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# Ecofriendly Iron Nanomaterial for Affordable Arsenic Free Drinking Water

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ABSTRACT

Arsenic in drinking water is a grave environmental and public health concern in several countries – especially India, Bangladesh, Nepal, and parts of South America. Long-term use of arsenic-tainted water leads to skin disorders, cancer, and various heart and brain illnesses. Conventional arsenic remediation techniques are usually not suitable for rural settings as they tend to be costly and complex. Ecofriendly iron nanomaterials have come forth as a highly effective, affordable, and sustainable solution to eliminate arsenic from water. Thanks to their large surface area and high adsorptive capacity, iron nanoparticles represent an effective means of removing arsenic from polluted water. The present work elaborates on the manufacturing, characteristics, mechanism, applications, benefits, shortcomings, and future trends of ecofriendly iron nanomaterials to produce affordable arsenic-free drinking water for rural population.

## Introduction

The adoption of eco-friendly iron nanomaterials for arsenic elimination aims at achieving sustainable, efficient, and cheap approaches to deal with the global problem of water pollution. Unlike traditional technologies, these eco-friendly materials are produced using natural extracts and some recycled components to make the arsenic removal process cheaper especially in the areas with limited resources.

**The global arsenic problem**: Geogenic arsenic contaminating groundwater is a significant public health issue because of chronic toxicity resulting from long-term exposure. Thus there is a huge need for "affordable and eco-friendly" arsenic removal technologies.

**Nano-advantage:** Iron nanoparticles (FeNPs)have a very large surface area in relation to their volume, thus enabling effective removal of arsenic from water at very low concentrations and generating minimum sludge.

**Eco-friendly synthesis (Green route):** Currently scientists focus on the "green synthesis" approach because it implies no use of toxic chemicals for iron reduction and stabilization since plant bio-antioxidants (such as polyphenols), derived from waste materials (such as banana and mango peels and green tea), are used for this purpose. The modern technologies of eco-friendly iron nanomaterials bring a revolutionary solution to the problem of providing affordable arsenic-free water.

## Literature Review

**Water pollution and arsenic contamination-**Water is necessary for human existence, but clean drinking water is getting rare because of industrialization and pollution. Water sources are getting contaminated with numerous substances; arsenic is one of the most toxic pollutants in groundwater. Though the sources of arsenic contamination can be many, the principal cause of arsenic contamination can be attributed to natural geological processes, which include the weathering and dissolution of arsenic minerals present in soils and sediments, which enter the groundwater supply. While industries play a role in arsenic contamination, this process appears to be the main cause of the widespread problem. Some of the geological processes that can be classified as natural arsenic contamination processes are- Geochemical processes resulting in the existence of arsenic in groundwater include:

**Geochemistry of aquifers**-Dissolution of arsenic from sediments into groundwater is the main cause because aquifers are found in abundance in the Bengal Delta region (basins of the Ganges and Brahmaputra rivers).

**Weathering of arsenic minerals**-Events of natural weathering of rocks and soils that contain arsenic minerals such as arsenopyrite. Natural processes of excavation of minerals from rocks

**Mining activity**-Mining activity is a process of obtaining valuable minerals from the Earth, which includes surface mining, underground mining, placer mining, and in-situ mining. Mining ensures the availability of invaluable raw materials for modern technologies and infrastructure but can also lead to adverse environmental consequences, such as soil degradation, deforestation, and pollution of water bodies.

**Types of mining activities include:**-Surface mining - includes removal of over Underground Mining involves gaining access to deeper mineral deposits by digging shafts and tunnels accompanied by complex safety and ventilation systems. Placer Mining refers to the process of mining valuable metals and minerals from riverbeds and floodplains. In-situ Mining refers to the mining technique that involves the dissolving of valuable metals without mining and pumping the solution to the surface.

**Industrial Waste-** Industrial waste is the unwanted or non-desired waste that arises from manufacturing, industrial and mining operations. It includes both solids and liquid waste. Industrial waste is usually toxic and bleak. The proper management of industrial waste involves collection and the use of recycling methods.

**Types of Industrial Waste**

**Solid Waste**: Consists of waste such as scrap metal, wood, concrete and sludge.

**Liquid Waste**: Includes solvents, paint, acids, as well as waste water from the washing process.

**Hazardous Waste**: Refers to toxic materials, including flammable, toxic and corrosive wastes.

**Non-Hazardous Waste**: This is the waste that does not qualify for disposal as hazardous waste according to EPA regulations.

**Use of Pesticides and Fertilizers-**Pesticides and Chemical fertilizers are the basic chemicals used in agriculture for improving the yields. While they ensure food security, improper and reckless use may cause great harm.

**Elements of Fertilizer and Pesticide Usage-**Fertilizers are special fertilizers that provide soil three important nutrients, namely nitrogen, phosphate, potassium. Over-usage will result in loss of nutrients and soil pollution. Pesticides can be defined as agents including insecticides, herbicides, and fungicides that are utilized to control pests, weeds, and diseases which would otherwise damage crops and crops. Around 80% of the pesticide applications made across the world consist of herbicides.

**Environmental/Human Health Effects**: If used in excess, pesticides are capable of reducing the fertility of soils, polluting water, and increasing the production of greenhouse gases through the emission of NOs. Pesticide residues introduce health risks.

**Reasonable Use**: The application of pesticides should involve practices, such as reading instructions carefully, using the least toxic products, and applying fertilizers/pesticides on the basis of the nutrients needed.

**Green Solutions**: IPM is the green solution that advocates the use of biological and cultural methods of pest control, while organic fertilizers are gaining ground.

**Iron Nanomaterials-**Iron nanomaterials are iron compounds measuring from 1 to 100 nm and comprising of iron oxide (Fe3O4, gamma-Fe2O3) as well as its zero valent form (nZVI). Iron nanomaterials have a broad range of applications in medicine (e.g. in drug delivery and as MRI contrast agents), environmental repair, and industry thanks to high surface area and super paramagnetic properties.

**Properties**

Iron oxide nanoparticles Magnetite ($Fe_3O_4$) and maghemite (gamma-$Fe_2O_3$). Very stable and biocompatible.

Superparamagnetic iron oxide nanoparticles. Small particles (2-20 nm in size) that become magnetized only in external magnetic fields.

Nanoscale zero valent iron. It has core-shell feature (metallic iron core surrounded by an oxide shell). It has a high reactivity and is highly applicable in good pollution control.

**Core-Shell Nanoparticles**: It is made of iron that is encased in a layer of carbon, silica, or any precious metals, so it does not get oxidized easily.

**Applications**

**Biomedicines:** As the contrasting agents in MRI scanning, in targeted medicine delivery, and for applying the medical method of magnetic hyperthermia for cancer treatment.

**Environmental Applications**: nZVI is a reducing agent is capable of removing heavy metals such as mercury, chromium, and lead, as well as eliminating organic compounds from water and soil.

**Industrial Applications**: Used as catalysts, data storage instruments, and detectors.

**Synthesis methods**

**Chemical synthesis**: The widely adopted method to obtain the nZVI is chemical reduction. In this method ferric chloride (FeCl3) is subjected to treatment by chemical agents good for operating that purpose, such as sodium borohydride (NaBH4).

**Green synthesis**: It consists of cheap and eco-friendly processes that utilize different plants and herbs or different microorganisms for measurements.

**Physical techniques**: The methods used include ball milling methods or laser ablation.

**Advantages and challenges-** Advantages include broad use in biomedicine due to its great biocompatibility, low level of toxicity in comparison to other products, and efficiency in various processes, including magnetic ones. Challenges include fast rate of oxidation due to reactivity, the tendency of the product to aggregate, and need for coating to ensure stability.

**Green methods of synthesis-** The methods described above aim at obtaining nanoparticles using eco-friendly methods with different plants and microbes.

**Core green approaches include:**

Plant approach: Based on methods of utilizing plant extracts.

Microbial approach: Process carried out by different microorganisms such as bacteria or algae.

**Enzymatic approach**: The utilization of enzymes in the process.

Detailed procedure (using plant extraction process as an example)

**Preparation**: The preparation of extracts involves washing and drying plant samples. The extracting procedure itself is carried out using boiling water/ethanol t extract useful ingredients.

**Reduction:** A metal precursor and the extract are mixed together and this process leads to the results in the aggregation of the metal ions in the form of nanoparticles.

**Capping:** The use of plant extract enables one to receive nanoparticles that further need to be purified and controlled.

**Advantages**

**Eco-friendliness**: The choice of plant extracts instead of poisonous chemicals greatly reduces the negative outcome of the procedure.

Energy effectiveness: The application of the method does not require complicated procedures.

**Being cost-effective:** This is due to the use of cheap and available materials.

**Applications**

**In biomedicine**: Antmicrobial compounds, cancer treatment drugs, and medicine delivery systems. In environmental sphere: Removal of wastes and treatment of heavy metals.

**In catalyzing processes**: In enhanced photo-catalysis and catalytic reduction processes.

## Methodology

**List of Required Materials-**This set of material is typically used for the green synthesis of iron nanoparticles (nZVI or $Fe_3O_4$) to remove arsenic from water through adsorption. Here, the plant extract works as both a reducing agent and a capping agent, replacing harmful chemical agents.

**Required Materials and Functions**

**Iron Precursors**:- Ferric chloride ($FeCl_3 6H_2O$): Provides ($Fe^{3+}$) ions. Ferrous sulfate ($FeSo_4,7H_2O$ ): Provides ($Fe^{2+}$) ions. Using a mix of ($Fe^{3+}$),$Fe^{2+}$) typically produces magnetic magnetite ($Fe_3O_4$) nanoparticles.

**Reducing/Capping Agent:** Plant extract (Tea leaves/Neem): Contains polyphenols and other biomolecules that reduce (Fe) ions to nanoparticles and stabilize them, preventing agglomeration.

**pH Adjuster/Precipitant:**

**Sodium hydroxide (NaOH)**: Used to adjust the pH, typically to alkaline conditions (pH approx 10-11) to induce the precipitation of iron oxide/hydroxide nanoparticles.

**Solvent**: Distilled water/Deionized water: For preparing all aqueous solutions to avoid interference from impurities.

**Target Sample:** Arsenic-contaminated water: To test the efficiency of the synthesized nanoparticles.

**Typical Experimental Procedure**

**Extract Preparation**: Boil tea leaves or neem leaves in distilled water, filter, and cool to prepare the plant extract.

Mixing Precursors: Dissolve ($FeCl_3$) and ($FeSo_4$) in distilled water (often in a 2:1 or 1:1 ratio) and add the plant extract.

**Synthesis**: Add (NaOH) dropwise to the mixture under stirring until a black precipitate (indicating magnetite) forms.

**Washing:** Centrifuge the mixture, discard the supernatant, and wash the resulting nanoparticles multiple times with distilled water and sometimes ethanol to remove impurities.

**Drying**: Dry the nanoparticles, often at (50-70 circ C).

**Performance Characteristics**

**Particle Size**: Green synthesis often yields particles < 100 nm.

Arsenic Removal: The synthesized nanoparticles effectively remove both (As (III)) and (As (V)) at optimal (pH) (4-9).

Mechanism: The iron oxides formed (like magnetite) have a high surface area to absorb arsenate/arsenite ions.

**Green Synthesis Procedure-**The green fabrication of iron nanoparticles (FeNPs) employing plant extracts provides an eco-friendly, budget-friendly, and non-harmful technique. The method depends on the presence of phytochemicals, for instance, polyphenols, flavonoids, and terpenoids, so that they can be the reducing and capping agents.

The following is an upgraded and amplified green fabrication protocol based on conventional methods.

Optimized Green Synthesis of Iron Nanoparticles

**1. Preparation of Plant Extract**

**Collection & Cleaning**: Thoroughly wash fresh leaves (e.g., green tea, neem, and guava) with tap water followed by distilled water to

remove impurities.

**Boiling/Extraction**: Boil 5–20 g of leaves in 100 mL of distilled water (often for 5–30 minutes) until the water changes color (e.g., green or yellow).

**Filtration:** Filter the mixture using Whatman No. 1 filter paper to obtain a clear aqueous extract.

**Preparation of Iron Salt Solution**

Prepare a 1–10 mM iron solution, commonly using Ferric Chloride ($FeCl_3$ $6H_2O$) or Ferrous Sulfate ($FeSo_4 7H_2O$) dissolved in deionized water.

**Synthesis (Reduction Process)**

**Mixing:** Combine the plant extract and iron salt solution. Common ratios include 1:1 or 1:9 (extract:salt).

Stirring: Stir the mixture using a magnetic stirrer. The reaction can be done at room temperature or elevated temperatures (50-80 circ C) to speed up the process.

**pH Adjustment**: Adding a base like (1M) (NaOH) until the pH reaches 10–11 is often required to enhance the formation of iron oxide nanoparticles (magnetite,($Fe_3O_4$).

**Formation Confirmation (Color Change)**

**Observation:** The reaction is complete when the mixture turns black, dark brown, or greenish-black. This color change indicates that the plant phytochemicals have reduced the ($Fe^{2+}$) ($Fe^{3+}$) ions into iron nanoparticles.

**Separation and Cleaning**

**Centrifugation:** Collect the nanoparticles by centrifuging the solution, typically at 6,000–15,000 rpm for 15–20 minutes.

Washing: Wash the resulting pellet 2–3 times with distilled water and/or ethanol to remove excess plant extract and unreacted ions.

**Drying and Storage**

**Drying:** Dry the purified nanoparticles in a hot air oven (60-80circ C) for 3–24 hours or use a vacuum oven to avoid oxidation.

Storage: Store the resulting nanopowder in an airtight container, preferably in a vacuum desiccator, to prevent oxidation, as small iron particles are highly reactive.

**Characterization Techniques-** Nanoparticle characterization techniques give proper knowledge of how nanoparticles are formed, their shape, and their structure. The main techniques are UV-Vis Spectroscopy, which helps in determining the generation of nanoparticles with the help of Surface Plasmon Resonance (SPR); SEM, which helps to see the detail of surface morphology of particles; and XRD, which involves the determination of phase purity and crystalline structure of nanoparticle.

Nanoparticle Characterization Techniques

UV-Visible Spectroscopy (UV-Vis)

Purpose: Confirms nanoparticle formation and estimates particle size/stability.

Mechanism: Measures the extinction (absorption + scattering) of light by colloidal nanoparticles in the UV-visible range.

Application: Identifies the characteristic Surface Plasmon Resonance (SPR) peak for metal nanoparticles (e.g., silver nanoparticles typically show peaks around 400–450 nm).

Scanning Electron Microscopy (SEM)

Purpose: Determines morphology (shape), size distribution, and surface features.

**Mechanism:** Uses a high-energy electron beam to scan the surface of a solid sample to create high-resolution 3D-like images.

**Application:** Provides visual evidence of nanoparticle shapes (spherical, rod, triangular) and surface topography.

X-Ray Diffraction (XRD)

**Purpose**: Determines crystalline structure, crystal phase, and crystall te size.

**Mechanism:** Analyzes the diffraction pattern of X-rays passed throug a solid powder sample to determine atomic spacing.

**Application**: Uses the Scherrer equation to estimate the average crystallite size based on peak broadening.

**Complementary Techniques-**Transmission Electron Microscopy (TEM): Provides higher magnification than SEM to determine inner structure and detailed size.

Energy Dispersive X-ray Spectroscopy (EDX/EDS): Typically attached to SEM to provide elemental composition.

**Dynamic Light Scattering (DLS):** Measures hydrodynamic size and Zeta potential (stability) in colloidal dispersions.

**Arsenic Removal Experiment-**In this experiment, a widely used yet successful laboratory technique for the removal of arsenic from water using iron nanoparticles is illustrated (often interpreted as Zero-Valent Iron (nZVI) or iron oxide nanoparticles). In this process, iron nanomaterials create wider surface area for the adsorption of arsenic (both As (III) and As (V)), which is later filtered out, typically achieving \ (>90\ %\) removal efficiency.

Procedure Breakdown

**Add iron nanoparticles to contaminated water:**

**Types**: Zero-valent iron (nZVI), Magnetite ($Fe_3O_4$), or Iron-doped Activated Carbon.

**Dosage**: Typically 0.24 g/L to 2.0 g/L is required depending on arsenic concentration.

**Tip**: If using nZVI, it is often more effective than magnetite alone, especially over a wide pH range (3–9).

**Stir for 30–60 minutes:**

**Reasoning**: Agitation ensures maximum contact between the adsorbent surface and the arsenic species.

Optimization: While the 30–60 min range is good, some studies show maximum adsorption can occur within 20–30 minutes.

**Filter the solution:**

**Method**: Centrifugation (e.g., 5,000 rpm) or filtration using 0.22 (mu m) – 0.45 (mu m) filter paper/syringe filters.

**Alternative:** If using magnetic iron nanoparticles, a magnet can be used for separation instead of filtration.

Measure arsenic concentration before and after treatment:

**Techniques:** Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectroscopy (AAS) are used to detect low levels of arsenic, often aiming to meet the WHO guideline of (<10 mug/L).

**Optimal Conditions**

pH: The process is often most effective in acidic to neutral conditions (pH 2–6), although some nanoparticles work well up to pH 9.

Result: When properly optimized, this method can remove over 90–99% of arsenite and arsenate from water.

## Results and Discussion

The change in color from light yellow to dark brown is a visible sign of AgNPs formation. This means that ions in the solution are going through the reduction process of turning into a solid that is metallic silver, due to one of the reducing agents found in either plant or microorganism extracts.

•Surface Plasmon Resonance (SPR): The brown color is a result of the surface plasmon resonance phenomenon that occurs due to free electrons moving when exposed to external light. It is the reason for the appearance of the color owing to the absorption of specific light wavelengths.

•Progress of Reaction: The stronger the color indicates the longer the nanoparticles formation process took.

•Green Synthesis: Change from yellow to brown is often seen in the cases of green synthesis methods in which phyto-materials serve as both reductive and capping agents.

•Confirmation: While the change in color is an indicator of the nanoparticles formation, it is usually confirmed by some other methods, such as UV-Vis spectroscopy that gives peaks indicating the presence of AgNPs.

The table below summarizes some common observations encountered in the literature:

•Silver (Ag): light yellow - brown

•Gold (Au): pale red or red, but not brown

•Nanoparticles formation: yellow (mixture) turns into brown indicating that the Ag+ ion URES were transformed into powders in a spherical or non-oriented form.

**Effectiveness of Arsenic Removal**

Based on the provided data, the process of arsenic removal is very efficient (90% - 92.5%), as it is observed also for other advanced technologies like coagulation-flocculation (using ferric chloride or aluminum sulfate) or membrane technologies, which include RO.

| Initial Arsenic (mg/L) | Final Arsenic (mg/L) | Removal Efficiency(%) |
|---|---|---|
| 0.50 | 0.05 | 90 |
| 1.00 | 0.08 | 92 |
| 2.00 | 0.15 | 92.5 |

**Efficiency**: The technique is able to remove more than 90%.

End Concentration: The minimum end concentration of this study is 0.05 mg/L (or 50 µg/L). It satisfies some district requirements however, it fails to meet WHO standard requirements of (0.01 mg/L) (or 10 µg/L), which calls for more effectiveness to attain the success.

**Concentration Efficiency**: Data reveals that starting with the concentrations of 2.00 mg/L; it is possible to extract a considerably larger part of 92.5%.

**Using Technological Solutions-** The set goal has been achieved with the help of:

**Coagulation/Filtration**: the implementation of ferric chloride and the usage of optimal pH for the emergence of ferric hydroxide flocs filled with arsenic compounds.

**Adsorption**: taking activated alumina and bulky hydroxide.

**Membrane Technologies**: applying nanofiltration and reverse osmosis methods.

**Drawbacks-** Problems related to the issues of the nanoparticle aggregation, large-scale manufacturing difficulties, and iron leaching mentioned in 4.6 of the paper related to iron-based nanoparticles make industrialization and biomedical application difficult. To be honest, these matters cause reduced effectiveness, lesser area of the surface, and higher toxicity levels.

**Limitations**

1. Nanoparticle Aggregation (or Agglomeration):

a. Reasons: the presence of high surface energy and Van der Waals forces cause's nanoparticles to agglomerate and thus lose their specific nanoscale features;

b. Impact: this process leads to a decrease of the surface area which hinders adsorption in such processes as wastewater treatment;

c. Magnetic dipole-dipole interaction: the attraction of the particles will be magnetic.

d. Prevention: Surface functionalization is one of the solutions.

2. Large-scale Production Problems:

a. Difficulties in the Manufacturing Process: one of the simplest methods but inefficient is co-precipitation.

b. Controlled Manufacturing Method: another one is thermal decomposition.

c. Cost Efficiency: moreover, partially high prices of nanoparticles production restrict its industrial application.

**Possible Iron Leaching (or Dissolution):**

a. Stability Problems: iron nanoparticles will dissolve and lose iron ions.

b. Toxicity Issues: this fact leads to serious issues connected with toxicity.

In order to overcome obstacles, the research investigates:

Modification of Surface: usage of capping agents, surfactants, coating materials to eliminate agglomeration as well as leaching.

Green Manufacturing: application of the types of materials which are either plant-based or microorganism-based in order to create more stable and biocompatible iron nanoparticles.

Exact Synthesis: making precise choices of the means of synthesis.

**Comparison of Technologies**

In light of the data provided in the table, let's make a comparison between the three above-mentioned technologies of treating water.

Comparison with Conventional Methods

| Method | Cost | Efficiency | Eco-friendly |
|---|---|---|---|
| **Reverse Osmosis** | High | High | Moderate |
| **Ion Exchange** | High | Moderate | Low |
| **Iron Nanomaterials** | Low | High | High |

• [Iron Nanomaterials] represent the most promising alternative, offering high efficiency and eco-friendliness at a low cost.

• [Reverse Osmosis] is highly efficient but comes with high capital and operating costs.

•[Ion Exchange] is limited by lower efficiency and lower environmental friendliness compared to modern nano-based solutions.

## Conclusion

Innovative eco-friendly iron nanomaterials promise to be a viable source of arsenic-free drinking water thanks to:

1. High efficiency
2. High level of safety
3. High cost-effectiveness
4. Use in rural water treatment facilities
5. Impact on global water pollution.

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