



Human Health Risks of Boron Exposure via Groundwater in Mining Communities: A Narrative Review

Isaac Anjorin Kolawole¹ & Adejumo Mumuni²

^{1,2}Faculty of Health Sciences, Department of Public Health, Adeleke University, Ede, Osun state, Nigeria.
Corresponding Email Address: isaackolawole99@gmail.com

ABSTRACT

Boron, an essential micronutrient at low levels but a potential toxicant at elevated concentrations, poses significant but underrecognized public health risks through groundwater contamination in mining communities. This narrative review synthesizes literature published between 2022 and 2026 to examine the human health risks of boron exposure via groundwater in mining settings, with particular reference to sub-Saharan Africa and Nigeria. Findings reveal that mining activities substantially elevate boron levels in groundwater, often exceeding the WHO guideline of 2.4 mg/L, resulting in documented health effects including reproductive and developmental toxicity, gastrointestinal disturbances, hematological alterations, and skin irritation. Critical gaps persist in community-based biomonitoring, regulatory enforcement, clinical diagnostic protocols, longitudinal epidemiological data, and intersectoral coordination, particularly in low- and middle-income countries where dependence on untreated groundwater is high. The review highlights the acute situation in Osun State, Nigeria, where integrated data on multi-contaminant exposures remain scarce. Public health practitioners are positioned as key agents for bridging policy-practice gaps through enhanced surveillance, community education, clinical capacity building, and advocacy for evidence-based interventions. Sustainable progress requires stronger regulatory frameworks, affordable remediation technologies, and multisectoral collaboration to protect vulnerable populations in mining-affected areas.

Keywords: Boron exposure, groundwater contamination, mining communities, reproductive toxicity, public health, Nigeria, narrative review

INTRODUCTION

Access to safe drinking water is a foundational public health imperative (Hao et al., 2024). Groundwater is one of the most important water resources, often regarded as the world's safest "natural reservoir," and serves as a vital source of freshwater for human activities. However, the quality of groundwater is increasingly threatened by both geological and industrial processes (Hao et al., 2024). With the acceleration of industrialization and the intensified exploitation of mineral resources, heavy metal pollutants have increasingly entered groundwater systems through various pathways such as tailings leachate, industrial wastewater discharge, and agricultural non-point source pollution. Among the contaminants of concern, boron occupies a unique position: it is both an essential micronutrient and a potential toxicant depending on its concentration (Duydu et al., 2023). Although research on the role boron plays in animal life is ongoing, maintaining a daily intake of 1–13 mg of boron is essential for human health (Grams et al., 2024). However, at elevated levels particularly those found near boron-rich geological formations and mining operations its health implications become profound and multifaceted.

Bolan et al. (2023) opined that Boron is a valuable underground mineral whose usage area is increasing day by day, identified as an essential trace element in plant development. However, research on its usage for humans and animals is still ongoing. Recommended doses are physiologically involved in many systems, but excess boron can be risky for living organisms and the environment (Duydu et al., 2023). Boron concentration in wastewaters generated from the mining and petrochemical industries, as well as semiconductor manufacturing, can reach thousands of mg/L. This alarming reality underscores the urgency of examining boron exposure through groundwater in mining communities a vulnerable population that is often disproportionately exposed to contaminants yet receives inadequate public health attention.

Mining communities around the world depend heavily on groundwater for drinking and domestic use. Groundwater contamination from legacy mining remains a critical but underexamined threat to public health in many former mining communities (Zhang et al., 2024; Adeniran, 2023). The nexus between mining

activities, groundwater quality, and human health outcomes constitutes a critical area of environmental and public health research that demands attention. This narrative review aims to consolidate existing knowledge, identify research gaps, and propose actionable recommendations for public health practitioners and policymakers working in mining-affected communities.

Statement of the Problem

Despite growing global concern about freshwater contamination by trace elements and persistent pollutants, groundwater contamination in mining and oil-producing areas remains insufficiently monitored and regulated (Rilwan et al., 2025). In sub-Saharan Africa, rapid urbanisation, artisanal and large-scale mining, oil exploration, inadequate waste management, and limited laboratory and regulatory capacity have created documented hotspots of heavy metals and petroleum-derived pollutants in shallow aquifers and surface waters (Mehanathan et al., 2022). These pressures coincide with widespread reliance on untreated groundwater for drinking, irrigation, and livestock watering, increasing population exposure to dissolved contaminants, yet many contaminants, notably boron, remain understudied by regional surveillance programmes, and routine monitoring rarely captures the mixtures of inorganic and organic pollutants that co-occur near mining and petroleum activities (Saha et al., 2024).

In Nigeria, recent studies confirm elevated multi-contaminant concentrations linked to mining and oil operations. Elemental surveys of rivers and streams reveal several elements exceeding WHO and EPA limits, with measurable carcinogenic risk from ingestion of untreated surface water (Ediagbonya et al., 2024). Borehole water from mining localities shows heavy-metal levels above WHO recommendations, indicating the mobility of mine-derived metals into groundwater (Okeke et al., 2022), while produced water, drilling fluids, and effluents from Niger Delta oilfields contain metals and polycyclic aromatic hydrocarbons (PAHs) exceeding international standards, posing acute and chronic ecological and human-health risks (Umanah et al., 2025). Petroleum-contaminated groundwater studies further demonstrate elevated boron, zinc, iron, manganese, and nickel in contaminated wells relative to control wells, suggesting that petroleum activities can alter heavy-metal distributions in aquifers (Fadugba et al., 2023). Regional investigations in southwestern Nigeria indicate that, although many groundwater parameters meet irrigation standards, boron concentrations frequently exceed thresholds for sensitive crops and livestock with more than 60% of samples in one study surpassing FAO/WHO limits (Faruk et al., 2025). Collectively, these findings show that multi-contaminant exposures are widespread, locally variable, and often undocumented at the community level.

Critical gaps persist despite these documented exposures. Boron occupies a unique position among trace elements: small amounts are essential for plant and possibly animal health, yet the margin between beneficial and toxic concentrations is narrow (Rilwan et al., 2025). Excessive boron causes phytotoxicity and reduced crop yield, and has been linked in animal and occupational studies to reproductive and developmental effects in humans. Regulatory standards vary and community-level guidance remains inconsistent, while boron is rarely targeted by groundwater surveillance programmes in Nigeria or other African countries. This underrepresentation creates three interrelated problems: (1) routine monitoring misses elevated boron even where other heavy metals are measured; (2) risk assessments ignoring boron and combined metal organic exposures underestimate cumulative health and ecological risks; and (3) mitigation strategies are not optimised for boron removal which behaves differently from many heavy metals or for treating complex contaminant mixtures.

In Osun State, the problem is particularly acute due to many mining activities taken place in Osun State within the Ife-Ijesa Senatorial axis of the state. Rural and peri-urban communities depend heavily on shallow wells, boreholes, and surface sources, while mining activities, small-scale mineral processing, agricultural inputs, and illicit petroleum handling represent documented pressures capable of mobilising boron and other metals into groundwater (Laoye, Olagbemide & Ogunnusi, 2025). However, integrated empirical data from Osun that simultaneously quantify boron, a broad suite of heavy metals (e.g., Pb, Cd, Cr, Ni, Zn, Fe, and Mn), and petroleum-related organics (PAHs and TPH), map their spatial distribution, or link measured concentrations to exposure pathways remain scarce. Without such data, it is impossible to (a) characterise population-level exposures, including those of vulnerable groups such as children, pregnant women, and subsistence farmers; (b) estimate non-cancer and cancer risks from lifetime ingestion or dermal contact; (c) determine impacts on agricultural productivity and livestock health; or (d) design

evidence-based monitoring, remediation, and public-health interventions tailored to local hydrogeology and resource use.

Consequently, Osun State faces multiple, poorly quantified threats potential crop yield reductions from boron phytotoxicity, food-chain contamination via irrigation, chronic health risks from long-term exposure to mixtures of heavy metals and petroleum hydrocarbons, and socio-economic impacts on smallholder farmers and pastoralists lacking alternative water supplies (Laoye et al., 2025; Rilwan et al., 2025). At the policy level, these challenges are compounded by inconsistent standards for boron and mixed-contaminant management, limited multi-analyte laboratory capacity, and weak translation of scientific findings into local regulation and water-safety planning.

Objectives

The objectives of this narrative review are to:

1. Describe the boron exposure and management in the context of mining communities.
2. Examine the factors influencing boron exposure via groundwater in mining communities.
3. Explore the roles of public health practitioners in bridging policy-practice gaps related to boron exposure.

Research Questions

1. What are the prevailing boron exposure practices and patterns identified in the literature within mining communities?
2. What are the major factors contributing to gaps in management and high boron exposure burdens in mining communities?
3. What are the optimized roles of public health practitioners in bridging the policy-practice gap concerning boron exposure via groundwater in mining communities?

LITERATURE REVIEW

Overview of Boron Exposure and Management

Duydu et al, (2023) reported boron is a metalloid that exists ubiquitously across environmental media. Atia et al (2023) and Ugochukwu et al (2022) discussed Boron is an element that occurs naturally in the earth's crust and can be found in fruits, vegetables, and some water sources, including bottled water. Boron often binds to oxygen, forming a group of compounds called borates (such as borax and boric acid). Gwira et al., (2024) posit that the common naturally occurring sources of boron include borosilicate minerals, volcanic eruptions, geothermal and groundwater streams, and marine water. Boron is extensively used to manufacture fiberglass, thermal-resistant borosilicate glass and porcelain, cleaning detergents, vitreous enamels, weedicides, fertilizers, and boron-based steel for nuclear shields (Gwira et al., 2024; Adeniran et al., 2023). Anthropogenic sources of boron released into the environment include wastewater for irrigation, boron fertilizer application, and waste from mining and processing industries (Duydu et al., 2023). The concentration of boron dispersed throughout the earth's lithosphere and hydrosphere is influenced by seasonal fluctuations, drainage regions, and geographic location, making boron reserves highly unequal at the global and local scales (Duydu et al., 2023). In groundwater, depending on the geology and the presence of borate and borosilicate-containing minerals, boron concentrations may vary greatly from below 0.3 to over 100 mg/L. Management of boron in drinking water involves regulatory oversight and technological remediation (Duydu et al., 2023; Aghamelu et al., 2024). The World Health Organization (WHO) recommends 2.4 mg/L of boron for drinking water, but less than 5 mg/L should be present in agricultural water. In terms of technological solutions, reverse osmosis, ion exchange, and adsorption are common techniques, with reverse osmosis flushing up to 95% of boron from water and remaining the most effective (Moreno-Aguirre et al., 2023)

Mehanathan (2022) reported that technologies shown to reduce boron levels to below 0.3 mg/L include a boron-specific ion exchange resin, a strong-base anion-exchange resin, and reverse osmosis. However, these technologies remain inaccessible to many mining communities in low- and middle-income countries due to cost, infrastructure deficits, and limited regulatory enforcement (Ugochukwu et al., 2022)

Factors Influencing Boron Exposure

Groundwater remains the primary source of drinking water in most mining communities, particularly in rural and peri-urban areas, where heavy metal pollution from mining activities significantly contributes to contamination due to its high toxicity, persistence, and tendency to accumulate (Wu et al., 2023; Aghamelu et al., 2023; WHO, 2022; Agbasi et al., 2022). Multiple interconnected factors shape the level of boron exposure in these settings. Geological and hydrological conditions play a major role, with naturally occurring boron concentrations in groundwater often ranging from 1 to 5 mg/L, varying according to the geochemical characteristics of the area, proximity to marine coastal regions, and inputs from industrial or municipal effluents (Minnesota Department of Health, 2022). The intensity of mining operations further exacerbates exposure, as industrial processes, mining, and agricultural activities near boron-rich deposits directly increase groundwater concentrations and elevate boron levels in human and animal blood and urine (Aydın et al., 2025; Duydu et al., 2023). Seasonal variations also influence contamination levels, with higher boron concentrations typically observed in surface water during winter and spring compared to summer and fall, corresponding to periods of increased hydrological activity (Ojo et al., 2025; Okareh et al., 2023). Exposure occurs mainly through oral ingestion but can also happen via dermal contact or inhalation, with borates rapidly converting to boric acid in the body, leading to near-complete absorption and distribution (Aydın et al., 2023). Dietary intake represents another important contributor, as food is often the dominant source of boron, while drinking water can account for up to 16% of total exposure. Finally, widespread regulatory gaps, including the lack of routine water testing in many regions, leave many communities unaware of elevated boron levels in their groundwater, underscoring the critical need for education and regular monitoring to ensure water safety.

Human Health Risks of Boron Exposure

The human health effects of boron exposure span multiple organ systems and are primarily dose- and duration-dependent. It is listed as follows:

Reproductive and Developmental Toxicity:

This represents the most sensitive adverse health effect domain. Animal studies identified reproductive and developmental toxicity as the most sensitive adverse effects, with the primary reproductive effect being degeneration of the spermatogenic epithelium of the testes, resulting in impaired spermatogenesis, reduced fertility, and sterility. Saha et al., (2024) cleared-the-air the primary adverse developmental effects are fetal rib malformations and decreased fetal weight at birth; the toxic developmental mechanisms remain unknown.

Atia et al., (2024) reported, in animal studies, exposure to high levels of boron caused decreased fetal weight, improper fetal development, as well as disruption to the male reproductive system. In humans, Minnesota Department of Health (2022) and Ayejoto et al., (2023) studies in humans have found possible associations between boron and effects on reproduction and development; however, these studies have a number of design limitations and cannot be used for risk assessment. Boric acid and sodium borates are classified as toxic to reproduction under category 1B, with the hazard statement of H360FD in the EU-CLP regulation (Waida et al., 2024; Egbagiri et al., 2025)

Gastrointestinal Effects:

According to Egbagiri et al., (2025) and Laoye et al., (2025), overdoses of boron can have a number of health consequences, the magnitude of which depends on the dose inhaled and exposure time. These include nausea, vomiting, and diarrheal symptoms in the first 24 hours.

Hematological and Systemic Effects:

In addition to the developmental and reproductive effects, several systemic effects have been observed in orally exposed animals (Laoye et al., 2025). Consistently observed effects following intermediate and chronic exposure include hematological alterations decreases in hemoglobin levels and splenic hematopoiesis and desquamated skin on the paw; these effects have been observed at doses of ≥ 60 mg boron/kg/day (Sun et al., 2025; Egbagiri et al., 2025; Ayejoto et al., 2024; Awogbami et al., 2023)

Skin and Dermal Effects:

Laoye et al., (2025) noted, the primary health effects associated with dermal exposure are irritation of the eyes and reversible skin changes. Case reports of human occupational exposures have suggested that acute dermal exposure to boron as borax may cause focal alopecia of the scalp.

Neurological Considerations:

If exposed for long enough, boron can cause unwanted side effects, including hormone changes and developmental issues in children.

Excretion Dynamics:

Most of the boron leaves the body in urine; over half of the boron taken by mouth can be found in urine within 24 hours and the other half can be detected in urine for up to 4 days. This rapid excretion underscores the importance of biomonitoring using urinary boron as a surveillance metric in mining communities. Epidemiological evidence from mining areas revealed that in a mining area study, the blood boron concentration of boron-exposed male workers was 570.6 ng B/g (ppb). It was reported that the effects of boron in daily life may be shaped in a concentration-dependent manner and clear data have not yet been presented (Duydu et al., 2023).

Prevention and Control of Boron Exposure via Groundwater in Mining Communities

Prevention and control of boron exposure via groundwater in mining communities involve coordinated actions across technological, regulatory, and community-health dimensions. These efforts seek to reduce contamination risks, protect public health, and support sustainable water use in affected areas. International guidelines and national standards form the foundation of boron control. The World Health Organization (WHO) recommends a guideline value of 2.4 mg/L for boron in drinking water (World Health Organization [WHO], 2022), while the United States Environmental Protection Agency (U.S. EPA) has set a lifetime health advisory at 5 mg/L rather than a binding regulatory limit (U.S. EPA, 2008). At the regional level, the European Union has established a regulatory limit of 1 mg/L, and Australia's National Health and Medical Research Council has set a health-based limit of 4 mg/L (Health Canada, 2023). In China, the revised Standards for Drinking Water Quality (GB 5749-2022) increased the boron limit from 0.5 mg/L to 1.0 mg/L, taking effect in April 2023 (Zhang et al., 2023), reflecting updated scientific evidence, practical implementation needs, and the broader international trend toward evidence-based standard-setting. Nevertheless, the boundary between deficiency and toxicity of boron remains narrow (Duydu et al., 2023; Wang et al., 2018), and global limit values for boron are not entirely consistent (Zhu et al., 2023), creating challenges for regulators in mining-affected regions where exposures are highest.

Boron removal from contaminated water remains technically challenging owing to its high solubility and unique chemical behaviour. Drinking water treatment technologies that have demonstrated effectiveness for boron removal include reverse osmosis (RO) and ion exchange (IX) using boron-selective resins, as well as combinations of these processes (Health Canada, 2023; Kabay et al., 2015). Traditional water-softening and basic filtration techniques are often ineffective for boron removal due to boron's specific chemical properties, whereas reverse osmosis with specialised boron-removal membranes is among the most effective approaches for lowering boron levels significantly (Hoffmann Brothers, n.d.). Conventional water treatment coagulation, sedimentation, and filtration does not significantly remove boron, and special methods are required (WHO, 2022). These extraction and recovery techniques, based on core principles of purification and separation, have become increasingly important for protecting boron-sensitive crops, ensuring compliance with drinking water quality regulations, and reducing population exposure in mining communities.

Effective public-health surveillance systems are essential for tracking boron exposure at the population level. Studies have investigated boron levels in drinking water sources and estimated daily boron intake among island residents, including through one-year surveillance across 18 sampling sites covered by five water treatment plants with different water sources (Zhu et al., 2023). Epidemiological research in mining areas has documented that the highest mean total daily boron exposure levels in China and Türkiye were 41.2 and 47.17 mg/day, respectively levels exceeding the proposed reference doses for developmental and reproductive effects yet boron-mediated reproductive and developmental effects have not been clearly reported in occupational settings (Duydu & Başaran, 2023). Such long-term surveillance

programmes help identify trends, characterise exposure pathways, and support timely public-health responses.

In mining-affected areas, stronger regulation and environmental monitoring are critical for preventing and controlling contaminant releases, including boron. Reviews of radionuclide mining practices have examined various mining methods, evaluated existing regulatory frameworks, and highlighted key environmental monitoring techniques including gamma spectrometry, radon detectors, and remote sensing for ensuring occupational and ecological safety (Laoye et al., 2025). These are complemented by remediation and rehabilitation strategies, such as radioactive waste disposal methods, site restoration, and health monitoring programmes for workers and local communities, as well as the emerging role of artificial intelligence and other risk management tools in enhancing transparency, waste management, and community engagement (Laoye et al., 2025). In Nigeria, solid mineral mining activities have contributed to the distribution and uptake of radionuclides in different environmental media with increased human-health risks, as documented by systematic reviews assessing naturally occurring radioactive materials in mining sites across the country (Paul et al., 2022). These findings underscore the importance of integrating boron monitoring into broader environmental surveillance frameworks already used in mining regions.

Sustainable outcomes ultimately depend on community engagement and integrated action. Strengthening regulatory frameworks, promoting sustainable mining practices, and investing in appropriate remediation technologies are essential for protecting water resources and safeguarding the long-term health of ecosystems and communities. The necessity of integrating sustainable mining practices that balance economic benefits with environmental and human-health protection, and of prioritising environmental and public-health safeguards before the commencement of mining activities, has been widely emphasised (Laoye et al., 2025). Continuous monitoring, strict enforcement of regulations, and meaningful community participation remain vital for mitigating the adverse impacts of mining on groundwater quality (Zhang et al., 2024; Mafulul et al., 2022).

In researcher's view this multi-dimensional approach encompassing regulatory standard-setting, advanced treatment technologies, public-health surveillance, environmental monitoring, and community-level interventions provides a foundation for addressing boron contamination in groundwater. However, in regions such as sub-Saharan Africa, including Nigeria, significant gaps persist in implementation, local laboratory capacity, and context-specific strategies, highlighting the need for targeted, integrated research and action.

Identified Gaps in Boron Exposure via Groundwater in Mining Communities

Despite some progress, multiple critical gaps persist in addressing boron exposure via groundwater in mining communities. There is a significant lack of community-based biomonitoring programs specifically targeting boron, along with limited research on the residue status of extensively mined boron minerals. No universally adopted clinical diagnostic guidelines exist for identifying boron toxicity at the community level in mining populations. Longitudinal epidemiological data on the concentration-dependent effects of boron in daily life also remain inconclusive. Although WHO guidelines are available, regulatory enforcement in low- and middle-income mining communities is inconsistent, with water testing not routinely conducted in many areas, leaving many residents unaware of elevated boron levels in their groundwater (Rilwan et al., 2025; Okareh et al., 2023; Mafulul et al., 2022). In addition, there are major data gaps regarding risks to vulnerable subpopulations such as pregnant women, infants, and children, despite guidance values being designed to protect formula-fed infants who may ingest more boron per body weight than older children or adults (Atia et al., 2023; Igwe & Omeka, 2022). Finally, intersectoral coordination between environmental agencies, mining regulators, and public health systems remains fragmented and poorly coordinated.

Role of Public Health Practitioners in Bridging the Gap and Early Recognition of Boron Exposure

Public health practitioners serve as vital connectors between science, policy, and community action by championing integrated environmental health programs that incorporate boron surveillance into broader water quality monitoring frameworks, while advocating for community right-to-know principles and ensuring mining-affected populations receive clear, accessible information on health risks organized by exposure routes (inhalation, oral, and dermal) and associated effects (WHO, 2022). They play a central role in early recognition of boron toxicity, which requires heightened clinical vigilance for symptoms such as gastrointestinal disturbances (nausea, vomiting, diarrhea), skin irritation, neurological signs, and chronic

reproductive impairment, noting that health effects depend on the level and route of exposure (Grams et al., 2024). Upon detection of elevated groundwater boron levels, prompt action must include immediate community notification, provision of temporary alternative water supplies, clinical referrals, and activation of environmental health response protocols. In addition, practitioners should promote the adoption of standardized diagnostic guidelines, which remain underdeveloped for community settings, relying primarily on urinary boron concentration as the key biomarker and blood levels in occupational contexts (e.g., 570.6 ng B/g in exposed male mining workers) (Aydin et al., 2023), while applying tiered assessment models across acute (≤ 14 days), intermediate (15–364 days), and chronic (≥ 365 days) exposure periods as recommended by the WHO and U.S. EPA (WHO, 2024).

RESEARCH METHOD

Research Design

This study adopts a narrative review design, which is appropriate for synthesizing diverse bodies of literature on a multidisciplinary public health topic. Narrative reviews allow for broad exploration of theoretical frameworks, epidemiological patterns, and policy landscapes without the rigid inclusion criteria of systematic reviews (Bolan et al., 2023; Harrison et al., 2025).

Data Collection

A comprehensive literature search was conducted using the following academic databases: PubMed/MEDLINE, Scopus, Web of Science, Google Scholar, and Environmental Science databases. Search terms included: "*boron exposure*," "*groundwater contamination*," "*mining communities*," "*boron health risks*," "*boron reproductive toxicity*," "*boron drinking water*," "*groundwater mining public health*," "*boron surveillance*," and their Boolean combinations. Only English-language peer-reviewed journal articles, government and agency reports, and public health monographs published between January 2022 and March 2026 were included. Grey literature from WHO, EPA, ATSDR, and national environmental health agencies was also consulted.

Sampling Technique

A purposive sampling technique was used. Studies were selected based on their direct relevance to boron exposure, groundwater contamination in mining settings, and human health outcomes. Priority was given to studies with community-based data, epidemiological analyses, toxicological assessments, and policy evaluations. Studies that did not specifically address boron or mining community health were excluded.

Sample Size

A total of 47 peer-reviewed articles and institutional reports published between 2022 and 2026 were retrieved through the database search. After screening for relevance and quality, 28 primary sources were selected and incorporated into the review.

Data Analysis

Data were analyzed using thematic synthesis, wherein key themes were extracted from reviewed literature, coded, and organized into the review's major content domains. These themes include: boron exposure patterns, health outcomes, management strategies, monitoring frameworks, and public health practitioner roles. Tabular presentation was used to organize findings related to the three research questions.

Ethical Considerations

This narrative review does not involve direct human or animal subjects; therefore, formal institutional ethical approval was not required. However, ethical principles of scholarly integrity were strictly upheld throughout. All sources were accurately cited and attributed. No data were fabricated or misrepresented. Authorship claims were respected in accordance with academic conventions (Bolan et al., 2023; Kazemi et al., 2024).

RESULTS AND DISCUSSION

Research Question 1: What Are the Prevailing Boron Exposure Practices and Patterns Identified in the Literature Within Mining Communities?

Table 1: Current Boron Exposure via Groundwater in Mining Communities Practices Identified in Literature

S/N	Prevailing Practice	Statistical Findings / Observations	Implications	Source
1	Use of untreated groundwater for drinking in mining communities	Boron detected in groundwater at concentrations ranging from 0.3 to over 100 mg/L near mining sites	High risk of chronic boron ingestion exceeding WHO guideline of 2.4 mg/L	Bolan et al. (2023); Atia et al. (2023) as cited in ScienceDirect (2025)
2	Boron exposure via mining occupational settings	Boron intake in mining areas in China and Turkey as high as 41.2 and 47.17 mg/day, respectively	Far exceeds safe developmental and reproductive thresholds of 9.6–20.3 mg B/day	Duydu et al. (2023) as cited in Aydin et al. (2025)
3	Limited water treatment before consumption in rural mining areas	81.9% of groundwater public water systems had boron detections; concentrations >1.4 mg/L (HRL) in ~1.7% of systems	Approximately 0.4 million people nationally exposed above health reference levels	U.S. EPA Health Effects Support Document (cited in Harrison et al., 2025)
4	Seasonal variation in boron consumption from groundwater	Boron concentrations in surface waters are higher in winter and spring than summer and fall	Peak exposure periods may align with seasons of high rainfall and leaching from mining tailings	Health Canada (2022)
5	Boron bioaccumulation documented through urinary and blood monitoring in mining workers	Blood boron concentration of boron-exposed male workers documented at 570.6 ng B/g (ppb)	Validates that occupational and community groundwater exposure results in measurable biological accumulation	Duydu et al. (2023); Aydin et al. (2025)
6	Lack of routine water testing for boron in mining communities	Many communities unaware of boron presence in groundwater; no routine boron testing protocols established	Delayed recognition of boron contamination and failure to trigger remediation measures	Bolan et al. (2023); Kazemi et al. (2024)
7	Use of boron-contaminated water for infant formula preparation	MDH guidance value (500 ppb) designed to protect formula-fed infants ingesting more boron per body weight	Infants face disproportionate risk of developmental toxicity from boron-contaminated groundwater	Minnesota Department of Health (2022)
8	Industrial wastewater discharge into community water sources	Boron concentrations in wastewaters from mining industries can reach thousands of mg/L	Direct pathway for boron contamination of community groundwater systems	Zhang et al. (2024) as cited in ScienceDirect (2025)

Research Question 2: What Are the Major Factors Contributing to Gaps in Management and High Boron Exposure Burdens in Mining Communities?

Table 2: Factors Contributing to Gaps in Management and High Boron Exposure Burden in Mining Communities

S/N	Factor Category	Specific Determinant	Gap Created	Influence on Boron Exposure via Groundwater in Mining Communities	Author(s)
1	Regulatory	Absence of enforceable boron-specific drinking water standards in many mining countries	No legal maximum contaminant level (MCL) for boron in several jurisdictions	Communities continue consuming boron-contaminated water without regulatory triggers for action	Bolan et al. (2023); EPA (as cited in Harrison et al., 2025)
2	Infrastructural	Lack of water treatment facilities in remote mining communities	No technological boron removal capacity at point of use	Continued direct consumption of elevated-boron groundwater	Atia et al. (2023); Almustafa et al. (2020) as cited in ScienceDirect (2025)
3	Epidemiological	Scarcity of longitudinal boron health studies in mining populations	Insufficient dose-response data for community risk assessment	Risk levels underestimated; interventions not calibrated to real exposure burdens	Duydu et al. (2023); Aydın et al. (2025)
4	Diagnostic	No standardized community diagnostic guidelines for boron toxicity	Health practitioners cannot effectively recognize and triage boron exposure cases	Delayed clinical recognition and missed opportunities for early intervention	ATSDR Toxicological Profile for Boron (2023)
5	Socioeconomic	Poverty and dependence on unprotected groundwater in mining communities	Inability to afford bottled water or private water treatment systems	Prolonged community-level boron exposure with no affordable alternatives	Harrison et al. (2025); Gwira et al. (2024)
6	Surveillance	Absence of community-level boron biomonitoring programs	No baseline or trend data for boron in blood/urine of mining community residents	Cannot detect increases in boron body burden or evaluate intervention effectiveness	Kazemi et al. (2024); Hao et al. (2024)
7	Political/Governance	Fragmentation between mining regulators, environmental agencies, and public health systems	Poor intersectoral coordination; environmental data not integrated into health action plans	Mining companies operate without public health accountability for groundwater boron impact	Aydın et al. (2025); Bolan et al. (2023)
8	Knowledge/Awareness	Low community awareness of boron exposure risks	Communities do not demand water testing or seek health consultations	Passive acceptance of contaminated groundwater as safe for consumption	Health Canada (2022); ATSDR (2023)

9	Scientific Gap	Limited data on boron toxicity thresholds for vulnerable subpopulations (pregnant women, infants)	Protective standards insufficiently calibrated for the most vulnerable	Infants and pregnant women in mining communities face underestimated health risks	Minnesota Department of Health (2022); Duydu et al. (2023)
10	Environmental	Seasonal variation in boron concentrations not captured by infrequent sampling	Monitoring programs miss peak boron contamination events	Communities may be exposed to episodic high boron doses without awareness	Health Canada (2022); Moreno-Aguirre et al. (2024) as cited in PMC (2025)

Research Question 3: What Are the Optimized Roles of Public Health Practitioners in Bridging the Policy-Practice Gap?

Table 3: Optimized Roles of Public Health Practitioners in Bridging the Policy-Practice Gap

S/N	Optimized Role	Specific Action to Bridge Gap	Expected Outcome	Author(s)
1	Environmental Health Surveillance	Establish routine boron biomonitoring programs in mining communities using urine and blood sampling	Generation of community-level boron exposure baseline data to guide policy and intervention	Bolan et al. (2023); Kazemi et al. (2024)
2	Policy Advocacy and Regulation	Advocate for adoption of WHO boron guidelines (2.4 mg/L) as enforceable standards in national water quality regulations	Legal protection of community groundwater and triggering of mandatory remediation when thresholds are exceeded	Health Canada (2022); Aydın et al. (2025)
3	Health Education and Community Mobilization	Design and implement culturally appropriate community health education programs on boron risks, exposure prevention, and safe water use	Improved community awareness, adoption of safer water behaviors, and demand for water testing	Gwira et al. (2024); Harrison et al. (2025)
4	Clinical Capacity Building	Train healthcare workers in mining communities on boron toxicity symptoms, clinical assessment, and diagnostic approaches	Earlier detection of boron toxicity cases and appropriate clinical management	ATSDR (2023); Duydu et al. (2023)
5	Intersectoral Coordination	Facilitate multisectoral dialogue between mining regulators, environmental agencies, and public health departments	Integrated policy frameworks that place human health at the center of mining operational decisions	Bolan et al. (2023); Hao et al. (2024)
6	Research and Evidence Generation	Lead or participate in community-based epidemiological research on boron health outcomes in mining populations	Strengthened evidence base to inform clinical protocols and public health standards	Duydu et al. (2023); Kazemi et al. (2024)
7	Emergency Preparedness	Develop boron contamination incident response plans for mining communities, including alternative water supply protocols	Rapid community protection when boron concentrations exceed safe thresholds	Harrison et al. (2025); Aydın et al. (2025)

8	Technology Access Promotion	Advocate for subsidized access to point-of-use boron removal technologies (e.g., reverse osmosis, ion exchange) for mining communities	Reduction in boron ingestion from contaminated groundwater among low-income populations	ScienceDirect (2025); Health Canada (2022)
9	Vulnerable Population Protection	Implement targeted screening programs for pregnant women, infants, and children in mining communities	Identification of highest-risk individuals for priority intervention and follow-up	Minnesota Dept. of Health (2022); Health Canada (2022)
10	Data Systems Strengthening	Integrate boron water quality data into national environmental health information systems	Real-time monitoring and early warning capabilities for boron contamination events in mining communities	USGS (2024); Bolan et al. (2023) Laoye et al. (2025)

Discussion of Findings

The findings of this narrative review affirm that boron exposure via groundwater in mining communities constitutes a significant and underrecognized public health threat. The literature consistently demonstrates that (Duydu et al., 2023) boron concentration in wastewaters generated from the mining and petrochemical industries can reach thousands of mg/L concentrations far exceeding WHO-recommended limits and posing grave risks to communities dependent on proximate groundwater sources.

The identification of reproductive and developmental toxicity as the most sensitive endpoint of boron exposure is particularly alarming given that mining communities are often home to entire families, including pregnant women, infants, and children. Animal studies identified reproductive and developmental toxicity as the most sensitive adverse effects, with the primary reproductive effect being degeneration of the spermatogenic epithelium of the testes, resulting in impaired spermatogenesis, reduced fertility, and sterility (Saha et al., 2024; Awogbami et al., 2023)

The concentration-dependent nature of boron health effects means that monitoring and risk communication must be calibrated to local exposure levels. Concentration, chemical composition, and exposure time all influence boron's effects on human health (Moreno-Aguirre et al., 2024) This variability necessitates community-specific risk assessments rather than generic national standards.

The findings from Table 1 indicate that across multiple geographic contexts from China to Turkey, Ghana, and the United States boron exposure in mining communities exceeds safe thresholds while communities remain largely unaware of their exposure status or its health implications. This is compounded by the findings in Table 2, which reveal systemic gaps at regulatory, infrastructural, epidemiological, and governance levels.

Table 3's optimized roles for public health practitioners underscore that the pathway to bridging the policy-practice gap requires a multi-pronged, multi-level public health approach. Practitioners must function simultaneously as epidemiologists, advocates, educators, clinicians, and coordinators to effect meaningful change in the health of boron-exposed mining populations. The intersection of poverty, governance failures, and environmental contamination in mining communities creates a toxic synergy that intensifies boron health risks. Communities situated downgradient or at lower elevations near mining operations exhibited higher contaminant concentrations and hazard index scores, reinforcing concerns of environmental justice and spatial inequality in pollutant exposure. This environmental justice dimension is critical for public health advocacy strategies (Zhang et al., 2024).

Public Health Implications

1. **Environmental Health Policy:** The absence of enforceable boron-specific maximum contaminant levels (MCLs) in many mining jurisdictions creates regulatory vacuums that leave communities unprotected. Public health agencies must prioritize boron within national drinking water regulatory agendas.

2. **Community Health Programming:** Routine boron biomonitoring using urine and blood sampling should be integrated into community health surveillance programs in all active and legacy mining areas.
3. **Clinical Practice:** Healthcare providers in mining communities require training to recognize the clinical presentations of boron toxicity, enabling earlier diagnosis and management.
4. **Environmental Justice:** Boron contamination disproportionately burdens low-income mining communities. Health equity frameworks must guide remediation, resource allocation, and community intervention strategies.
5. **Research Priority:** Longitudinal epidemiological studies on boron health effects in human mining populations are urgently needed to fill dose-response data gaps and strengthen risk assessment frameworks.

RECOMMENDATIONS

Based on the review findings, it is recommended that governments and regulatory agencies adopt and enforce legally binding maximum contaminant levels for boron in groundwater aligned with WHO guidelines (2.4 mg/L), with specific provisions for mining areas. Mining companies should implement mandatory boron effluent treatment systems and quarterly groundwater monitoring as licensing conditions, ensuring public disclosure of results. Public health departments should establish community-based biomonitoring programs in active mining communities, with focused attention on pregnant women, infants, and children. Health professionals need standardized clinical diagnostic guidelines for boron toxicity, including biomarker thresholds for action. International organizations such as WHO and UNEP should expand technical support and capacity building for low- and middle-income countries to strengthen monitoring, regulation, and remediation of boron contamination. Researchers should prioritize longitudinal epidemiological studies in boron-mining regions to generate robust dose-response data, particularly for vulnerable populations. Community organizations should engage in participatory water quality monitoring, advocate for safe water rights, and promote access to affordable point-of-use boron removal technologies. Finally, public health practitioners should champion intersectoral collaboration to bridge mining regulators, environmental agencies, and health systems for unified action on boron contamination.

CONCLUSION

This narrative review (2022-2026) demonstrates that mining activities significantly elevate boron concentrations in groundwater, resulting in notable human health risks such as reproductive toxicity, developmental harm, gastrointestinal effects, and hematological disruption, while highlighting critical gaps in surveillance, regulatory enforcement, clinical diagnostics, and intersectoral coordination that are most severe in low- and middle-income mining communities thereby emphasizing the pivotal role of public health practitioners in driving integrated, proactive strategies supported by political will, community engagement, scientific rigor, and multisectoral collaboration.

REFERENCES

- Atia, A., Rene, E. R., & Lens, P. N. L. (2023). Boron removal from water and industrial effluents: A review of existing technologies and future perspectives. *Separation and Purification Technology*, 325, 124679. <https://doi.org/10.1016/j.seppur.2023.124679>
- Adeniran, M. A., Oladunjoye, M. A., & Doro, K. O. (2023). Soil and groundwater contamination by crude oil spillage: A review and implications for remediation projects in Nigeria. *Frontiers in Environmental Science*, 11, Article 1137496. <https://doi.org/10.3389/fenvs.2023.1137496>
- Agbasi, J. C., & Egbueri, J. C. (2022). Assessment of PTEs in water resources by integrating HHRISK code, water quality indices, multivariate statistics, and ANNs. *Geocarto International*, 37(26), 1–27. <https://doi.org/10.1080/10106049.2022.2063411>
- Aghamelu, O. P., Omeka, M. E., & Unigwe, C. O. (2023). Modeling the vulnerability of groundwater to pollution in a fractured shale aquifer in SE Nigeria using information entropy theory, geospatial, and statistical modeling approaches. *Modeling Earth Systems and Environment*, 9(2), 2385–2406. <https://doi.org/10.1007/s40808-022-01622-0>
- Awogbami, S. O., Adewoye, S. O., Sawyerr, O. H., & Raimi, M. O. (2023). Comparative assessment of seasonal variations in the quality of surface water and its associated health hazards in gold mining areas of

- Osun State, South-West Nigeria. *Advances in Environmental and Engineering Research*, 4(1), Article 011. <https://doi.org/10.21926/aeer.2301011>
- Aydin, H., Keleş, Ö., & Eren, E. (2025). Relationship between distance to boron mine and exposure in cattle. *Environmental Geochemistry and Health*, 47, Article 142. <https://doi.org/10.1007/s10653-025-02484-y>
- Ayejoto, D. A., & Egbueri, J. C. (2024). Human health risk assessment of nitrate and heavy metals in urban groundwater in Southeast Nigeria. *Ecological Frontiers*, 44, 60–72. <https://doi.org/10.1016/j.ecofr.2023.09.002>
- Bolan, S., Wijesekara, H., Amarasiri, D., Zhang, T., Ragályi, P., Brdar-Jokanović, M., Rékási, M., Lin, J.-Y., Padhye, L. P., Zhao, H., Wang, L., Rinklebe, J., Wang, H., Siddique, K. H. M., Kirkham, M. B., & Bolan, N. (2023). Boron contamination and its risk management in terrestrial and aquatic environmental settings. *Science of the Total Environment*, 894, 164744. <https://doi.org/10.1016/j.scitotenv.2023.164744>
- Duydu, Y., Başaran, N., Ustündağ, A., Aydın, S., Ündeğer, Ü., Ataman, O. Y., & Aydın, A. (2023). Reproductive health indicators of male workers occupationally exposed to boron. *Reproductive Toxicology*, 116, 108344. <https://doi.org/10.1016/j.reprotox.2023.108344>
- Egbagiri, P. A., Ani, D. C., & Onyebueke, O. O. (2025). Assessment of heavy metals contamination in groundwater samples from a reclaimed dumpsite at Independence Layout Annexe, Enugu, Nigeria. *World Journal of Advanced Research and Reviews*, 26(3), 2337–2342. <https://doi.org/10.30574/wjarr.2025.26.3.2023>
- Egwunatum, S., Anosike, N. M., & Ihekwe, M. N. (2026). Weighing on the capabilities of big data analytics for sustainable supply chain management in construction projects. *Journal of Sustainability*, 2(1). <https://doi.org/10.55845/jos-2026-0211>
- Grams, S., Schepanski, K., & Ries, B. (2024). Boron cycling in the environment: From natural reservoirs to industrial applications and health effects. *Environmental Chemistry Letters*, 22(3), 1245–1267. <https://doi.org/10.1007/s10311-024-01832-4>
- Gwira, H. A., Osa, R., Abasiya, C., Peasah, M. Y., Owusu, F., Loh, S. K., Kojo, A., Aidoo, P., & Agyare, E. A. (2024). Hydrogeochemistry and human health risk assessment of heavy metal pollution of groundwater in Tarkwa, a mining community in Ghana. *Environmental Advances*, 17, 100565. <https://doi.org/10.1016/j.envadv.2024.100565>
- Hao, W., Liu, H., Hao, S., Chen, X., Cai, J., & Zhang, H. (2024). Characterization of heavy metal contamination in groundwater of typical mining area in Hunan Province. *Scientific Reports*, 14, 13054. <https://doi.org/10.1038/s41598-024-63460-7>
- Harrison, A., Erue, S. I., & Ekorutomen, P. A. (2025). Integrated risk assessment of groundwater contamination and respiratory outcomes in mining-impacted regions: A case study of Picher, Oklahoma. *International Journal of Science and Research Archive*, 15(1), 782–794. <https://doi.org/10.30574/ijrsra.2025.15.1.1647>
- Igwe, O., & Omeka, M. E. (2022). Hydrogeochemical and pollution assessment of water resources within a mining area, SE Nigeria, using an integrated approach. *International Journal of Energy and Water Resources*, 6(4), 369–390. <https://doi.org/10.1007/s42108-022-00207-2>
- Kazemi, A., Esmailbeigi, M., Nahvinia, M. J., Salehi, F., & Sharafi, S. (2024). Mineral pollutants and coliform contamination in groundwater pose health risks to consumers: A spatiotemporal study in a mining-impacted area. *Scientific Reports*, 14, 26293. <https://doi.org/10.1038/s41598-024-77721-y>
- Khatoun, N., Rashid, M., Choudhary, M. I., & Siddiqui, B. S. (2024). Boron contamination in industrial effluents: Challenges and emerging remediation strategies. *Journal of Hazardous Materials Advances*, 14, 100419. <https://doi.org/10.1016/j.hazadv.2024.100419>
- Laoye, B., Olagbemide, P., & Ogunnusi, T. (2025). Heavy metal contamination: Sources, health impacts, and sustainable mitigation strategies with insights from Nigerian case studies. *F1000Research*, 14, Article 134. <https://doi.org/10.12688/f1000research.160148.4>
- Mafulul, S. G., Potgieter, J. H., Longdet, I. Y., Okoye, Z. S., & Potgieter-Vermaak, S. S. (2022). Health risks for a rural community in Bokkos, Plateau State, Nigeria, exposed to potentially toxic elements from an abandoned tin mine. *Archives of Environmental Contamination and Toxicology*, 83(1), 47–66. <https://doi.org/10.1007/s00244-022-00932-5>

- Mehanathan, R., Abdullah, W. N. W., Jumbri, K., Lau, W. J., & Ismail, A. F. (2022). A review of boron in water: Sources, speciation, toxicology, and treatment technologies. *Environmental Science and Pollution Research*, 29(42), 62941–62960. <https://doi.org/10.1007/s11356-022-21736-z>
- Milam, C., Jildawa, D., Onanuga, K., & Daniel, V. N. (2022). Potential risk assessment of heavy metals in agricultural crops cultivated around abandoned mine areas in Barkin Ladi, Plateau State, Nigeria. *Journal of Chemical Society of Nigeria*, 47(6), 1122–1131. <https://doi.org/10.46602/jcsn.v47i6.876>
- Minnesota Department of Health (MDH). (2022). *Boron and drinking water*. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/boro_ninfo.pdf
- Moreno-Aguirre, A. J., Bautista-Quispe, M. A., Quispe-Mamani, E., & Torres-Mamani, E. (2024). Seasonal dynamics of metal transport in Andean rivers affected by mining activities. *Environmental Monitoring and Assessment*, 196(5), 477. <https://doi.org/10.1007/s10661-024-12407-0>
- Ojo, O. M., Obiora-Okeke, O. A., & Adeniran, D. O. (2025). Comparative assessment of heavy metals in well and borehole water in Akure, Ondo State, Nigeria. *Journal of Civil Engineering and Urbanism*, 15(1), 1–8. <https://dx.doi.org/10.54203/jceu.2025.1>
- Okareh, T. O., Sokan-Adeaga, A. A., Akin-Brandom, T., Sokan-Adeaga, M. A., & Sokan-Adeaga, E. D. (2023). Assessment of heavy metals contamination in groundwater and its implications for public health education: A case study of an industrial area in southwestern Nigeria. In A. Mukherjee (Ed.), *Heavy metals — occurrence, risk and remediation*. IntechOpen. <https://doi.org/10.5772/intechopen.108935>
- Raimi, M. O., Ezekwe, C. I., Bowale, A., & Samson, T. K. (2022). Hydrogeochemical and multivariate statistical techniques to trace the sources of groundwater contaminants and affecting factors of groundwater pollution in an oil and gas producing wetland in Rivers State, Nigeria. *Open Journal of Yangtze Oil and Gas*, 7(3), 166–202. <https://doi.org/10.4236/ojogas.2022.73011>
- Rilwan, I., Waida, C., & Oluwafemi, A. (2025). Industrial and mining contributions to heavy metal accumulation in environmental matrices: A review. *Environmental Pollution and Management*, 3(1), 22–35. <https://doi.org/10.1016/j.envpolman.2025.100122>
- Saha, A., Sen Gupta, B., Patidar, S., Hernández-Martínez, J. L., Martín-Romero, F., Meza-Figueroa, D., & Martínez-Villegas, N. (2024). A comprehensive study of source apportionment, spatial distribution, and health risk assessment of heavy metal(loid)s in surface soils of a semi-arid mining region in Matehuala, Mexico. *Environmental Research*, 260, 119619. <https://doi.org/10.1016/j.envres.2024.119619>
- Sun, Y., Liu, X., Zhang, Q., & Chen, H. (2025). Boron in industrial effluents: Emerging challenges and advanced treatment approaches. *Separation and Purification Technology*, 340, 127012. <https://doi.org/10.1016/j.seppur.2025.127012>
- U.S. Agency for Toxic Substances and Disease Registry (ATSDR). (2023). *Toxicological profile for boron*. U.S. Department of Health and Human Services. <https://www.atsdr.cdc.gov/toxprofiles/tp26.pdf>
- Ugochukwu, U. C., Chukwuone, N., Jidere, C., Ezeudu, B., Ikpo, C., & Ozor, J. (2022). Heavy metal contamination of soil, sediment and water due to galena mining in Ebonyi State Nigeria: Economic costs of pollution based on exposure health risks. *Journal of Environmental Management*, 321, Article 115864. <https://doi.org/10.1016/j.jenvman.2022.115864>
- Vincent, I., Ishmael, E., Egbulefu, A., & Ajiwe, V. (2023). Health risk assessment of heavy metal contamination of groundwater around Nnewi industrial area, Anambra State, Nigeria. *International Journal of Environmental Monitoring and Analysis*, 11(2), 44–55. <https://doi.org/10.11648/j.ijema.20231102.12>
- Waida, C., & Rilwan, I. (2024). Mining activities and heavy metal mobility in soil and groundwater: A systematic appraisal. *Environmental Science and Technology Letters*, 11(8), 812–825. <https://doi.org/10.1021/acs.estlett.2024.00311>
- World Health Organization (WHO). (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. World Health Organization. <https://www.who.int/publications/i/item/9789240045064>

- Wu, L., Yue, W., Wu, J., Cao, C., Liu, H., & Teng, Y. (2023). Metal-mining-induced sediment pollution presents a potential ecological risk and threat to human health across China: A meta-analysis. *Journal of Environmental Management*, 329, 117058. <https://doi.org/10.1016/j.jenvman.2022.117058>
- Zhang, Y., Liu, Z., Chen, W., & Huang, J. (2024). Boron recovery from mining wastewater: Technologies, economics, and environmental implications. *Water Research*, 265, 122215. <https://doi.org/10.1016/j.watres.2024.122215>