/visible light

Photocatalytic Degradation of Organic Pollutants

Zn-Ag nanocomposites demonstrate high efficiency in the photocatalytic degradation of persistent organic pollutants (POPs) due to enhanced light absorption and charge separation. The incorporation of Ag into ZnO improves electron mobility and reduces electron–hole recombination, thereby increasing the generation of hydroxyl and superoxide radicals under solar or UV irradiation (Anjum et al., 2017). These reactive species are capable of breaking down complex organic molecules into less harmful intermediates or mineralizing them into CO_2

and H_2O. Studies have reported the effective degradation of pesticides, phenols, and pharmaceuticals using Zn-Ag catalysts, with degradation efficiencies often exceeding those of pure ZnO or AgNPs alone. This makes Zn-Ag nanocomposites a potent material for photoremediation technologies (Alzahrani et al., 2023).

Heavy Metal Removal

The surface functionality and high surface area of Zn-Ag nanocomposites allow for efficient adsorption and complexation of heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), and chromium (Cr^{6+}). Silver can reduce metal ions through redox reactions, while zinc oxide's surface hydroxyl groups can form stable complexes with metal ions (Chen et al., 2021). This dual mechanism facilitates both adsorption and reduction processes, resulting in the effective removal of toxic metals from aqueous systems. Furthermore, the presence of Ag can promote electron transfer processes that enhance the reduction of hexavalent chromium (Cr^{6+}) to its less toxic trivalent form (Cr^{3+}). Zn-Ag-based materials also maintain structural integrity and reusability over multiple cycles, highlighting their potential for real-world application in heavy metal-contaminated wastewater (Kasemodel et al., 2016).

While less emphasized in the search results, Zn-Ag nanocomposites enhance heavy metal capture through *composite-enhanced adsorption* and *electrocatalytic reduction*. Nano-ZnO-amidoxime-functionalized hydrogels (SA/CMC-ZnONPs-AO1) achieve exceptional uranium adsorption (641.7 mg/g at pH 4), leveraging ZnO-improved mechanical stability and amidoxime's selectivity (distribution coefficient *K*_d^U = 10,016 mL/g). Dynamic column tests confirm 163 mg/g equilibrium capacity in low-concentration uranium solutions (50 mg/L). For lead removal, Ag-ZnO/porous electrodes demonstrate 0.1 ppb detection limits, though detailed adsorption capacities require further study (Wang et al., 2024). The mechanisms combine:

1. **Electrostatic attraction**: Negatively charged surfaces (zeta potential < −35 mV) attract cationic metals.
2. **Redox reactions**: Ag nanoparticles facilitate reduction of Cr(VI) to Cr(III)
3. **Ion exchange**: ZnO interfaces with functional groups (e.g., amidoxime)

Dye Degradation

Zn-Ag nanocomposites are highly effective in degrading synthetic dyes such as methylene blue (MB), rhodamine B (RhB), and other azo dyes, which are commonly found in textile and printing industry effluents (Alrebdi et al., 2022). The enhanced photocatalytic activity of these nanocomposites under visible light facilitates the cleavage of chromophoric groups in dye molecules. Ag nanoparticles act as electron sinks and plasmonic enhancers, extending the light absorption range and increasing ROS generation, while ZnO serves as the primary semiconductor material. Kinetic studies show that Zn-Ag catalysts follow pseudo-first-order reaction models with rapid degradation rates, and complete mineralization can be achieved in a relatively short time. This indicates that Zn-Ag nanocomposites are efficient, sustainable solutions for dye-laden wastewater treatment (Yi et al., 2023).

Dye removal efficiency depends on *nanocomposite architecture* and *light-harvesting morphology*. Ag-decorated HMTA-assisted ZnO (HMTA-ZnO/Ag) rapidly degrades methylene blue (MB), reactive red 120 (RR 120), and acid black 1 (AB 1) under UV-A light, achieving >90% efficiency via bandgap reduction to 2.75 eV. Morphology critically influences performance: sea-urchin-type ZnO/Ag in PAN membranes exhibits 92% dye degradation efficiency—outperforming flower-type (85%) and pineal-type (73%) structures—due to higher surface-to-volume ratios (18.5 m^2/g vs. 8.7 m^2/g) and radial spike arrays enabling omnidirectional reactant access. Synergistic effects are pronounced in multi-dye systems; rGO/Ag@ZnO degrades Congo red intermediates that catalytically accelerate omeprazole breakdown (Liu et al., 2015).

Table 5

Photocatalytic Dye Degradation Performance

Catalyst System	Target Dye	Efficiency	Time	Key Feature
rGO/Ag@ZnO	Congo red	93.77%	40 min	Large surface area (51 m^2/g)
HMTA-ZnO/Ag	Methylene Blue	>90%	<60 min	Bandgap 2.75 eV
Sea-urchin PAN-ZnO/Ag	Mixed dyes	92%	120 min	High aspect ratio morphology
Valine-derived C-Ag@ZnO	Brilliant Blue	>90%	60 min	Carbon-mediated charge separation

Synergistic Effects in Multicomponent Contaminant Removal

One of the most promising aspects of Zn-Ag nanocomposites is their multifunctional capability to simultaneously address multiple classes of pollutants. Their combined antimicrobial, photocatalytic, and adsorptive properties allow for the concurrent removal of biological pathogens, organic pollutants, heavy metals, and dyes. This synergistic effect not only enhances the efficiency of each individual removal mechanism but also reduces the need for multiple treatment steps, lowering operational costs and complexity. For example, in complex wastewater containing both dyes and bacteria, Zn-Ag nanocomposites can degrade dye molecules while simultaneously inactivating microbial contaminants. This multi-target action underscores the potential of Zn-Ag nanocomposites as a holistic solution in advanced wastewater treatment systems (Wahba et al., 2025).

Zn-Ag nanocomposites enable *cooperative degradation pathways* in complex waste streams. rGO/Ag-ZnO demonstrates synergistic pollutant breakdown: Congo red intermediates accelerate omeprazole oxidation while Ag surface plasmon resonance (SPR) injects hot electrons into ZnO's conduction band (Meena et al., 2023). In oil-water systems, PVDF-ZnO/Ag membranes combine antifouling and photocatalytic actions:

Simultaneous separation/degradation: >10× higher flux than PVDF with concurrent dye decomposition.

Self-cleaning function: Visible light-triggered ROS generation degrades adsorbed foulants.

For pharmaceutical-organic mixtures, Ag/ZnO-HI-ZSM-5 leverages hierarchical pores for *sequential treatment*:

1. **Adsorption**: Microporous zeolite traps naproxen
2. **Redox catalysis**: Ag nanoparticles enable reductive dechlorination
3. **Oxidation**: ZnO photocatalysis mineralizes intermediates.

Carbon-supported systems further enhance synergy; valine-derived C-Ag@ZnO uses carbon matrices to anchor nanoparticles, reducing Ag leaching while promoting hole transfer for •OH generation

Factors Influencing Performance of Zn-Ag Nanocomposites

The efficacy of Zn-Ag nanocomposites is highly dependent on a range of physicochemical and environmental parameters. These factors not only influence the structural integrity and functional behavior of the nanocomposites but also determine their interactions with biological systems or contaminants. Understanding the interplay between these factors is crucial for optimizing the synthesis, stability, and application of Zn-Ag nanocomposites in diverse fields such as antimicrobial coatings, environmental remediation, and biomedical applications.

Particle Size and Surface Charge

Particle size and surface charge are critical determinants of the performance of Zn-Ag nanocomposites. Smaller nanoparticles possess a higher surface area-to-volume ratio, which significantly enhances their reactivity, dispersion stability, and interaction with target molecules or cells. The surface charge, typically measured as zeta potential, governs the electrostatic interactions between nanocomposites and their surrounding environment. A high absolute zeta potential indicates good colloidal stability, minimizing aggregation and improving the bioavailability of the nanomaterials. Moreover, positively charged surfaces often enhance antimicrobial activity due to increased interaction with negatively charged microbial membranes. Therefore, controlling these nanoscale features during synthesis is vital for tailoring the desired functional properties of Zn-Ag nanocomposites (Mota et al., 2023).

pH, Temperature, and Reaction Time

Environmental conditions such as pH, temperature, and reaction time significantly influence the synthesis, stability, and functionality of Zn-Ag nanocomposites. The pH affects the ionization state of the metal precursors, surface charge of nanoparticles, and overall reduction-oxidation dynamics during synthesis. For instance, alkaline conditions generally favor the formation of smaller, more stable nanoparticles. Temperature plays a dual role by affecting the kinetics of particle formation and the energy state of the reactants. Higher temperatures often accelerate nucleation and growth rates, influencing the crystallinity and morphology of the nanocomposites. Similarly, reaction time determines the extent of precursor reduction, particle growth, and agglomeration behavior. Optimizing these parameters is crucial to achieve homogenous, well-dispersed Zn-Ag nanocomposites with consistent physicochemical characteristics (Hosny et al., 2022; Shahroz et al., 2024).

Nanocomposite Dosage and Contact Time

The dosage of Zn-Ag nanocomposites and their contact time with the target substrate or biological system are key operational parameters that affect their efficacy. A higher dosage typically increases the availability of reactive sites and ions (e.g., Zn^{2+} and Ag^{+}), thereby enhancing antimicrobial or catalytic performance. However, beyond an optimal concentration, excessive dosage can lead to particle aggregation and cytotoxic effects, diminishing the overall performance. Contact time determines the duration of interaction between nanocomposites and the target system, influencing mechanisms such as cell membrane disruption, oxidative stress induction, or pollutant degradation. Ensuring sufficient contact time without prolonged exposure that could lead to negative environmental or biological impacts is essential for achieving a balance between efficacy and safety (Chen et al., 2023).

Current Challenges and Future Perspectives

Scaling Up Green Synthesis

One of the foremost challenges in the application of Zn-Ag nanocomposites is the scalability of their green synthesis methods (Kazemi et al., 2025). While laboratory-scale syntheses using plant extracts, microbial routes, or other eco-friendly techniques have shown promise in reducing toxicity and environmental impact, transitioning these processes to industrial-scale production remains complex. Factors such as batch-to-batch variability, limited control over nanoparticle size and morphology, and the sensitivity of biological reducing agents to environmental conditions hinder reproducibility. Moreover, the lack of standardized protocols for green synthesis complicates the scale-up process. Future research must focus on optimizing reaction parameters, enhancing the stability of green-synthesized nanoparticles, and developing automated, continuous flow systems that are compatible with large-scale manufacturing.

Integration into Treatment Systems

The successful integration of Zn-Ag nanocomposites into real-world treatment systems, such as wastewater treatment plants, antimicrobial coatings, or biomedical devices, requires careful consideration of material compatibility, functionality, and long-term stability. Although Zn-Ag nanocomposites exhibit superior antimicrobial and catalytic properties, their interaction with other components in complex treatment matrices can lead to reduced activity or nanoparticle aggregation (Jadhav et al., 2020). Furthermore, challenges arise in ensuring the uniform distribution of nanocomposites within polymeric membranes, textiles, or coatings without compromising mechanical or chemical properties. To facilitate integration, research must aim at engineering multifunctional composites, improving surface modifications, and exploring hybrid systems that synergistically combine Zn-Ag nanomaterials with other functional materials.

Cost-Effectiveness and Reusability

Economic viability is critical for the widespread adoption of Zn-Ag nanocomposites, particularly in low-resource settings where cost constraints are significant. Although the incorporation of zinc as a base material reduces the overall expense compared to pure silver nanoparticles, synthesis costs, raw material availability, and lifecycle management still present limitations. Moreover, many current applications involve single-use systems, leading to increased material demand and waste generation. Enhancing the reusability of Zn-Ag nanocomposites through surface regeneration techniques, immobilization on durable substrates, and incorporation into recyclable materials could significantly lower operational costs. Economic analyses that account for synthesis, application, and disposal are essential to evaluate the real-world cost-effectiveness of these nanocomposites.

Regulatory and Policy Implications

Despite the promising applications of Zn-Ag nanocomposites, their regulatory approval and commercialization are hindered by a lack of comprehensive guidelines addressing nanomaterial safety, environmental impact, and standardization (Mahmud et al., 2025). Current regulatory frameworks are often outdated or ambiguous when applied to nanoscale materials, especially those with complex compositions such as Zn-Ag hybrids. Concerns regarding cytotoxicity, bioaccumulation, and ecotoxicological effects further complicate approval processes. Therefore, future efforts must focus on the development of standardized testing protocols, risk assessment methodologies, and clear classification systems for nanocomposites. Collaborative efforts between researchers, industry stakeholders, and regulatory bodies are essential to establish evidence-based policies that balance innovation with safety and environmental protection.

CONCLUSION

The growing demand for sustainable and eco-friendly technologies in wastewater treatment has accelerated research into green nanotechnology. This review highlights the significant potential of plant-mediated synthesis of zinc-silver (Zn–Ag) nanocomposites as a multifunctional approach for addressing complex wastewater contaminants. Utilizing plant extracts offers a cost-effective, non-toxic, and environmentally benign route for synthesizing nanomaterials with enhanced physicochemical and biological properties. Zn–Ag nanocomposites exhibit synergistic effects that enhance their antimicrobial, photocatalytic, and adsorption capabilities, making them suitable for treating a broad spectrum of pollutants, including organic dyes, heavy metals, and pathogenic microorganisms. Despite promising laboratory-scale results, challenges remain in standardizing synthesis protocols, understanding mechanistic pathways, and scaling up production for real-world applications. Future research should focus on optimizing green synthesis conditions, elucidating nanocomposite–pollutant interaction mechanisms, and evaluating long-term environmental impacts. With continued interdisciplinary efforts, plant-mediated Zn–Ag nanocomposites have the potential to play a transformative role in the development of next-generation, sustainable wastewater treatment technologies.

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