IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Inorganic Pollutants In Groundwater Of Birbhum District, West Bengal: Detection And Removal Techniques

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Abstract

The groundwater in the Birbhum district of West Bengal plays a critical role in meeting domestic, agricultural, and industrial needs. However, it is increasingly threatened by contamination from various inorganic pollutants. Naturally occurring elements such as fluoride, arsenic, iron, and manganese, alongwith anthropogenic substances like nitrate, phosphate, and heavy metals, have been identified at concentrations that exceed permissible limits in several parts of the district. These pollutants arise from both geogenic processes, including the weathering of mineral-laden rocks, and human activities such as unregulated mining, huge agricultural activity, and industrial effluents. This review provides a comprehensive overview of the occurrence, hydrogeochemical behaviour, and spatial distribution of different inorganic pollutant found in this region. It also highlights both traditional and innovative methods for detection and removal techniques of inorganic pollutants from groundwater. Finally, the review addresses the main challenges, including seasonal fluctuations, inadequate infrastructure, and community involvement, and suggests future directions for developing low-cost, decentralized, and sustainable groundwater treatment systems.

Introduction

Groundwater is one of the most important natural resources supporting life on Earth. The majority of the global population rely on groundwater to meet their daily needs, particularly for drinking water [1]. In India, many people, particularly those in rural and semi-arid areas, rely on groundwater as their main source of drinking water, agricultural irrigation, and household use. This is due to the unreliable availability and often poor quality of surface water [2]. The Birbhum district, located in western West Bengal, is geologically and environmentally sensitive. It consists of granite gneiss, laterite and lateritic soils, and experiences significant mining activity [3]. In recent decades, this area has faced growing threats from inorganic pollutants in its groundwater and soil systems.

Inorganic pollutants, such as nitrate, heavy metals (e.g., lead, cadmium, chromium), and selenium are naturally present in the Earth's crust but can become hazardous when mobilized into the environment in concentrations exceeding permissible limits. These pollutants often originate from geogenic sources, such as the weathering of fluoride or arsenic-bearing minerals [4], as well as from anthropogenic activities like unregulated mining, industrial discharge, and excessive use of fertilizers. The presence of fluoride in drinking water, while beneficial in trace amounts for dental health, becomes a serious health hazard when it exceeds 1.5 mg/L as per WHO guidelines, leading to dental and skeletal fluorosis. Similarly, arsenic, often mobilized under reducing conditions in groundwater [5], is a known carcinogen associated with various forms of cancer and chronic health conditions. Iron and manganese, though essential micronutrients, become problematic in high concentrations, affecting the palatability and colour of water and leading to infrastructural corrosion. Birbhum, especially its western blocks such as Rajnagar, Khoyrasol, and Dubrajpur, is known for extensive stone quarrying and mining activities that significantly contribute to silica dust and heavy metal contamination.

Over the years, various techniques have been developed to detect and remove these inorganic contaminants. These range from traditional chemical tests to newer geospatial and spectrometric methods. Innovative treatment strategies, such as adsorption, coagulation, electrochemical methods, and in-situ remediation, have also been explored to effectively reduce these pollutants [6, 7].

This review aims to examine the occurrence, sources, and distribution of major inorganic pollutants in Birbhum district. It specifically focuses on detection methods and removal technologies that fit the region's environmental and socio-economic conditions. By combining available literature, field studies, and government reports, this review highlights current challenges and suggests future directions for effective pollutant management in the district.

2. Occurrence & Hydrogeochemical Characterization

The distribution of inorganic pollutants in the groundwater and surface environment of Birbhum district is influenced by natural geological processes and human activities like mining, agriculture, and overuse of groundwater. The spatial distribution, source pathways, and hydrogeochemical processes affect the movement and concentration of major inorganic pollutants.

Fluoride

It was in 1997 that the first presence of fluoride-contaminated groundwater was found in West Bengal. Nasipur, in the district of Birbhum and part of Nalhati I block, has been reported to have exceeded the standard [8]. Mostly Tube wells which extract water from basaltic rocks of the Rajmahal Traps (Western Part of Birbhum District) were discovered to be the primary source of fluoride issues. Low levels of fluoride were detected in dug wells, ponds, and shallow tube wells that accessed alluvial deposits.

Fluoride in groundwater primarily originates from a geogenic source [9]. The majority of fluoride in groundwater comes from weathering of granites and felsites rocks, which contain fluoride-bearing minerals such as fluorspar, cryolite, fluorapatite, and hydroxyapatite, leaching processes, and subsequent percolating through soil and sediments [10]. A number of anthropogenic activities also significantly increase the concentration of fluoride in groundwater with fluorinated industrial waste from iron, steel, glass, and aluminum industries, or agricultural activities by using phosphate fertilizers and certain pesticides [11]. The factors contributing to groundwater fluoride poisoning include pH-dependent dissolution, aqueous ionic concentrations, interactions between rock and water, prolonged contact time, atmospheric deposition, and the mobilization of carbonate and bicarbonate ions. [10, 12]

Arsenic

In India, the groundwater contamination of arsenic was first recognized in the state, West Bengal in the early 1980s [13]. A significant geographical region of India is impacted by the issue of geogenic arsenic, however, the majority of the affected states are located in the extensive alluvial plains and delta of the Ganges-Brahmaputra river system, specifically Assam, Bihar, and West Bengal, which account for approximately 92% of the affected population. The mechanism of arsenic release from sediments to aquifers is yet not well established, although several processes were proposed for responsible for the excessive groundwater arsenic concentration such as alkali desorption, reductive dissolution of iron-containing minerals, sulfide minerals oxidation, crustal processes and geothermal activity, leaching and weathering of silicate and carbonate minerals, redox processes, exchange with surface water, and anthropogenic actions [14 -18].

Iron & heavy Metals

Groundwater quality in the Birbhum district of West Bengal is greatly impacted by iron (Fe) and other trace metals like manganese (Mn), lead (Pb), and chromium (Cr). These metals are naturally found in aquifer systems due to geological processes, but they often exceed safe limits because of natural and human influences. The western and central parts of Birbhum, known for their lateritic and granitic landscapes along with extensive mining operations, have shown troubling levels of metal contamination in groundwater. This situation poses risks to public health and water use.

Iron gets into groundwater through the breakdown of ferric oxides in low-oxygen conditions. The deeper confined aquifers, especially in lateritic areas, promote this process due to their low oxygen levels.

Manganese (Mn) usually occurs with iron and is released under even stronger reducing conditions, often at the same time as iron [19]. In certain blocks, such as Rampurhat II, Dubrajpur, and Suri I, iron levels often go beyond the safe limit for drinking water [20]. However, the problem of heavy metal contamination in groundwater has not been fully explored in this district yet.

Nitrate and phosphate

Birbhum district's economy is mostly dependent on agriculture. The district's irrigation sites frequently utilise phosphate and nitrate fertilisers and pesticides. The primary source of nitrate and phosphate pollution in groundwater is the unscientific use of nitrogen and phosphorus based fertilisers [21]. Leaching from agricultural fields, large amounts of NO_3^- and PO_4^{3-} enter into the subsurface. Nitrate is easily carried by percolating water because it is not readily adsorbed onto soil particles. It is common to find high nitrate levels in shallow aquifers. Unlike nitrate, groundwater phosphate concentrations are often low but they can increase in regions with high levels of organic matter and microbial activity.

3. Detection Techniques

Several analytical techniques are used to detect inorganic pollutants in groundwater. The selection of techniques depends on the factor like sensitivity, specificity and applications. UV-Visible spectrophotometry is widely used for detection of nitrate, phosphate, and iron because of easy to use and cost-effectiveness. Atomic Absorption Spectroscopy (AAS) and its more advanced form to quantitative detection of trace metals, Ion Chromatography (IC) is effective for separating and quantitative detection major anions and cations. Electrochemical methods like ion-selective electrodes (ISE) and anodic stripping voltammetry (ASV) operate for precise detection of specific ions. X-ray Fluorescence (XRF) spectroscopy is very useful for finding metal in solids and sediments. Biosensors present promising possibilities for real-time, selective pollutant monitoring. Together, these techniques provide a thorough toolset for evaluating the pollutant of groundwater (Table 1) [21, 22].

Table 1. Comparison studies of various Detection Techniques

Technique	Pollutants Detected	Detection Limit	Applications
UV-Vis Spectrophotometry	Nitrate, phosphate, iron	~mg/L	Common in field labs
AAS / GFAAS	Heavy metals	~µg/L – ng/L	Single-element analysis
ICP-OES	Multi-element (metals/metalloids)	~µg/L	Fast, multi-element
ICP-MS	Ultra-trace metals	~ng/L – ppt	Very sensitive, costly
Ion Chromatography	Major anions/cations	~µg/L	High accuracy
ISE	Nitrate, fluoride	~mg/L	Portable, quick results
XRF	Metals (mostly solids/sediments)	~ppm	Field deployable, less sensitive
Field Kits	Nitrate, iron, fluoride, arsenic	mg/L	Good for preliminary screening
Biosensors	Heavy metals, nitrate	Variable	Advanced, still developing

4. Removal Techniques

Adsorption

One of the most widely used and effective techniques for removing inorganic pollutants such as fluoride, arsenic, phosphate, lead, cadmium, and chromium from groundwater is adsorption [23]. Simple mechanism, low cost and relatively low energy requirement make it ideal for rural and decentralized water treatment. Absorbents like activated alumina, biochar, zeolites, iron oxides etc. are use to adsorb contaminants onto their surface. In this process molecules or ions from groundwater adhere to the surface of solid materials. The regenerability of adsorbents is the advantages of this technique. Materials like activated alumina can be regenerated using alkaline or acid solutions but it required Periodic regeneration or replacement.

Ion exchange

Ion exchange is a widely used physicochemical water treatment process that involves the reversible exchange of ions between a ion exchange resin and groundwater. This technique has high efficiency, especially for anions. It is particularly effective for the removal of charged inorganic species such as nitrate (NO_3^-), fluoride (F^-), sulfate (SO_4^{2-}), arsenate (AsO_4^{3-}), and heavy metals (e.g., Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}). Due to its high selectivity ability to regeneratel, ion exchange is commonly utilised in both domestic and industrial-scale groundwater treatment [24, 25]. The resins are synthetic polymers that contain functional groups capable of binding and exchanging specific ions.

Coagulation-flocculation

Coagulation-flocculation is a well known and fundamental physicochemical process used in to remove inorganic pollutant like fluoride, arsenic, iron, manganese, and heavy metals from groundwater. This technique involves addition of a coagulant like alum or ferric chloride to groundwater to destabilize dissolved and colloidal particles by neutralizing their surface charges. This is followed by rapid mixing to disperse the coagulant, and then by gentle stirring, termed flocculation which promotes the aggregation of smaller particles into larger flocs. The efficiency of flocs formation is further increased by the addition of polymeric flocculants which trap contaminants and settle out in a sedimentation tank. The treated water is then passed through filtration for additional purification. This method is widely used due to its operational simplicity, cost-effectiveness, and efficiency [26].

Reverse Osmosis (RO)

Reverse osmosis (RO) is a high-efficiency membrane filtration process used to remove dissolved inorganic pollutant like, fluoride (F^-), nitrate (NO_3^-), arsenic (As^{3+} / As^{5+}) and the metal like, iron (Fe^{2+}), Manganese (Mn^{2+}), Lead (Pb^{2+}) and Chromium (Cr^{6+}). In natural osmosis, water moves from low solute concentration to high solute concentration through a semi-permeable membrane, but in reverse osmosis, this process is reversed by applying external pressure greater than the osmotic pressure (typically 4–30 bar for groundwater), forcing water from high solute concentration to low solute concentration, leaving behind salts and other inorganic materials. The common membranes are Polyamide thin-film composite. The limitation of Reverse osmosis technique is needed high energy costs, membrane fouling, expensive maintenance, and disposal of concentrated waste [27].

Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) are the powerful chemical techniques that used to purification of groundwater on the generation of highly reactive hydroxyl radicals (•OH) which are highly reactive, short-lived and non-selective oxidants [28]. These highly reactive hydroxyl radicals oxidise and degrade a wide verity of inorganic contaminants. The AOPs, such as UV/H_2O_2, O_3/UV, Fenton (Fe^{2+}/H_2O_2), and photo-Fenton, are very effective in transforming toxic inorganic pollutants like arsenic (As^{3+} to As^{5+}), iron (Fe^{2+} to Fe^{3+}), and manganese (Mn^{2+} to Mn^{4+}) into less harmful or easily removable forms. These techniques have benefits such as high efficiency, broad-spectrum pollutant removal, and the potential for complete mineralisation, nevertheless, they are restricted by high energy and chemical needs, the necessity for pH adjustment, and the possibility of by product formation [29].

Table 2. Comparison studies of different removal Techniques

Technique	Target Contaminants	Advantages	Reference
Adsorption	Fluoride, Arsenic, Phosphate, Lead, Cd	Low cost, effective at low concentrations	[23]
Ion Exchange	Nitrate, Fluoride, Sulfate, Heavy metals	High selectivity, good for anions	[25]
Coagulation-Flocculation	Arsenic, Iron, Phosphate, Chromium	Simple, scalable, effective for particulates	[26]
Reverse Osmosis (RO)	Nitrate, Fluoride, Arsenic, Heavy metals	High efficiency, broad contaminant removal	[27]
Advanced Oxidation Processes (AOPs)	Arsenic, Iron, Chromium, Manganese	Highly efficient, on-site treatment of contaminated aquifers.	[28]

5. Other Innovative removal technologies

Nanomaterials

Recently, Nanomaterials have emerged as highly efficient for removal of inorganic pollutants such as arsenic (As^{3+} / As^{5+}), fluoride (F^-), nitrate (NO_3^-), and heavy metals (e.g. Pb^{2+}, Cd^{2+} , Cr^{6+}) from groundwater due to their large surface area, high reactivity, and tunable physicochemical properties.Various nanomaterials, such as metal and metal oxide nanoparticles (e.g., Fe_3O_4, TiO_2, ZnO), carbon-based nanomaterials (e.g., graphene oxide, carbon nanotubes), and nanoscale zero-valent iron (nZVI), are used to immobilise or degrade pollutants through adsorption, redox reactions, and catalysis [30, 31]. To improve stability and reusability these materials can be incorporated into membranes, composites, or supported systems. Despite their considerable efficiency, issues such as possible toxicity, aggregation, and environmental impact necessitate additional research.

Hybrid systems

Hybrid systems in groundwater treatment mean combination of two or more technologies to enhance removal efficiency, overcome limitations of individual methods, and target multiple pollutants simultaneously. These systems often combine physical, chemical, and biological processes like, adsorption with membrane filtration, reverse osmosis with advanced oxidation processes (AOPs), or constructed wetlands with nanomaterials, to treat complex groundwater matrices. Hybrid systems are particularly useful for removal of mixed inorganic pollutants, since they provide higher selectivity, less fouling, and more operating flexibility. However, design complexity, cost, and maintenance are critical issues [32].

Constructed Wetlands & Phytoremediation

Wetlands and phytoremediation offer sustainable and eco-friendly solutions for the removal of inorganic pollutant, such as arsenic, fluoride, nitrate, phosphate, iron, manganese, and heavy metals from groundwater. Constructed wetlands utilize natural processes involving vegetation, soil, and microbial activity to remove contaminants through mechanisms like sedimentation, adsorption, precipitation, plant uptake, and microbial transformations. Phytoremediation, a plant-based remediation strategy, employs specific plant species to absorb, immobilize, or degrade inorganic contaminants via processes such as phytoextraction, rhizofiltration, and phytostabilization. These methods are cost-effective, require low energy input, and enhance ecological value, making them ideal for long-term, passive treatment. However, they are limited by slower removal rates, seasonal variations, and land requirements, and are best suited for areas with low to moderate levels of contamination [33].

6. Challenges and Future Directions

Groundwater in the Birbhum district faces significant contamination from inorganic pollutants largely due to the region's complex lithology, intensive agriculture, unregulated use of fertilizers and pesticides, and localized mining activities. A major concern is the regional and seasonal variability of pollutant levels, which complicates reliable detection and monitoring. Additionally, limited access to modern analytical equipment, a lack of skilled personnel in rural areas, and inadequate maintenance of existing treatment facilities all hinder effective management. Traditional removal methods such as coagulation, adsorption, and ion exchange have been thoroughly investigated, yet they often face challenges related to cost, maintenance, and waste disposal. Innovative technologies, such as nanomaterial-based adsorbents, hybrid filtration systems, and advanced oxidation processes (AOPs), hold potential; however, they require large-scale validation, community acceptance, and evaluation for long-term sustainability. Future initiatives should focus on creating affordable, decentralized treatment systems, integrating real-time water quality monitoring, and promoting interdisciplinary research that merges hydrogeology, materials science, and environmental engineering to ensure the provision of safe and sustainable drinking water in this at-risk region.

7. Conclusion

In West Bengal, particularly, Birbhum district is experiencing a threat with groundwater quality caused by various inorganic contaminants, such as fluoride, arsenic, iron, manganese, nitrates, phosphates, and heavy metals. Both natural geogenic processes as well as anthropogenic activities, including intensive agriculture, uncontrolled mining, and industrial discharge, are the sources of these contaminants. The mobilization and dispersion of these pollutants are further influenced by the hydrogeological diversity of the region, which makes their detection and removal difficult and spatially variable. Even while conventional techniques like adsorption, ion exchange, and coagulation-flocculation are frequently employed to treat groundwater, their limitations in terms of efficiency, cost, and scalability highlight the need for more advanced and adaptable solutions. Emerging technologies, including advanced oxidation processes (AOPs), hybrid treatment techniques, nanomaterial based systems, and nature-based remedies like phytoremediation and engineered wetlands are viable substitutes in this regard. However, challenges remain with community acceptance, cost-effectiveness, environmental safety, and technical viability. Future initiatives must focus on interdisciplinary cooperation, localized treatment planning, cost-effectiveness, decentralized, and long-lasting solutions that meet the requirements of the district's socioeconomic and environmental conditions. A robust framework combining continuous monitoring, policy enforcement, public awareness, and scientific innovation is essential for safe groundwater

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