

Green Nanotechnology for Sustainable Environmental Remediation

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ABSTRACT

Green nanotechnology integrates environmentally friendly approaches with nanoscience to develop sustainable solutions for environmental remediation. By utilizing biogenic and eco-friendly methods for nanoparticle synthesis, green nanotechnology minimizes hazardous byproducts and promotes the use of renewable resources. These nanoparticles, often derived from plant extracts, microorganisms, or biodegradable materials, exhibit enhanced catalytic, adsorptive, and antimicrobial properties critical for treating pollutants in air, water, and soil. The application of green-synthesized nanomaterials offers promising avenues for removing heavy metals, degrading organic contaminants, and neutralizing toxic substances without introducing additional ecological risks. Furthermore, this approach aligns with circular economy principles by emphasizing waste valorization, resource efficiency, and energy conservation. As a transformative discipline, green nanotechnology holds significant potential for advancing cleaner production processes, fostering ecosystem restoration, and contributing to global sustainability goals through innovative remediation strategies that are both effective and eco-compatible.

Keywords: Green nanotechnology, sustainable remediation, eco-friendly nanoparticles, environmental sustainability, pollutant removal.

Introduction

Green nanotechnology has emerged as a transformative field that merges the principles of nanoscience with green chemistry to address pressing environmental challenges. Unlike conventional nanotechnology, which often relies on toxic chemicals and energy-intensive processes, green nanotechnology focuses on sustainable, non-toxic, and energy-efficient methods for nanoparticle synthesis and application. This shift is driven by the growing awareness of environmental degradation, climate change, and the urgent need for sustainable remediation technologies [1]. Green nanotechnology aims to create solutions that not only address pollution but also reduce the environmental footprint of the technologies themselves, setting a new benchmark for responsible innovation in nanoscience. One of the core objectives of green nanotechnology is the development of eco-friendly nanoparticles synthesized using biological entities such as plants, bacteria, fungi, and algae. These biosynthesized nanoparticles offer numerous advantages, including biocompatibility, reduced toxicity, and lower production costs [2]. The use of natural reducing agents and stabilizers eliminates the need for hazardous chemicals traditionally used in nanoparticle fabrication. Additionally, the synthesis process often occurs at ambient temperatures and pressures, conserving energy and reducing greenhouse gas emissions. This green synthesis approach aligns with the principles of green chemistry, promoting sustainable manufacturing practices that are safe for both human health and the environment.

Environmental remediation using green nanotechnology encompasses a range of applications, including the removal of heavy metals, degradation of organic pollutants, treatment of wastewater, and purification of air. Nanoparticles produced via green methods possess unique physicochemical properties, such as high surface area, reactivity, and tunable surface functionalities, making them highly effective in capturing and neutralizing contaminants [3].

For instance, green-synthesized silver and iron nanoparticles have shown exceptional performance in breaking down toxic dyes, pesticides, and industrial effluents. These applications not only improve the efficacy of remediation efforts but also ensure that the remediation agents themselves do not introduce secondary pollution. The integration of green nanotechnology into environmental remediation is also contributing to advancements in water purification technologies. Nanomaterials like nano-zerovalent iron (nZVI), titanium dioxide (TiO₂), and graphene oxide, when synthesized via green methods, demonstrate enhanced capabilities for contaminant removal through adsorption, photocatalysis, and reduction mechanisms. These nanomaterials can effectively target a wide spectrum of pollutants, including pathogens, heavy metals, and organic compounds, making them versatile tools in addressing water scarcity and pollution. Moreover, their ability to be regenerated and reused supports the principles of circular economy and resource efficiency, critical aspects of sustainable development.

Soil remediation is another critical area where green nanotechnology shows significant promise. Contaminated soils, often laden with heavy metals, hydrocarbons, and persistent organic pollutants, pose severe risks to ecosystems and human health. Green-synthesized nanomaterials, such as iron oxide and carbon-based nanoparticles, can immobilize or degrade these contaminants, enhancing soil quality and reducing bioavailability of toxic substances [4]. The use of biodegradable and plant-based nanomaterials ensures that soil remediation processes do not disrupt microbial communities or soil structure, thereby preserving soil health and promoting ecological balance. Green nanotechnology represents a holistic approach to environmental remediation, offering innovative solutions that harmonize technological advancement with ecological responsibility. By leveraging natural resources for nanoparticle synthesis and focusing on non-toxic, energy-efficient processes, green nanotechnology addresses both the

causes and consequences of environmental pollution. Its applications across air, water, and soil remediation highlight its versatility and effectiveness, positioning it as a key driver in the global effort toward sustainable development and environmental protection. As research in this field progresses, the integration of green nanotechnology into mainstream environmental management strategies holds the potential to transform remediation practices and foster a more sustainable future.

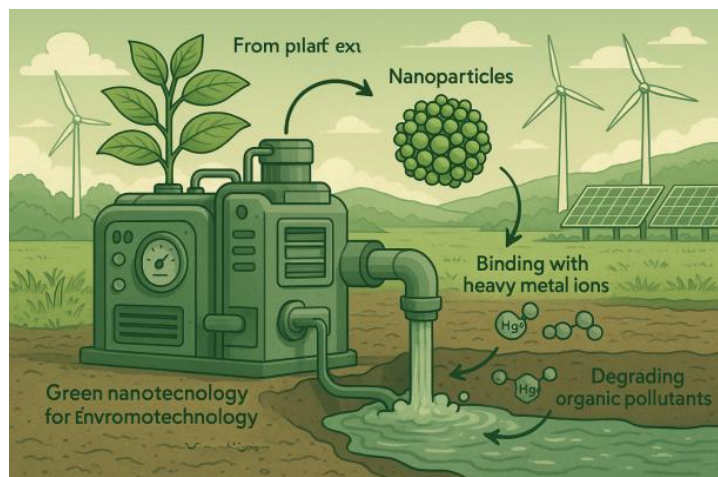


Fig 1: mechanism of green nanotechnology in environmental remediation

Table 1: Sources of Green Nanoparticle Synthesis

| Biological Source | Nanoparticles Produced | Advantages | Applications |
|-------------------|--------------------------------|---------------------------------|--|
| Plant Extracts | Silver, Gold, Iron Oxide | Eco-friendly, Biocompatible | Antimicrobial agents, Water treatment |
| Bacteria | Zinc Oxide, Iron Nanoparticles | Rapid synthesis, Cost-effective | Heavy metal removal, Soil remediation |
| Fungi | Gold, Titanium Dioxide | High yield, Stability | Dye degradation, Catalysis |
| Algae | Silver, Gold Nanoparticles | Sustainable, Renewable resource | Water purification, Sensor development |

Table 2: Applications of Green Nanotechnology in Environmental Remediation

| Application Area | Nanomaterials Used | Mechanism | Benefits |
|----------------------|--|-----------------------------|--|
| Water Purification | Nano-zerovalent Iron, Silver Nanoparticles | Adsorption, Catalysis | Effective contaminant removal |
| Air Purification | Titanium Dioxide, Zinc Oxide | Photocatalysis | Degradation of air pollutants |
| Soil Remediation | Iron Oxide, Carbon Nanoparticles | Immobilization, Degradation | Enhanced soil health, Reduced toxicity |
| Wastewater Treatment | Graphene Oxide, Silver Nanoparticles | Adsorption, Disinfection | Safe water reuse, Pathogen removal |

Table 3: Mechanisms of Action in Green Nanotechnology

| Nanomaterial | Action Mechanism | Target Pollutants | Environmental Impact |
|----------------------|------------------------------------|---------------------------------|-----------------------------|
| Silver Nanoparticles | Disruption of microbial cell walls | Pathogens, Bacteria | Reduced pathogen spread |
| Iron Nanoparticles | Reduction of heavy metals | Lead, Arsenic, Mercury | Safe detoxification |
| Titanium Dioxide | Photocatalytic degradation | Organic dyes, VOCs | Minimal secondary pollution |
| Graphene Oxide | Adsorption of contaminants | Heavy metals, Organic compounds | Eco-friendly purification |

Table 4: Comparative Benefits of Green vs Conventional Nanotechnology

| Parameter | Green Nanotechnology | Conventional Nanotechnology |
|----------------------|--------------------------|-----------------------------|
| Synthesis Method | Biological, Eco-friendly | Chemical, often toxic |
| Energy Requirement | Low, Ambient conditions | High, Harsh conditions |
| By-products | Minimal, Biodegradable | Hazardous, Toxic |
| Environmental Safety | High | Moderate to Low |
| Cost-effectiveness | Economical | Often expensive |

Green Synthesis of Nanoparticles: A Sustainable Approach

Green synthesis of nanoparticles represents a shift from conventional chemical methods to environmentally friendly techniques that utilize biological resources. Plant extracts, bacteria, fungi, and algae serve as natural reducing and stabilizing agents in nanoparticle production [6]. These biological entities contain biomolecules like proteins, enzymes, flavonoids, and alkaloids, which reduce metal ions to nanoparticles under mild conditions. Unlike traditional synthesis, green methods do not require hazardous chemicals or extreme reaction environments, making them safer and more sustainable. This approach reduces toxic by-products, promotes biodegradability, and aligns with green chemistry principles, contributing to cleaner production practices, green-synthesized nanoparticles often exhibit enhanced biological activity, such as improved antimicrobial properties and better interaction with pollutants, due to the surface-capping by biomolecules. This increases their functional versatility in environmental

The Fig 1 illustrates the core mechanism of green nanotechnology in environmental remediation. It showcases how nanoparticles, synthesized from plant extracts, are deployed through a specialized machine to bind with heavy metal ions and degrade organic pollutants in contaminated water and soil. The setup emphasizes the eco-friendly nature of this technology, supported by renewable energy sources like wind turbines and solar panels, reinforcing the commitment to sustainable and clean environmental practices [5]. The process depicted highlights the dual role of green nanotechnology in both pollutant removal and minimizing ecological impact, making it a vital tool for modern environmental management.

applications like pollutant degradation, heavy metal removal, and microbial inactivation. The simplicity and cost-effectiveness of green synthesis allow for scalable production, enabling broader use in industrial and environmental settings, this method supports the circular economy by utilizing agricultural waste or biomass for nanoparticle fabrication, promoting waste valorization alongside environmental remediation.

2. Applications in Water Purification and Wastewater Treatment

One of the most impactful applications of green nanotechnology lies in water purification and wastewater treatment. Nanomaterials synthesized via green methods, such as silver nanoparticles, nano-zerovalent iron, and titanium dioxide, are highly effective in removing a wide range of contaminants, including pathogens, heavy metals, and organic pollutants. Their high surface area and unique surface properties enhance

adsorption capacities and catalytic efficiency, leading to effective detoxification of polluted water bodies. Photocatalytic nanomaterials like green-synthesized TiO_2 further break down harmful organic compounds under sunlight, offering a sustainable route for water treatment in low-resource settings, these nanomaterials enable multifunctional treatment processes such as simultaneous disinfection, adsorption, and degradation. Green nanotechnology supports the development of advanced filtration systems, including nanocomposite membranes and hybrid filters, enhancing the efficiency of conventional treatment plants [7]. The ability of these nanoparticles to be regenerated and reused reduces operational costs and minimizes environmental impact. Furthermore, their biocompatibility ensures that treated water remains safe for consumption and ecological discharge, addressing both public health concerns and environmental sustainability.

3. Role in Soil Remediation and Pollution Control

Soil contamination from industrial effluents, mining activities, and agricultural chemicals poses significant risks to ecosystems and human health. Green nanotechnology offers innovative solutions for soil remediation through the deployment of eco-friendly nanomaterials. Iron oxide nanoparticles and carbon-based nanomaterials, synthesized through green methods, can immobilize heavy metals, degrade organic pollutants, and enhance the soil's physicochemical properties [8]. These nanoparticles work by binding with contaminants, reducing their mobility and bioavailability, which prevents them from leaching into groundwater or being absorbed by plants. The biocompatibility of green-synthesized nanomaterials ensures minimal disruption to soil microbial communities, preserving soil fertility and ecosystem balance. Their application in phytoremediation—a technique where plants and nanoparticles work synergistically—enhances the effectiveness of contaminant removal while promoting soil health. Green nanotechnology also facilitates the development of slow-release fertilizers and soil conditioners, contributing to sustainable agricultural practices. By integrating these materials into soil management strategies, it is possible to rehabilitate contaminated sites, prevent land degradation, and support sustainable land use.

4. Air Purification and Control of Atmospheric Pollutants

Air pollution, a critical global challenge, can be addressed through the innovative applications of green nanotechnology. Nanoparticles such as titanium dioxide and zinc oxide, when synthesized using green methods, can act as photocatalysts to degrade airborne pollutants, including volatile organic compounds (VOCs) and particulate matter. These nanomaterials, incorporated into coatings, paints, and filtration systems, actively purify the air by breaking down harmful substances upon exposure to sunlight or UV light. The process not only reduces indoor and outdoor air pollution but also minimizes the formation of secondary pollutants, ensuring a healthier environment [9]. Green nanotechnology supports the creation of sustainable air purification systems that are energy-efficient and environmentally benign. For example, photocatalytic coatings on building exteriors and urban infrastructures can continuously combat air pollution without requiring external power sources. Additionally, the integration of these nanomaterials into air filtration devices improves their efficacy in capturing fine particulate matter, allergens, and microbial contaminants.

This dual role of pollutant degradation and particulate capture enhances the overall air quality, contributing significantly to public health and urban environmental management.

5. Environmental and Economic Benefits of Green Nanotechnology

The environmental benefits of green nanotechnology extend beyond pollutant removal to include reduced ecological risks and lower carbon footprints. By eliminating the need for hazardous chemicals and high-energy synthesis methods, green nanotechnology minimizes environmental contamination and conserves natural resources. The use of biodegradable materials ensures that nanoparticles do not accumulate in ecosystems, reducing the risk of nanoparticle-induced toxicity. Furthermore, the capacity for regeneration and reuse of green nanomaterials supports long-term environmental sustainability and resource conservation, making remediation processes more eco-efficient [10]. Economically, green nanotechnology offers cost-effective solutions due to its reliance on abundant natural resources and low-energy production methods. The simplicity of biological synthesis processes reduces manufacturing costs, making advanced remediation technologies accessible to developing regions. Additionally, the scalability of green synthesis allows for mass production without significant capital investment, promoting widespread adoption. These economic advantages, coupled with the environmental benefits, position green nanotechnology as a viable and sustainable alternative to traditional remediation methods, driving progress toward cleaner industries and greener communities.

6. Principles of Green Nanotechnology and Sustainable Chemistry

Green nanotechnology is grounded in the principles of green chemistry, which emphasize the reduction of hazardous substances and the promotion of environmentally benign processes. This discipline aims to design materials and products that minimize toxicity and environmental impact throughout their life cycle. By adopting renewable resources, using less energy-intensive processes, and eliminating harmful by-products, green nanotechnology aligns scientific innovation with sustainability goals. Its holistic approach ensures that the solutions created for environmental remediation do not contribute to new environmental problems, a critical aspect of sustainable science, green nanotechnology promotes the development of eco-compatible materials that perform specific environmental functions without adverse side effects. It encourages lifecycle analysis in the design of nanomaterials, considering factors such as raw material sourcing, production impact, usage safety, and disposal effects [11]. This approach not only protects ecosystems but also fosters innovation in green product design, making technologies inherently safer and more sustainable. The integration of these principles is essential for advancing sustainable industrial practices and addressing environmental challenges effectively.

7. Phytogenic Nanoparticles: Role of Plant-Based Synthesis

Plant-based synthesis of nanoparticles, often termed phytogenic synthesis, leverages the natural reducing agents found in plant extracts to convert metal ions into nanoparticles. This method utilizes a wide range of biomolecules such as polyphenols, flavonoids, alkaloids, and terpenoids, which act as stabilizers and capping agents.

The process occurs under mild conditions, typically at room temperature and neutral pH, eliminating the need for harsh chemicals or extreme temperatures. This not only makes phylogenetic synthesis environmentally friendly but also cost-effective and suitable for large-scale production [12]. The nanoparticles produced through phylogenetic methods often display enhanced stability and bioactivity due to the surface coating by plant biomolecules. These properties make them highly effective in environmental applications such as antimicrobial treatment, pollutant degradation, and heavy metal adsorption. The method also allows for customization of nanoparticle properties by selecting specific plant sources, tailoring the particles for desired applications. This flexibility and green approach position phylogenetic nanoparticles as a key player in sustainable environmental technologies.

8. Microbial Synthesis of Nanoparticles for Environmental Applications

Microbial synthesis involves the use of bacteria, fungi, and algae to produce nanoparticles through natural metabolic processes. Microorganisms act as bio-factories, reducing metal ions and stabilizing nanoparticles without the need for external chemicals. This biosynthesis can occur intra- or extracellularly, offering different advantages for nanoparticle recovery and application. The microbial approach is particularly advantageous due to its low cost, scalability, and the ability to manipulate microbial strains for specific nanoparticle production, microbial-synthesized nanoparticles are utilized for their high reactivity and specificity towards contaminants. They have been successfully applied in bioremediation strategies to remove heavy metals, degrade toxic chemicals, and control microbial contamination in water and soil. The natural origin of these nanoparticles ensures compatibility with biological systems, minimizing ecological risks [13]. Moreover, the use of industrial microbial strains can enhance production rates, making this approach viable for commercial-scale environmental remediation projects.

Nanoparticles in Heavy Metal Removal and Detoxification

Heavy metal contamination poses a serious threat to both ecosystems and human health due to the toxicity and persistence of metals like lead, arsenic, cadmium, and mercury. Green-synthesized nanoparticles, particularly iron, silver, and carbon-based nanoparticles, have demonstrated exceptional ability to adsorb, immobilize, or chemically transform these toxic metals into less harmful forms. Their high surface area and active surface functionalities enhance their interaction with metal ions, making them effective in both water treatment and soil remediation.

The use of such nanoparticles in remediation offers a targeted and efficient approach to detoxifying contaminated environments. They can be deployed in filtration systems, dispersed directly into polluted water bodies, or integrated into soil treatments [14]. The minimal environmental impact of green-synthesized nanoparticles ensures that their application does not introduce secondary contamination. This capability provides a sustainable method for addressing heavy metal pollution, critical for protecting public health and restoring ecological balance in affected areas.

Photocatalytic Degradation of Organic Pollutants Using Green Nanomaterials

Organic pollutants such as dyes, pesticides, pharmaceuticals,

and industrial chemicals are persistent in the environment and challenging to remove through conventional methods. Green-synthesized photocatalytic nanomaterials like titanium dioxide, zinc oxide, and silver nanoparticles have proven highly effective in degrading these contaminants. When exposed to light, these nanoparticles generate reactive oxygen species (ROS) that break down complex organic molecules into harmless substances like water and carbon dioxide [15]. The photocatalytic activity of green nanomaterials offers a sustainable and energy-efficient solution for environmental cleanup. Their use in water treatment plants, industrial effluent treatment, and even in air purification systems underscores their versatility. The incorporation of these materials into coatings, membranes, and reactors facilitates continuous and long-term pollutant degradation with minimal maintenance. This approach not only mitigates environmental pollution but also supports the development of advanced treatment technologies that align with sustainable environmental management practices.

Environmental Impact and Ecotoxicological Assessment of Green Nanomaterials

Despite the green synthesis approach, it is critical to assess the environmental impact and potential ecotoxicity of nanoparticles before large-scale deployment. Factors such as nanoparticle size, concentration, surface chemistry, and degradation products influence their interaction with ecosystems. Comprehensive ecotoxicological assessments ensure that the use of green nanomaterials does not harm aquatic life, soil microorganisms, or human health. These studies help in understanding bioaccumulation, potential toxicity, and environmental persistence of nanomaterials. Moreover, environmental impact assessments guide the safe design and application of nanotechnologies, aligning with regulatory frameworks and sustainability goals [16]. They promote responsible innovation by ensuring that remediation efforts do not result in unforeseen negative consequences. Such evaluations also facilitate public acceptance and regulatory approval of green nanotechnology applications. By prioritizing safety and environmental compatibility, the field of green nanotechnology can advance responsibly and sustainably.

Integration of Green Nanotechnology with Renewable Energy Systems

The integration of green nanotechnology with renewable energy systems enhances the sustainability of environmental remediation technologies. Nanomaterials synthesized via green methods can improve the efficiency of renewable energy devices such as solar cells, photocatalytic reactors, and energy storage systems. For example, green-synthesized titanium dioxide is widely used in dye-sensitized solar cells for its photocatalytic properties, improving solar energy harnessing while maintaining eco-friendly production standards, renewable energy-powered systems incorporating green nanotechnology offer off-grid solutions for water purification, air filtration, and soil treatment [17]. This synergy supports decentralized and sustainable remediation strategies, particularly in remote or underdeveloped regions. Furthermore, the combined use of green nanotechnology and renewable energy reduces the carbon footprint of remediation processes, contributing to climate change mitigation. This approach exemplifies the interdisciplinary potential of green technologies in promoting global sustainability.

Advancements in Nano-enabled Filtration and Membrane Technologies

Nano-enabled filtration systems and membranes, enhanced with green-synthesized nanoparticles, have revolutionized water and air purification technologies. These membranes exhibit superior properties such as increased permeability, selectivity, and resistance to fouling, making them ideal for removing a wide range of contaminants. The incorporation of nanoparticles like silver, graphene oxide, and iron oxide improves the antimicrobial activity and pollutant capture efficiency of filtration systems. Green nanotechnology ensures that these filtration systems are not only effective but also environmentally safe. The use of biodegradable or renewable materials in membrane fabrication supports sustainable production and disposal. Such advancements have significant implications for addressing global water scarcity and improving air quality, especially in urban and industrial areas [18]. Moreover, the ability to regenerate and reuse nano-enabled membranes reduces operational costs and promotes long-term sustainability in environmental management.

Contribution to Circular Economy and Waste Valorization

Green nanotechnology aligns with circular economy principles by promoting the reuse and recycling of materials throughout their lifecycle. The use of agricultural waste, industrial by-products, and biomass for nanoparticle synthesis supports waste valorization, transforming potential environmental liabilities into valuable resources. This approach reduces dependence on virgin raw materials and contributes to sustainable industrial practices, green nanomaterials can be regenerated and reused, minimizing waste generation and resource consumption [19]. This supports closed-loop systems where materials are continuously cycled back into production and application processes. Such integration of green nanotechnology within the circular economy framework enhances the sustainability of environmental remediation technologies and drives innovation in resource-efficient practices. By converting waste into functional nanomaterials, this approach not only mitigates pollution but also adds economic value to waste streams.

Future Prospects and Research Directions in Green Nanotechnology

The future of green nanotechnology holds significant promise for addressing emerging environmental challenges. Research is increasingly focused on developing multifunctional nanomaterials with enhanced reactivity, selectivity, and environmental compatibility. Innovations in synthesis methods aim to further reduce energy consumption, improve scalability, and utilize a wider range of sustainable raw materials. The integration of nanotechnology with biotechnology, materials science, and environmental engineering is paving the way for advanced solutions in pollution control, resource recovery, and ecosystem restoration [20-22], interdisciplinary collaboration and investment in research and development are essential to realize the full potential of green nanotechnology. Establishing standardized testing protocols, environmental safety guidelines, and regulatory frameworks will facilitate the responsible deployment of nanotechnologies. Public awareness and acceptance, driven by transparent communication of benefits and risks, will also play a critical role. As the field evolves, green nanotechnology is poised to become a cornerstone of sustainable environmental management,

contributing significantly to global sustainability and environmental protection goals.

Conclusion

Green nanotechnology stands at the forefront of sustainable environmental remediation, offering innovative solutions that harmonize technological advancement with ecological responsibility. By leveraging biological systems and renewable resources for the synthesis of nanoparticles, this field minimizes the use of hazardous chemicals and reduces environmental footprints. The unique physicochemical properties of green-synthesized nanoparticles, such as high surface area, catalytic activity, and biocompatibility, enable effective removal of various pollutants from water, air, and soil. These applications address some of the most pressing environmental challenges of our time, including heavy metal contamination, organic pollutant degradation, and microbial control, all while promoting eco-safe and energy-efficient methodologies. The environmental benefits of green nanotechnology are complemented by its potential for economic sustainability. The use of abundant natural materials and low-energy synthesis processes reduces production costs, making advanced remediation technologies accessible even in resource-constrained settings, the adaptability of green nanotechnology to integrate with renewable energy systems and circular economy practices enhances its role in promoting a holistic approach to sustainability. This multifaceted contribution extends beyond mere pollution control to include the advancement of sustainable industrial practices, resource conservation, and climate change mitigation efforts. As industries and governments increasingly prioritize green technologies, green nanotechnology emerges as a vital tool for achieving environmental protection and economic resilience, the challenges related to scalability, standardization, and ecological safety will ensure that this technology contributes positively without unintended consequences.

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