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Green-Synthesized Biomedical Nanoparticles for Sustainable Arsenic Water Remediation

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ABSTRACT

Arsenic contamination of drinking water poses a serious environmental and public health challenge, particularly in developing regions where groundwater serves as the primary water source. Green-synthesized biomedical nanoparticles have emerged as an eco-friendly and highly effective alternative for sustainable arsenic remediation. Produced using biological resources such as medicinal plant extracts, algae, fungi, and bacteria, these nanoparticles eliminate the need for hazardous chemicals while offering excellent biocompatibility and environmental safety. Their high surface reactivity, tunable morphology, and abundant active binding sites enable efficient adsorption and transformation of both [As(III)] and arsenate [As(V)] species. Iron oxide, zinc oxide, silver, and biopolymer-based nanoparticles synthesized through green routes have demonstrated remarkable removal efficiency, operational stability, and reusability under diverse water conditions. Beyond arsenic sequestration, several biomedical nanoparticles possess antimicrobial properties that simultaneously reduce pathogenic contamination, enhancing overall water quality. Despite these advantages, issues related to large-scale production, long-term environmental behavior, regeneration efficiency, and economic feasibility require further investigation. Integrating green nanotechnology with advanced water treatment systems can provide sustainable and affordable solutions for arsenic-affected communities. This paper summarizes recent developments in the synthesis, physicochemical characteristics, remediation mechanisms, biomedical significance, and future prospects of green-synthesized nanoparticles, highlighting their potential to support safe drinking water and environmental sustainability.

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INTRODUCTION

At the atomic and molecular scale, the deliberate engineering of matter has matured into one of the most dynamic forces driving progress toward a more sustainable world. What began in 1974 when Norio Taniguchi coined the term “nanotechnology” to describe the precise separation, joining and reshaping of materials atom by atom has since evolved far beyond its original manufacturing roots. Today the field encompasses everything from quantum-dot photonics and surface-enhanced Raman sensing to nanobiotechnology, antimicrobial nanomaterials and neuromorphic computing architectures.

Recent years have accelerated this transformation. Researchers can now fabricate once-impossible metal-nitride nanocrystals, design logic-gated nanoparticles that activate immune pathways only inside tumors, and screen hundreds of millions of catalyst compositions in a single afternoon to discover low-cost alternatives for green-hydrogen production. Self-assembling “smart” nanostructures that reshape into tumor-clinging fibers, ultra small silica particles that remodel the tumor microenvironment without any drug cargo, and biochar-derived nanocomposites that simultaneously store energy and sequester carbon illustrate how nanoscale control is already translating into clinical, environmental and industrial impact.

As the ability to organize these building blocks into functional superstructures continues to advance-and as AI-driven design and high-throughput synthesis further compress discovery timelines-nanotechnology is poised to reshape materials science, medicine, energy systems and environmental remediation on a commercial scale.

Nanotechnology continues to reshape innovation across an expanding range of fields-from advanced manufacturing and photonics to biomedicine, energy conversion, catalysis, space systems, and next-generation electronics-by exploiting the distinctive behaviors that emerge when matter is engineered at the atomic scale.

Recent progress has made it possible to form germanium quantum dots smaller than 10 nm with precise spatial control and tunable confinement, opening pathways to CMOS-compatible single-electron devices, high-speed photo detectors spanning visible-to-telecom wavelengths, and efficient light-emitting structures. Because the optical absorption and emission of these dots shift systematically with size, researchers can now engineer band gaps on demand, accelerating the development of quantum-dot lasers, room-temperature single-photon sources, and plasmon-enhanced optical links. Complementary advances in perovskite and cadmium-free colloidal quantum dots have delivered continuous photon emission lasting many hours without blinking, while scalable synthesis routes now embed germanium nanocrystals in oxide matrices with atomic-level precision.

At the same time, the defining feature of nanomaterials-their extremely high surface-to-volume ratio-remains the source of their exceptional chemical reactivity, mechanical strength, thermal and electrical conductivity, and optical response. These surface-dominated properties underpin a new generation of MRI contrast agents, including manganese-doped carbon nanodots that match the relaxivity of traditional gadolinium compounds while offering lower toxicity and dual fluorescence–MRI capability, as well as iron-oxide and fullerene-based constructs that improve both sensitivity and biocompatibility.

Collectively, these developments illustrate how control at the 1–100 nm scale is translating fundamental surface and quantum effects into practical technologies for imaging, energy, catalysis, and information processing.

Biogenic routes for nanoparticle fabrication and morphological tuning

Eco-friendly hybrid strategies continue to refine the production of multifunctional nanocomposites. In one established semi-biological approach, magnetite cores are first generated by conventional co-precipitation of ferrous and ferric ions; an ethanolic extract of *Eucalyptus camaldulensis* then simultaneously reduces Au^{3+} ions onto the iron-oxide surface and caps the resulting Au–Fe_3O_4 particles, yielding stable 6–20 nm hybrids suitable for magnetic separation and biomedical functionalization. More recent green protocols have expanded this concept, employing extracts from related *Eucalyptus* species or other medicinal plants (e.g., *Pimenta dioica*, *Myrtus communis*) to generate biocompatible iron-oxide–gold or pure magnetite nanoparticles with improved dispensability, super paramagnetic behavior and theranostic potential for MRI, hyperthermia and photo thermal applications.

Early landmark work by Armendariz and colleagues demonstrated that wheat biomass could reduce aqueous Au(III) (0.3 mM potassium tetrachloroaurate) at ambient temperature across pH 2–6, producing a diverse population of face-centred-cubic gold nanostructures-tetrahedral, hexagonal, decahedral, icosahedral multi-twinned, irregular and rod-like particles. Parallel experiments with powdered oat (*Avena sativa*) biomass under identical conditions (0.1 mM Au(III), pH 2–6, 1 h) yielded the same morphological spectrum. Biomass surface chemistry is decisive: at lower pH the prevalence of protonated amino, sulfhydryl and carboxyl groups brings Au(III) ions into closer proximity to reductive sites, facilitating both nucleation and anisotropic growth. Across alfalfa, wheat and oat systems, acidic conditions (especially pH 2) favour irregular shapes, yet pH exerts its strongest influence on particle size rather than absolute morphology. Complementary observations with sterilized geranium (*Pelargonium graveolens*) leaves showed rapid, spontaneous reduction of chloroaurate ions to polydisperse yet stable colloidal gold.

Contemporary reviews reaffirm that plant- and microbe-mediated synthesis remains highly tunable by reaction parameters-particularly pH, precursor concentration and phytochemical profile-allowing deliberate selection of spherical, rod-like, flower-like or multi-twinned architectures without toxic chemical reductants. These advances are driven by the intrinsic nanoscale phenomena that distinguish nanoparticles from bulk materials: as diameter decreases, the surface-to-volume ratio rises sharply, elevating the fraction of surface atoms and thereby generating distinctive optical, electronic, magnetic, catalytic and mechanical properties. The same size-dependent surface energy underpins the design of next-generation MRI contrast agents, including ultra small iron-oxide particles, gadolinium-encapsulating fullerenes and carbon-nanotube nanocages, as well as a broadening suite of biogenic metal and metal-oxide platforms for oncology, antimicrobial therapy and environmental remediation.

Green Plant Routes for Tunable Silver and Gold Nanoparticles

Early work with sundried *Cinnamomum camphora* leaf biomass showed near-complete reduction of $AuCl_4^-$ within 60 minutes, producing 20–40 nm gold particles that were mainly decahedral or icosahedral. The same material also generated 55–80 nm silver nanoparticles or triangular and spherical gold particles at room temperature, with size and shape easily adjusted simply by changing the biomass-to-precursor ratio.

Current approaches have moved beyond whole biomass to concentrated plant extracts rich in flavonoids, polyphenols and terpenoids. These molecules rapidly reduce Ag^+ and Au^{3+} ions while capping the nascent particles, yielding highly stable 5–50 nm nanoparticles of controlled morphology under mild aqueous conditions. Recent studies confirm that extracts from *C. camphora*, *Stevia*, *Ocimum*, *Aloe* and many other species produce biocompatible Ag and Au nanoparticles with strong antimicrobial activity and selective cytotoxicity against cancer cells, outperforming chemically synthesized counterparts in safety and efficacy.

The same green platform is now used to nanoformulate traditional herbal actives from turmeric, ginseng, ashwagandha and related plants, markedly improving their bioavailability for oncology, metabolic and neurodegenerative therapies. Collectively, plant-mediated synthesis has become a scalable, eco-compatible route that delivers both functional nanomaterials and enhanced phytomedicines.

Global Arsenic Threat in Groundwater Remains Urgent

Naturally occurring and anthropogenic arsenic continues to endanger drinking-water supplies for hundreds of millions of people, especially in rural South and Southeast Asia. Recent assessments confirm that more than 100 countries report groundwater arsenic above the WHO guideline of 10 µg/L, with particularly severe exposure in the Ganga–Brahmaputra–Meghna basin and the Delta of Myanmar, where tens of millions remain at risk of skin, lung, bladder and other cancers as well as chronic systemic disease.

Arsenic occurs mainly as inorganic arsenate (As^{5+}) and the more mobile, toxic arsenite (As^{3+}). Redox conditions, microbial activity and interactions with iron oxides and sulfide minerals control its release from Holocene sediments into shallow aquifers. Microorganisms and higher organisms further transform inorganic arsenic into methylated organic forms, altering both mobility and toxicity. In Bihar and the broader Indo-Gangetic plains, 2024–2025 surveys show widespread exceedances in shallow wells, with arsenic also entering the food chain through irrigated rice and wheat, compounding dietary exposure.

Although the WHO limit of 10 µg/L remains the international benchmark, new evidence indicates that even lower chronic exposures carry measurable cancer risk, prompting calls in some jurisdictions for stricter standards. Mitigation efforts-safer deep aquifers, household filters and switching to alternative sources-have reduced exposure in parts of Bangladesh and elsewhere, yet large unprotected populations still face elevated health risks across the affected regions.

Geological Controls on Arsenic Occurrence and Green Nanotechnology-Based Remediation

The spatial distribution of arsenic in the Ballia and Ghazipur districts of eastern Uttar Pradesh is strongly governed by the hydrogeological characteristics of the Indo-Gangetic alluvial aquifer. The region comprises both Pleistocene (older) and Holocene (younger) alluvial deposits, with groundwater from the younger Holocene sediments consistently exhibiting higher arsenic concentrations. These younger sediments are rich in fine-grained clay, silt, iron oxyhydroxides, and organic matter, creating reducing (anoxic) subsurface conditions that promote the microbial dissolution of iron minerals and the subsequent release of adsorbed arsenic into groundwater. In contrast, the older oxidized alluvial formations generally contain comparatively lower arsenic concentrations due to their better-drained and more stable geochemical environment.

Recent investigations indicate that the primary source of arsenic is geogenic rather than anthropogenic. Arsenic-bearing minerals, transported from the Himalayan hinterland through the Ganga river system over geological time, became incorporated into floodplain sediments. Continuous sediment deposition, periodic flooding, and natural redox transformations have resulted in localized arsenic enrichment, particularly in low-lying floodplain areas of Ballia, while Ghazipur generally exhibits moderate but spatially variable contamination. Seasonal hydrological processes further influence arsenic mobility; groundwater levels, recharge patterns, and changes in oxidation-reduction conditions following the monsoon can alter dissolved arsenic concentrations and its speciation between As(III) and As(V).

Sustainable Nanomaterials for Arsenic Removal

The growing burden of arsenic contamination has accelerated the development of advanced groundwater treatment technologies. Conventional methods such as chemical coagulation, ion exchange, reverse osmosis, membrane filtration, and electro coagulation are effective but often involve high operational costs, sludge generation, or complex maintenance. Adsorption remains the most practical and economically feasible approach because of its operational simplicity, high efficiency, and suitability for decentralized rural water treatment systems.

Among emerging adsorbents, iron-based nanomaterials have attracted considerable attention owing to their exceptionally high surface area, abundant reactive sites, magnetic recoverability, and strong affinity for both [As(III)] and arsenate [As(V)]. Commonly investigated nanomaterials include magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), hematite (α-Fe_2O_3), iron oxyhydroxides (FeOOH), and nanoscale zero-valent iron (nZVI). Magnetite and maghemite are especially promising because their super paramagnetic nature enables rapid separation from treated water while maintaining excellent adsorption performance.

Traditional nanoparticle synthesis techniques-including sol-gel processing, hydrothermal methods, co-precipitation, micro emulsion, and electrical wire explosion-generally require hazardous chemicals, elevated temperatures, and substantial energy inputs. Consequently, research has shifted toward green synthesis strategies that utilize renewable biological resources as environmentally benign reducing and stabilizing agents. Plant extracts, algae, fungi, bacteria, and other biological materials contain naturally occurring phytochemicals such as flavonoids, phenolic acids, tannins, polysaccharides, proteins, and enzymes that facilitate nanoparticle formation under mild reaction conditions without toxic reagents.

Agricultural residues have emerged as particularly attractive feedstocks for sustainable nanoparticle production because they combine low cost with waste valorization. Onion peel (*Allium cepa* L.), an abundant agro-industrial by-product, is exceptionally rich in quercetin, polyphenols, flavonoids, and antioxidant compounds that efficiently reduce and stabilize iron nanoparticles. Likewise, corn silk (*Zea mays* L.), another underutilized agricultural residue, contains bioactive phytochemicals, carbohydrates, proteins, minerals, and natural antioxidants capable of supporting eco-friendly nanoparticle synthesis.

Recent studies have demonstrated that magnetite nanoparticles synthesized from onion peel and corn silk extracts exhibit excellent physicochemical properties and significant arsenic adsorption capacity. Comprehensive characterization using scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), Brunauer-Emmett-Teller (BET) surface area analysis, vibrating sample magnetometry (VSM), and zeta potential measurements confirms their crystalline structure, surface functionality, magnetic behavior, and adsorption characteristics. Compared with chemically synthesized nanoparticles, these green nanoadsorbents offer lower production costs, reduced environmental impact, improved sustainability, and comparable or superior arsenic removal efficiency. Consequently, plant-mediated magnetic nanoparticles represent a promising next-generation technology for developing affordable, environmentally sustainable, and scalable groundwater purification systems in arsenic-affected regions such as Ballia, Ghazipur, and the wider Indo-Gangetic Plain.

Green Water Treatment: Emerging Directions

Green water treatment is entering a new phase, especially in the fight against arsenic contamination in groundwater. In recent years, advanced nanomaterials have gained strong attention because of their high efficiency, tunable surface properties, and broad usefulness in areas such as catalysis, purification, medicine, and food processing. At the same time, the urgent pressure on freshwater supplies has accelerated the search for cleaner, smarter, and more sustainable treatment technologies. Even though the environmental footprint of nanotechnology is still debated, its rapid progress shows clear potential for future water remediation. Among the most promising developments is the membrane bioreactor (MBR), which combines biological treatment with membrane-based separation such as microfiltration and ultra filtration. When MBR is linked with systems like electro coagulation, reverse osmosis, forward osmosis, biofilm membranes, and granular MBR, it becomes a more robust and eco-friendly solution. These hybrid approaches are increasingly viewed as the next step in wastewater treatment, offering better removal efficiency, improved safety, and stronger sustainability.

Conclusion

The growing occurrence of arsenic and other emerging contaminants in groundwater continues to challenge global efforts toward achieving universal access to safe drinking water. Climate change, rapid industrialization, urban expansion, and increasing freshwater scarcity have further intensified the need for innovative, sustainable, and energy-efficient water treatment technologies. In this context, nanotechnology has emerged as a transformative approach owing to the exceptional physicochemical properties of engineered nanomaterials, including high adsorption capacity, tunable surface chemistry, and superior catalytic performance. Recent advances in nanocomposites, bio-inspired nanomaterials, membrane-based nanofiltration, and photo catalytic systems have significantly improved the removal of toxic metals while reducing operational costs and chemical consumption. Furthermore, the integration of nanotechnology with artificial intelligence, real-time sensing, and decentralized treatment systems is creating new opportunities for smart and resilient water purification. Nevertheless, concerns regarding nanoparticle toxicity, environmental persistence, large-scale manufacturing, material recovery, and regulatory compliance must be addressed before widespread implementation. Future research should prioritize the development of eco-friendly, recyclable, and commercially scalable nanomaterials that support circular economy principles and sustainable water management. With continued technological innovation and appropriate environmental safeguards, nanotechnology is expected to play a pivotal role in securing clean and safe water resources for future generations.

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