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Hydrogeochemical Characterization and Groundwater Quality Assessment in Mining Areas: A Review

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Abstract

Mining activities adversely affect the groundwater quality. Human health also subsequently gets affected because of many environmental and ecological risks due to mobilization of contaminants and alteration of hydrogeochemical processes. This review assesses the hydrogeochemical characteristics and groundwater quality in mining areas emphasizing the crucial processes like rock-water interaction, acid mine drainage formation, and heavy metal contamination. These processes impact the end uses of groundwater quality like drinking, irrigation and industrial uses. To understand the causes of contamination and the availability and suitability of the water, groundwater investigation is required such as assessment of physicochemical parameters and hydrogeochemical faces. By using isotopic techniques and integration of spatial and temporal changes with remote sensing and GIS application, pollution load can be evaluated on water resources. A bibliographic analysis highlights the current research progress in mining sector, focusing on global and regional studies and their impact on water resources. Contamination from heavy metals like arsenic, chromium, cadmium, and other toxic elements has posed serious illnesses to human health and the surrounding ecosystem. The review also highlights the research gaps and prospects for improving groundwater resources through appropriate mitigation strategies like sustainable mining practices and water treatment technologies.

1. Introduction

1.1. Background of Groundwater Resources and its Vulnerability

Groundwater is necessary for both human existence and growth, as well as preserving the fragile equilibrium of the ecosystem [1]. The groundwater availability in many areas, particularly those with little rainfall, frequently needs to be assessed to support sustained economic expansion [2]. Water scarcity is caused due to the rapid rise in the population, urbanisation, industrial and agricultural activity. Inadequate access to clean drinking water is a significant problem affecting many regions in India. According to a study conducted in the coalfield areas of Jharia, in Jharkhand, the water availability was found very low throughout the year [3]. The local population has significant challenges due to the irregular and unreliable water supply system and the uneven distribution of water resources. The management of the available water resources are needed to address this problem [4,5]. Groundwater, both treated and untreated, is a common source of drinking water worldwide due to its relatively low danger of bacterial and chemical pollution [6]. Groundwater resources are the main water supply for industrial, agricultural, and drinking purposes [7,8]. Groundwater, the world's largest freshwater resource, is essential to the world's water supply since it provides drinking water to billions of people worldwide [9]. In fact, during the past few decades, groundwater quality has declined due to several issues, including increased urbanisation, more human activity, and increased waste disposal. This has become a primary global concern [10,11]. In mining operations water is required for ore processing and dust suppression. It is also important to use water sustainably in mining sector [56]. Mining changes the natural

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environment and makes it more reactive. This exposes the minerals to water and air. It also gets exposed to micro-organisms which quickly start to break them down. Mine water is enriched with sulfate due to the oxidation of iron-sulfide minerals like pyrite, marcasite, and pyrrhotite, commonly found in coal, base metal, and gold deposits. The Microorganism mediated oxidation converts these minerals into sulfate and acids [57]. Anthropogenic sources of contamination include mining and industrial waste, agricultural practices, landfills, and inappropriate chemical disposal. Natural sources of contamination include mineral deposits, the recharge-discharge, oxidation-reduction process, residence times, ion exchange processes, and the dissolution of mineral phases and their precipitation. These pollutants can seep into groundwater systems, changing the chemical makeup of the water and possibly endangering the health of people who drink it [15].

1.1. Mining activities and its environmental Impact

The mining of precious minerals is the most essential economic activity in many parts of the world, as it serves the purpose of developing the society and boosting the economy of any nation. However, ferrous, non-ferrous, precious, industrial, and mineral fuels have been extracted for centuries as they provide raw materials that are processed and used for different purposes [16,17,18]. A nominal trend value of mineral extraction has been observed in 2010, which is approximately four times higher than in 2002 [19]. The waste produced by mining significantly negatively influences the environment and is likely to cause long-term environmental harm. Although the chemical and physical makeup of the mineral determines the type of mining and treatment method used, the wastes produced by mining are not all the same [16]. The major problems with mining activities are the mine overburden, waste dumps, and mine tailings which have a detrimental effect on the environment. It can pose a threat to the flora and fauna in the region. The most fatal issue with mining activities is mine tailing/dump storage around the operation site, which may cause severe environmental degradation [17]. Mine tailings and dump waste removal of metals remain crucial in treating them before releasing into the environment because it may result in various risks to the human health and aquatic ecosystems [20,21]. The lack of preventive measures is before dumping mine waste is crucial in mine waste management. Thus, the generation of hazardous materials such as pyrite or pyrrhotite, which have reactive sulphide minerals, are common waste problem related to mining operations. The wastes are usually seen in waste dumps, open cuts, leach pads, tailing disposal/spillage locations, impoundments, and pit walls, and remain within the borders of previously mined areas. It leaves behind the footprints of re-mining of tails which further mixes with the waste [22,23].

The universal concern of mine waste disposal becomes a significant challenge in reducing the waste released into the groundwater aquifers and surface water bodies in and around disposal sites [17]. Mining activities have severe effects on land, water and air quality as shown in Figure 1. Mining waste have deteriorated the waterbodies. Mining disrupts natural landscapes through deforestation, removal of the soil surface, and excavation of minerals, which leads to soil erosion, loss of fertile land, and sometimes landslides. Heavy metal and chemical contamination in groundwater, lakes and rivers are some of the causes of mine waste. Acid mine drainage is a byproduct of mining activities containing high sulphate ions. Sulphate ions form acids when in contact with water, which in turn form metal-sulphide when they react with heavy metal ions. The waste containing metal sulphide is usually dumped into the site. This mobilises the heavy metals by acidic waters, releasing harmful chemicals into the surrounding. Also, mining sites become dusty with air pollution, which can cause respiratory problems among the people working and living near the mining zone. The particular concern due to mining is the impact on waterbodies. Water contamination is very difficult to remediate, thus not only harming human health but also disturbing the ecosystem that relies on clean and good quality water. Therefore, it becomes necessary to improve mining practices, focus on land reclamation, and provide stricter regulations to ensure proper mining practices.

1.2. Assessment of hydrogeochemical characteristics of groundwater

Groundwater chemistry is very important in understanding the hydrogeochemical characteristics of water quality, which are influenced by various hydrological, geological and anthropogenic factors. This helps to understand the quality of groundwater and identify its application for drinking, irrigation, and industrial use. Major ion chemistry in groundwater are cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO^{3}, SO_4^{2-}, Cl^{-}, NO_3^{-}

), which are dissolved from various minerals. The present ions help in identifying the sources of contamination that may be due to geological processes, water-rock interaction, hydraulic linkage and mixing of local flow water, evaporation dominance and cation exchange [1]. The underlying bedrock geology, structural elements, weathering processes, recharge water qualities, evapotranspiration, and interactions between rocks and water all substantially impacted chemical features of the groundwater [12,13].

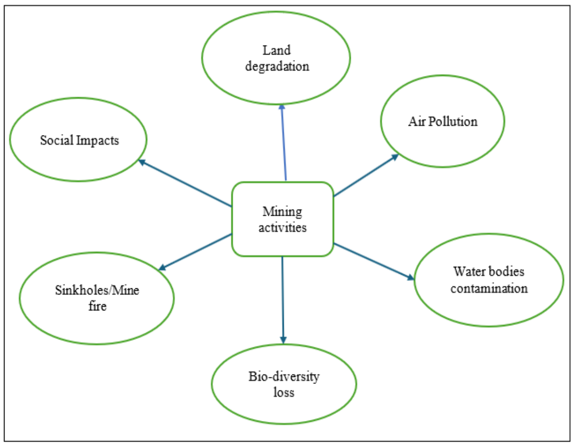


Figure 1. Environmental impact of mining activities.

1.3. Objective and Scope of Review

The primary objective of this review is to analyse and synthesize existing research on hydrogeochemical characterisation and groundwater quality assessment in mining at global, regional, and local levels. The objectives and scope are mentioned below:

- Examination of key processes of hydrogeochemical characteristics,
- Groundwater quality assessment,
- Methodology in evaluating and identification,
- Assess the impacts of mining activities,
- Case studies from around the globe, regional and local zones,
- Environmental and human health risks,
- Spatial and temporal changes in land use and land cover changes in mining areas.

The scope of this review of hydrogeochemical characterisation and groundwater quality assessment in mining areas focuses on understanding the hydrogeochemical processes and groundwater quality variations in the mine-affected zone. This review can provide a comprehensive study of groundwater quality which is deteriorating due to mining activity in the region, can help to identify the sources, mechanisms, assess the potential damage caused, provide solutions to environmental degradation and assess health risks associated with the changes in water resources.

2. Hydrogeochemical processes in the mining area

2.1. Water-Rock Interaction

The interaction between water and rock is a fundamental geochemical process that deals with the quality of groundwater, with an emphasis on mining areas. The interaction includes chemical reactions between geological materials and groundwater, which leads to dissolution, precipitation, and exchange of ions and minerals. Kazapoe, in 2024, investigated the water quality of groundwater used in Wassa region mining and non-mining areas for irrigation, livestock rearing, and human consumption. The findings showed that the groundwater quality parameter like TDS, Na^+, Ca^{2+}, NO_3^-, Mg^{2+}, and Cl^- levels varied and had a slightly acidic pH. The WQI analysis revealed that 61% of the groundwater samples were of perfect quality for domestic use. The hydrogeochemical facies investigation indicated that the primary processes affecting the groundwater chemistry were the weathering and dissolution of rocks. The samples were deemed excellent for irrigation based on the irrigation assessment, which included 88% for SAR, 9% for Sodium Percentage, 1% for residue sodium bicarbonate, 61% for Kelly Ratio, and 77% for magnesium risks. However, the groundwater quantity evaluation indicated that more sources are needed for suitable use in agriculture and residential settings [25].

2.2. Acid mine drainage

Acid mine drainage is a serious problem released by mining activities and is a widespread global problem. This impacts the aquatic ecosystem and communities which leads to economic burden [76]. In inactive and abandoned mines, the problems become more serious where pumping is not active, and the water table is drawn back, whereas in active mines, the water table levels are kept low through pumping is not active, and the water table is drawn back, whereas in active mines, the water table levels are kept low through pumping [77,78,79]. The water seeps through regions of oxidised pyrites, it results in the formation of sulphuric acid and is released into the surrounding environment which results in acid mine drainage [80,81,82]. An assessment in Korba, Chhattisgarh, India, examines the environmental risks of heavy metal water pollution from coal mining wastes. Due to possible acid mine drainage (AMD) from metal sulfide minerals, the Dipka coal mining zone in Korba contains mining waste facilities from coal extraction and coal washeries. These facilities pose a risk to the environment, especially water resources. The proximity of these garbage piles to surface water, agricultural areas, and residential areas particularly near Dipka town increases the possibility of contaminated migration. The study aims to find and analyse the most contaminated water sources, emphasising the increased environmental risk that mining waste facilities provide. The results showed that heavy metal concentrations have grown downstream, exacerbating ecological problems. Heavy metals, such as Pb, Zn, Cd, Cu, and Ni, are major contaminants that exceed permissible contamination limits in water samples. High concentrations of heavy metals in groundwater affect agricultural and drinking water use [30].

2.3. Heavy Metals Concentration

The elevated concentration of heavy metals through mining activities is widely reported and documented [2, 23]. The extraction of mineral and their procedure, which leads to the release of toxic heavy metals such as arsenic, lead, manganese, cadmium, chromium, etc, have contaminated the water resources. The Jharia coalfield is one of the examples of both opencast and underground coal mining, which suffers from heavy metal contamination by leaching from overburden dumps [83]. Research on the coal mines of Kuju and Charhi showed that even though the groundwater contained high levels of arsenic and selenium, it was safe for irrigation but unsuitable for human consumption [38].

2.4. Total dissolved solid and salinity

The variation of TDS and Salinity are some of the crucial indicators of groundwater quality. The variation may result from acid mine drainage, leaching toxic heavy metals from overburden and waste, and altering natural water flow in the aquifers. A high salinity level was observed in the Oder River, Poland, due to discharge from coal mine waste, which has resulted in the death of fish species and raised concern about the environmental imbalance [84]. A case of Lithium mining in the Atacama region of Chile has witnessed land subsidence and potential impacts on local water resources due to the over-extraction of brine, which alters the hydrological balance and increases salinity in the region [85].

3. Materials and Methodology

For this review, several relevant research papers from Web of Science, Scopus, Google Scholar, Science Direct and other database libraries were searched thoroughly from 2019 to 2024, with keywords like hydrogeochemical characteristics, groundwater quality assessment, mining areas, impacts, environment, and human health risk were searched for the review. The research papers were segregated into different types of mining areas like coal, manganese, gold, chromite, copper, etc. Further bibliographic analysis was done with the help of a VOS viewer to visualize the insights into evolving trends, collaboration, and co-occurrences in the groundwater quality assessment in the mining region from the past 5 years. The review also identifies the sources of pollution in the groundwater quality assessment, hydrogeochemical characteristics and hydrochemical processes in groundwater quality. It also identifies the risks associated with the consumption of such types of pollution and their health impacts in the region. It also assesses the new and emerging techniques for understanding the hydrogeochemical characteristics and groundwater quality assessment in mining areas with the integration of remote sensing and geographic information systems to understand the characteristics better through Spatial analysis, identification of pollution sources, land use land cover analysis, water quality mapping, groundwater vulnerability assessment, monitoring of temporal changes, Machine learning, predictive modelling, and hydrogeochemical data integration. Water quality remediation strategies are suggested to properly manage groundwater resources. The review methodology is shown in Figure 2.

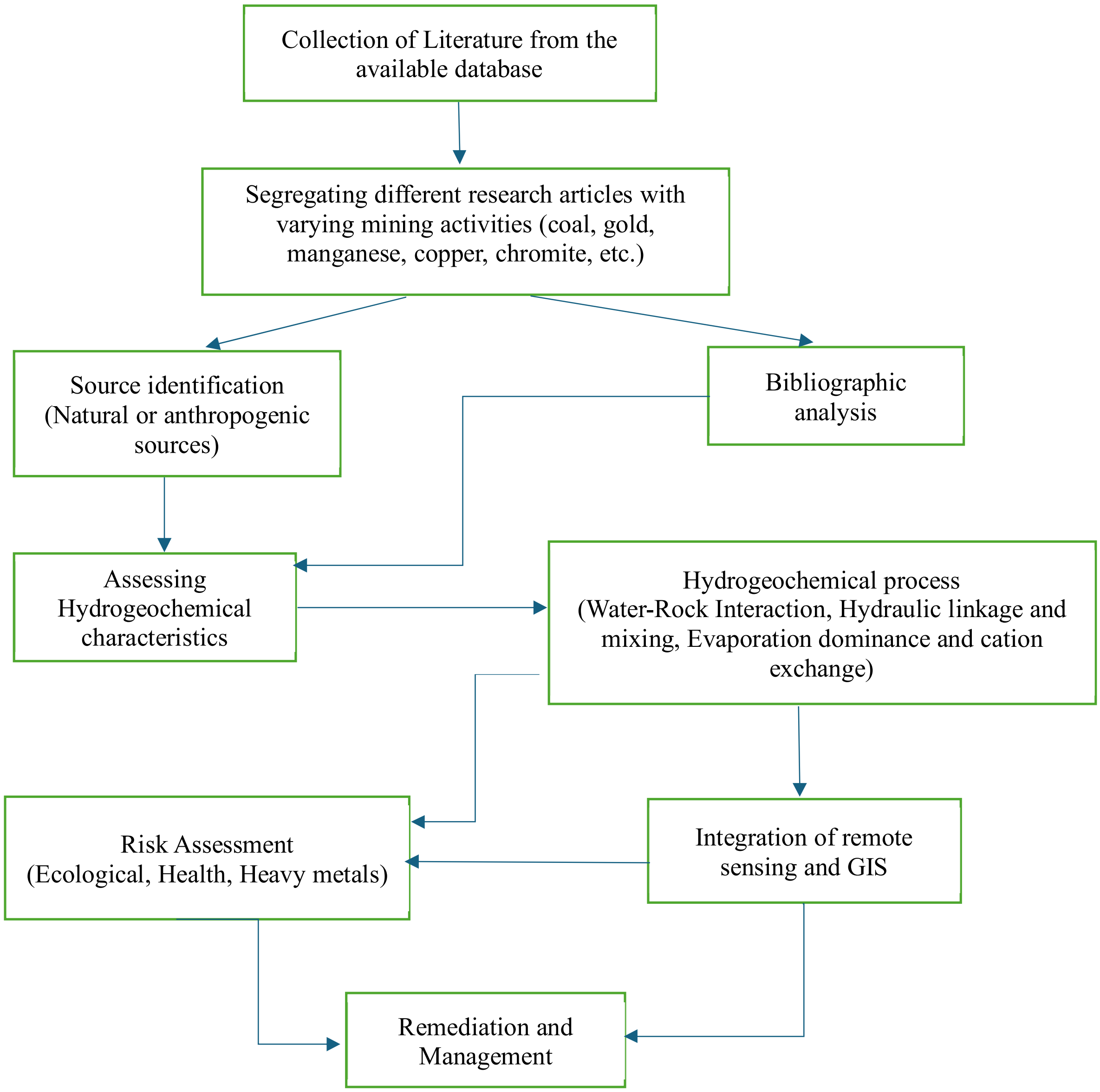


Figure 2. Literature Review Methodology

3.1. Current Trends in Mining Research

To analyse the recent trend in the field of research on hydrogeochemical characterisation and groundwater quality assessment in mining areas, a thorough search was performed with the help of dimension.ai, which is a database tool to search for relevant research in the field of interest. In Figure 3(a), the publication concerning sustainable development goals was analysed by filtering the criteria: - hydrogeochemical characterisation and groundwater quality assessment. The graph depicts that the number of publications on the research reveals that the focus was on goal 6 of SDGs with 69 publications, goal 15 of SDGs with 37 publications, goal 7 with 27 publications, goal 13 with 23, goal 2 with 11, goal 12 with 11, goal 14 with 10, goal 3 with 7, goal 11 with 3, goal 4 with only 2 and goal 1 with 1 publication during the year 2019 to 2024.

The exact search was also performed to analyse the number of publications in different research journals, as presented in Figure 3(b), where Earth Sciences had the highest number of publications of 1,607, 2nd highest Environmental Sciences with 861 publications, 3rd Engineering with 404 publications, Biological Sciences with 101 publications, Chemical sciences 72, Information and Computer Sciences 46, Human Society, Agricultural, Veterinary and Food Science 36, Biomedical and Clinical Sciences 24, Buit Environmental and Design 23, Health Sciences 21, Law and Legal Studies 18, Economics 16, Physical Sciences 15, Commerce Management Tourism 9, History Heritage and Archaeology 8, Philosophy and Religious Studies 3, and last with the least publication Mathematical Sciences with 2 publications with the duration of 2019 to 2024 onwards. In Figure 3(c), the number of citations is presented to understand the trends in the research analysed from 2019 to 2024.

3.2. Bibliometric analysis

The bibliometric map of the review of hydrogeochemical characteristics and groundwater quality assessment in mining areas has been shown in Figure 4(a), which shows the co-occurrence network visualisation from the relevant literature, which provides insight into the research where the terms with large labels have higher weightage and their co-citation links between other terms indicates the relatedness of journals in terms of co-citations. Four different clusters have been presented with a total of 47 items, 579 links between the items with a total link strength of 1738 were identified from the VOS viewer, and their interpretation of different clusters with the relevant keywords has been shown in Figure 4(a).

Overlay visualisation gives insight into the colour of the items, which is determined by three different colour columns that the user can also specify. So here, the colour range of blue suggests the lowest score, to green to yellow with the highest score. The colour bar in the bottom right indicates how colour columns provide a strong or weak relationship between the terms with respect to the colour range (shown in Figure 4(b)). The density visualisation in Figure 4(c) shows that the terms in yellow have the highest density with higher weights of the neighbouring items. The lower the weights of the neighbouring points, the smaller the number of items.

4. Results and Discussion

4.1. Global mining

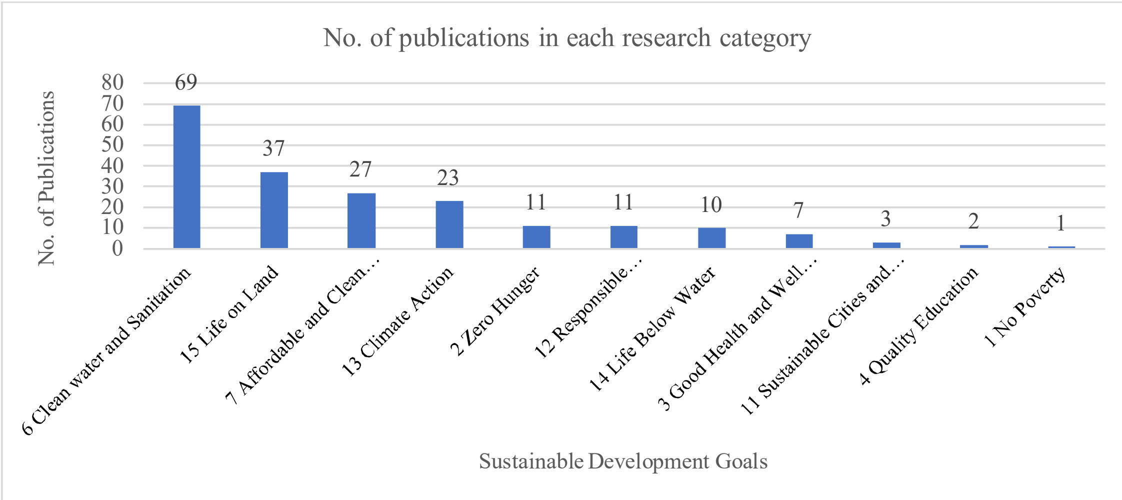
The studies from global mining highlight the crucial role of hydrogeochemical characteristics and their various properties that play an essential role in groundwater quality, especially in mining areas. The groundwater mineralization and ageing provide insight into the type of groundwater quality like in the case of groundwater in Côte d'Ivoire. It is undersaturated with calcite and dolomite, which indicates slow circulation and significant ageing [26]. Also, studies of Mongolia's Longwanggou coal mine determine the cation exchange, leaching, and mineral dissolution drive through groundwater chemistry [28].

The hydrogeochemical processes in the Guqiao Caol mine and Ordos basin identify the desulfurization, halite dissolution and cation exchange as major hydrogeochemical processes in the region [27,28]. The dominant factors that shape the groundwater characteristics in the Guanzhong basin of China were rock weathering and pyrite oxidation [29]. Several other research findings are summarised in Table 1, which provides insights into different mining activities and their associated problems.

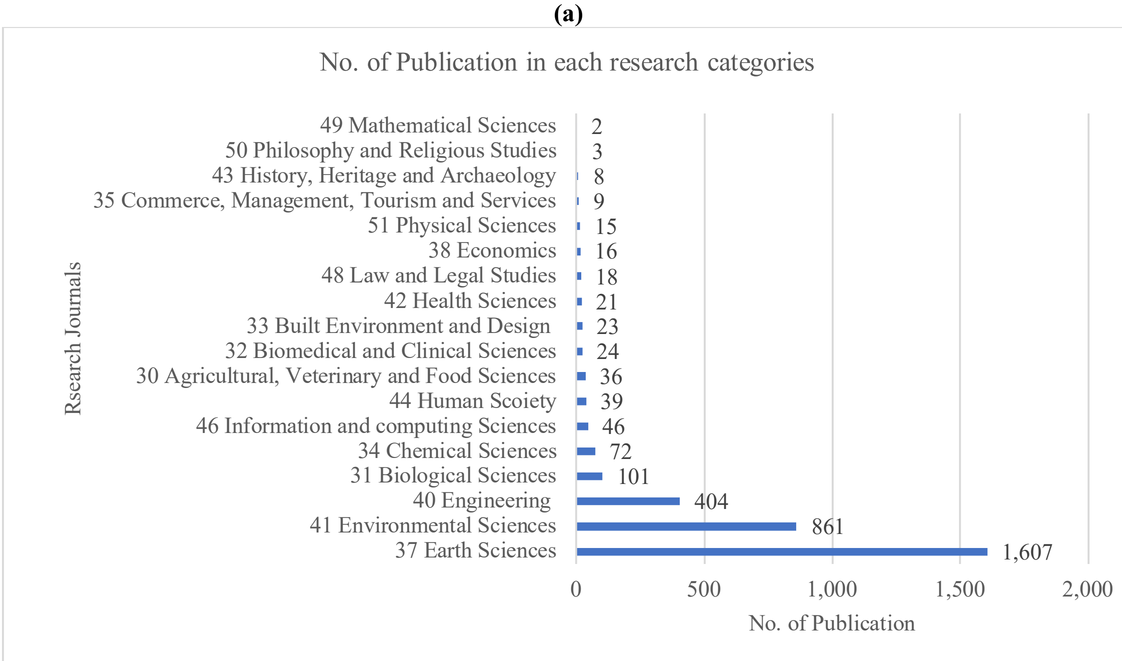
All these studies highlight that mining-related operations or activities possess significant changes in groundwater quality, contributing to changes in pH, salinity and ion concentration due to water-rock interaction and additional anthropogenic inputs. The finding also suggests monitoring and managing groundwater sustainably to prevent contamination, mitigate environmental risks, and ensure water sustainability. Advanced techniques and tools integrated with remote sensing, like Self-Organizing Maps (SOM), PHREEQC modelling, and multivariate statistical analysis, can provide groundwater sustainable water management in assessing mining areas [26,27].

4.2. Indian mining

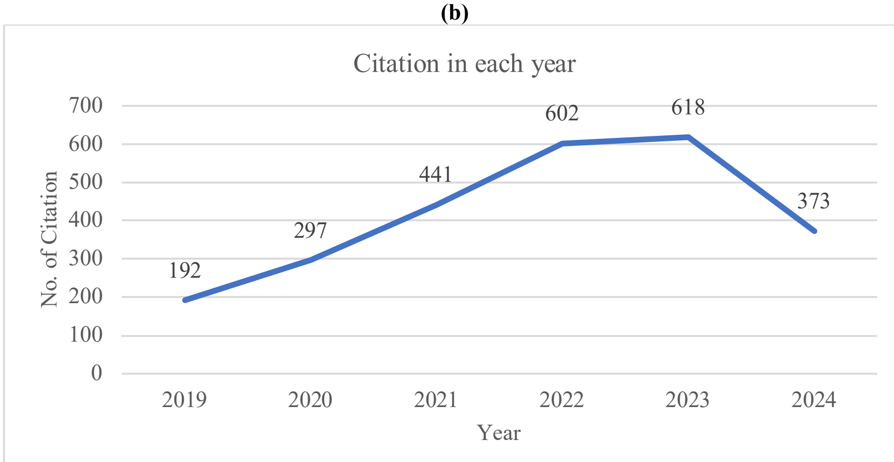
The Indian mining scenario assesses heavy metals contamination, deteriorating groundwater quality and contamination risk. The groundwater in Korba Coalfields investigation revealed higher concentrations of heavy metals like Al, Mn, Ni and Zn, which exceed the BIS and WHO drinking standards [2]. In addition to heavy metals, the fluoride and nitrate levels in opencast mines in Raigarh, India exceeded the safe limits in several areas, which also require monitoring [33]. The acid mine drainage in Jaintia Hills, Meghalaya, also suggests degraded water quality in the region due to mining activities [31], and Neyveli coal mines in Tamil Nadu in India are influenced by evaporation and phosphate contamination due to agricultural practices [32]. These findings suggest the complex interaction between mining activities, groundwater chemistry and anthropogenic activities, which ultimately need remediation strategies and sustainable water resources management. Several other types of research have also been summarised in table 2 for a better understanding of the mining practices.



(a)

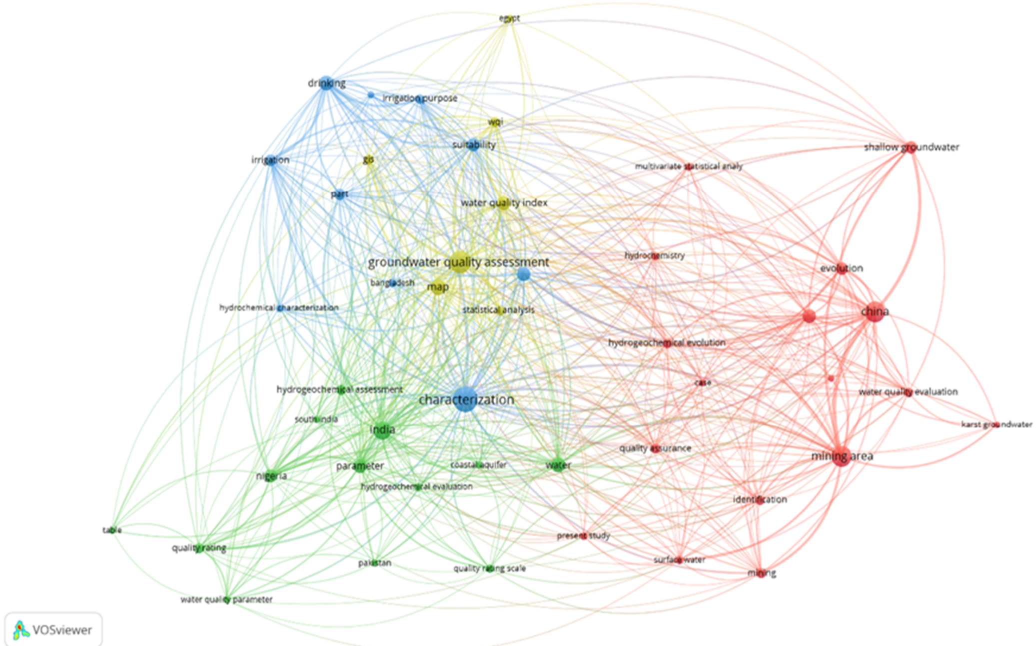


(b)



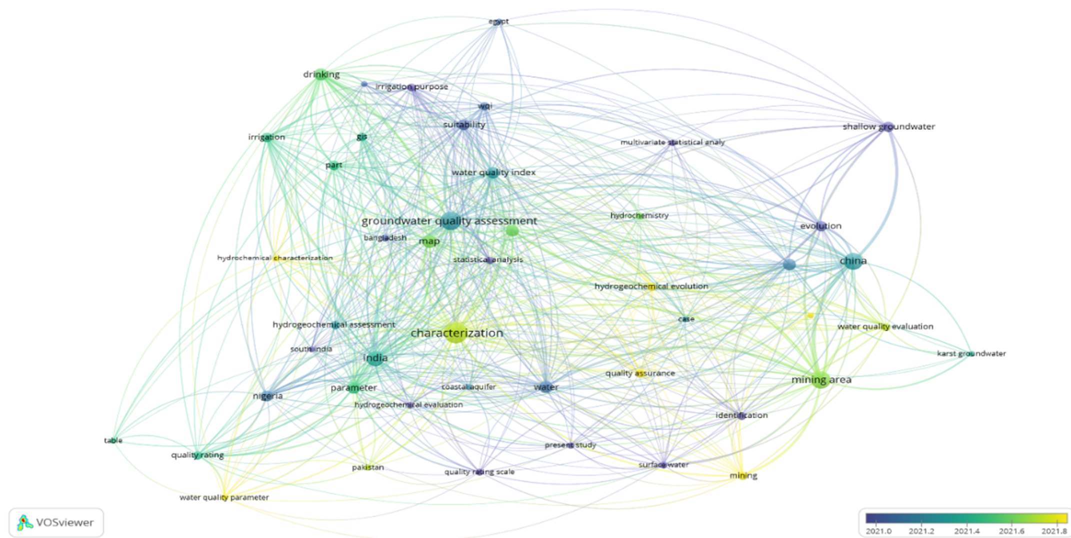
(c)

Figure 3. (a) Publication with respect to the sustainable development goals; (b) Publication with respect to Journals; (c) No. of citations from 2019 to 2024



(a)

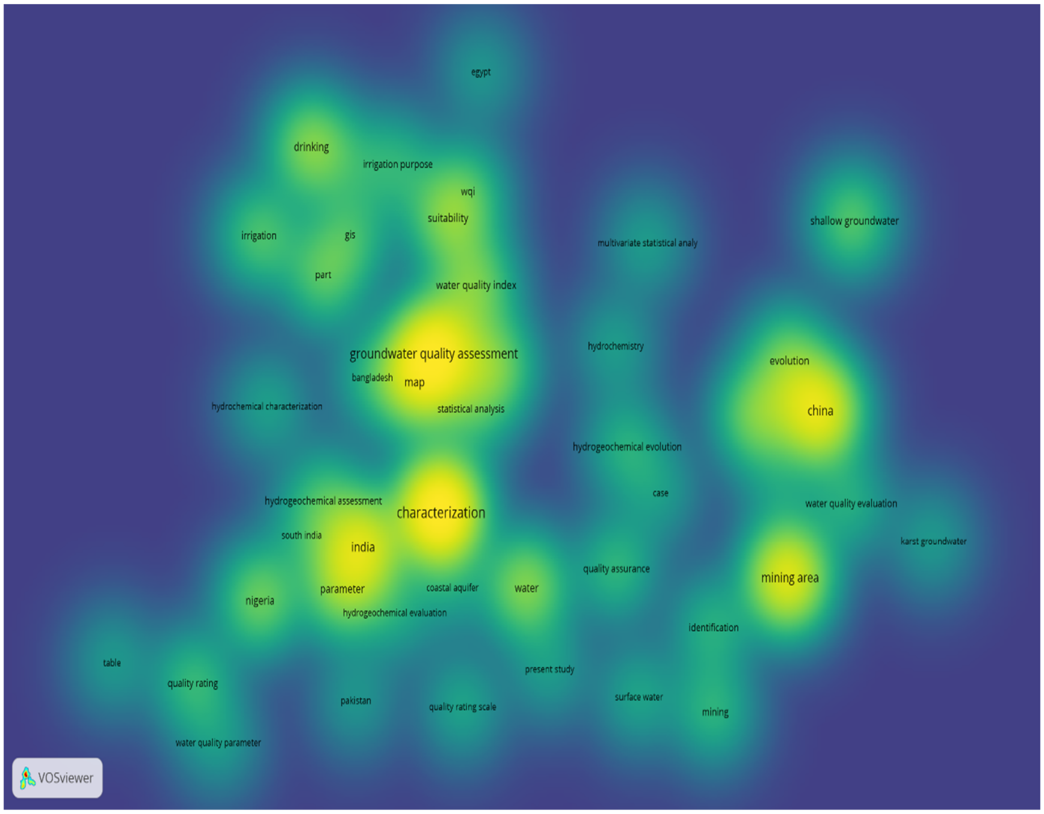
Blue Cluster	The cluster represents on the focus on drinking, irrigation, WQI, and groundwater assessment, and suitability of usage with respect to agriculture and drinking purposes
Green Cluster	It focuses on regional studies and water quality, which includes India, Nigeria, Pakistan, and hydrogeochemical assessment.
Red Cluster	Keywords like China, mining area, evolution, water quality evaluation and shallow groundwater represent groundwater contamination and mining-related studies.



(b)

Blue Nodes	Keywords that were widely researched in the years 2010-2012. Keywords like shallow groundwater, evolution, and multivariate statistical analysis have appeared during the metioned year
Green Nodes	Keywords that gained prominence in the year 2014-2016. Keywords like groundwater assessment, hydrogeochemical evolution, water quality index etc.
Yellow Nodes	Keywords that have emerged in recent years. Keywords like mining area, identifiaction, surface water, quality rating scale etc.

Figure 4. (a) Co-occurrence network visualization; (b) Temporal Co-occurrence network visualization; (c) Density visualization.



(c)

Bright Yellow (High-Density)	This represents core research, with keywords like characterisation, groundwater quality assessment, China and mining area, etc., apperaing frequently.
Green (Moderate-Density)	Keywords like, hydrogeochemcial assessments, WQI and hydrochemistry are lessc entred but are significant, while region studies like India and Nirgeria appear in moderate emphasis.
Blue/Purple (Low-Density)	Keywords, like Egypt, Table, Quality rating scale, Pakistan have been less emphasis in the research

Continues of Figure 4. (a) Co-occurrence network visualization; (b) Temporal Co-occurrence network visualization; (c) Density visualization.

4.3. Mining in Jharkhand

Jharkhand, being rich in mineral and coal deposits, also possesses several implications due to mining activities. Groundwater quality variability in seasons plays an important role in shaping groundwater; one of the cases in Jamunia basin in Jharkhand where coal mining areas suggest the need for sustainable mining practice to prevent the effects on downstream water resources, which was derived from digital elevation model and soil water assessment tool (SWAT) [36]. Remote sensing tools and WQI tools helps in analyzing the seasonal variation in groundwater quality, i.e. in the research of Hazaribagh and Ramgarh. In the post-monsoon season, the groundwater quality was fit for drinking, while in the pre-monsoon season, the same area had poor or unsuitable water for drinking [37]. Several other studies have been summarized in Table 3 for a better understanding of the influences of mining in the region.

Table 1. Different types of mining activities in the world and their groundwater pollution source assessment

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and other Risk	Author and year
			Natural sources	Anthropogenic sources		
Nile Valley, Egypt	New artisanal and small-scale gold mining	Amalgamation-tailing ponds: 1200–8470 ng/L Irrigation canals: 50–100 ng/L Drainage canals: THg > 200 ng/L Groundwater (shallow and deep aquifers): 80–500 ng/L		Mercury and methylmercury due to gold mining	Surface and groundwater contamination, soil, livestock, vegetation Serious health issues, respiratory issues, skin ailments, chronic diseases	Abdelaal *et al*., 2023 [39]
Huainan Coalfield China	Coal Mine (Guqiao)	hydrochemical types, such as HCO_3^-–Cl–Na, Na-Cl, and HCO_3^- TDS values = 505.47 mg/L to 2859.71 mg/L	Cenozoic groundwater dolomite, calcite, gypsum, and halite	Mining Activities Mine drainage, Agriculture activities, domestic wastewater	Poses risks to both ecological systems and human health	Xue *et al*., 2024 [27]
Ghana	Manganese mine	Ca-Mg-SO_4 Ca-Mg-HCO_3-SO_4 Ca-Mg-Na-Cl to Ca-Na-Cl-HCO_3 water type	Intense water-rock interaction Water supersaturated goethite and hematite. This interaction dissolves rocks from the Banded Manganese Formation and the Birimian metasediments.	Mine pit water very high Fe, Mn, Ni, As and Sb concentrations. This results from the hydromorphic dispersion of heavy metals into surface water and groundwater.	Water Hazard Index- minimal to extreme toxicity, Surface water and mine pit water are at the highest risk. Hazard Index-health risks associated with consuming the water from surface water and the mine pit	Ewusi *et al*., 2022 [40]
China	Coal Mining (Shendong)	**High Sodium (Na^+) levels** affect soil quality and crop yields if used for irrigation. **High levels of Fluoride (F^-)**: Fluoride above safe limits can cause health problems. **High Sodium Ion Adsorption Ratio (SAR):** a risk of sodium accumulating in soil, impacting its structure and permeability. **High Total Dissolved Solids (TDS):** water unsuitable for drinking and some irrigation purposes.	**Dissolution of minerals:** halite (NaCl) and silicate rocks dissolve in the mine water. **Na^+:** contributing to Total Dissolved Solids (TDS). **Water-rock interaction in mine goaf** increases the concentration of fluoride and calcium.		Na^+ presence suggests = water is likely saline or brackish. Water quality is not suitable for drinking or most irrigation purposes, requires treatment. Potential health risks from fluoride.	Guo *et al*., 2023 [41]
Ghana (South-Western)	Manganese mine	**Water quality:** 82% of the water sources were classified as low quality, unfit for drinking. High levels of turbidity, total suspended solids (TSS), low dissolved oxygen (DO), and heavy metals (Fe, As, Mn) in the water to these mining activities.		**Possible causes:** The high levels are likely due to leaching, runoff, and dissolution of hazardous substances used in mining.	**Health risks:** People are at risk of contracting water-related diseases and health problems from ingesting iron (Fe), arsenic (As), and manganese (Mn).	Anang *et al*., 2023 [42]
China	Coal mine	**High Sulfate Levels:** Over 64.7% of the groundwater samples exceeded the safety standard for sulfate concentration.	The presence of pyrite (iron sulfide) is a natural geological feature.	**Changing Hydrochemical Type:** In karst groundwater (dissolved rock formations), the water type shifted from HCO_3-Ca-Mg (recharge area) to SO_4-Ca-Mg (discharge area) due to anthropogenic sulfate input.	Groundwater quality in the Xishan mining area is poor and unsuitable for drinking or many other uses due to high sulfate levels.	Chen *et al*., 2023 [43]

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and other Risk	Author and year
			Natural sources	Anthropogenic sources		
China	Coal mine (Changhe River Basin, Shanxi)	**Dominant Water Type:** Both surface water and groundwater are classified as HCO_3-Ca type, with HCO_3^- accounting for a major portion of the anions and Ca^{2+} being the dominant cation. **Midstream Water Quality:** The water quality in the midstream of the CRB is identified as poor.	**Rock Weathering:** The primary factor influencing the hydrochemistry of both surface water (SW) and groundwater (GW) is identified as rock weathering. **Weathering of Silicate and Carbonate Rocks:** Surface water is affected by the weathering and dissolution of both silicate and carbonate rocks, contributing to the dominant HCO_3-Ca water type. **Weathering of Silicate Rocks:** Groundwater is mainly influenced by weathering and dissolution of silicate rocks.	**Coal Mining:** The study reveals a negative impact of coal mining activities on the hydrochemistry of the CRB, particularly in the midstream area where water quality is classified as poor.	Coal mining activities are linked to a serious decline in water safety in the midstream area. This suggests potential health risks associated with water contamination.	Yan *et al*., 2023 [44]
China	Coal mine (Handan)	**Groundwater:** 16.7% and 50% of samples classified as medium and high-level pollution, respectively. Higher levels of most measured elements. **Surface Water:** Higher levels of most measured elements compared to non-mining area.	**Geology:** The study mentions the lithology of the aquifer (various rock types) as a natural factor influencing groundwater composition. **Sulfide Mineral Oxidation:** This process is identified as a source of iron (Fe) and sulfate (SO_4^{2-}) in the water. **Evaporative Concentration:** Concentration of sulfate in the aquifer is another natural process affecting water quality**.**	Higher levels of various elements (TH, NO_3^-, SO_4^2, Ca, K, Co, Se, Rb, Fe, Ni) were found in the mining area compared to the non-mining area. The study specifically links increased nitrate (NO_3^-) to coal mining activities. Oxidation and leaching of selenium-rich coal and coal ash sedimentation are identified as sources of elevated selenium (Se) in the mining area.	**Non-carcinogenic risk:** Elevated chloride levels pose a non-carcinogenic health risk for drinking water in both areas. **Carcinogenic risk:** Lead (Pb) concentrations in the mining area pose a potential carcinogenic health risk. **Selenium:** While high selenium levels in the mining area exceed regional averages, the study suggests they might be within a range suitable for selenium supplementation (dietary requirement).	Hussain *et al*., 2019 [45]
Côte d'Ivoire (Central-West)	Angovia Gold mine area	**Temperature:** Averages around 27.5°C in the rainy season and 27.9°C in the dry season. **pH:** Slightly basic, averaging around 7.1 during the rainy season and 7.3 during the dry season. **Electrical conductivity (EC):** Indicates moderate mineralization, with an average EC of 506 µS/cm in the rainy season and 450 µS/cm in the dry season. **Saturation indices:** Undersaturated with respect to calcite and dolomite, suggesting the groundwater is old with slow circulation.	**Water-rock interaction:** This is likely a major factor influencing water chemistry, although the study doesn't specify the exact rock types. **Oxidation-reduction processes:** These influence the overall water chemistry. **Surface inflow:** This suggests some interaction with surface water sources.			Yao *et al*., 2024 [26]

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and other Risk	Author and year
			Natural sources	Anthropogenic sources		
Mongolia	Opencast Coal Mine (Dongming)	**Hydrochemical similarities:** Quaternary aquifer pore water (QGW) and Morigele River water (MRW) Coal-bearing aquifer pore-fissure water (CGW) and mine pit drainage sump water (DSW)	**Morigele River Water (MRW):** Isotope data suggests this river water is the primary source for all groundwater in the area. **Snow Water (SNW):** While not explicitly linked to groundwater recharge, its presence indicates potential natural snowmelt contributions.	No direct mention of anthropogenic sources	**Groundwater leakage:** The study focuses on this as a major threat to the mine, suggesting potential contamination or safety concerns. **Limited information:** The study doesn't elaborate on the specific risks associated with leakage or water quality concerns.	Zhong *et al*., 2024 [46]
China	Coal Mining (Fengfeng)	**Shallow Pore Water (SPW):** Poorer quality compared to DKW. **Higher Total Dissolved Solids (TDS).** **Hydrochemical type:** HCO_3-Ca changing to SO_4-Ca (potentially due to anthropogenic influence). **Deep Karst Water (DKW):** Better quality compared to SPW. Lower TDS. Elevated nitrate levels in SPW pose a high non-carcinogenic health risk, especially for children.	**Weathering of Silicates and Carbonates:** This is identified as the primary influence on the chemical composition of both shallow pore water (SPW) and deep karst water (DKW). **Weathering of Sulfidic Minerals:** This process is identified as a contributor, especially for SPW.	The study mentions human activities as a contributing factor to the overall water chemistry but doesn't specify the exact sources. Coal mining is a likely suspect in this area.	**SPW not suitable for drinking:** The poor water quality and high nitrate levels make shallow pore water unsuitable for consumption. **Potential health risks:** Nitrate contamination in SPW poses a health risk, particularly for children.	Zhang *et al*., 2023 [47]
Serbia	Copper Mine/Smelter (Bor)	**Highly Contaminated:** The study reveals high levels of PTEs, particularly Cu and Zn, exceeding safe limits.	**Iron (Fe):** Identified as a naturally occurring element in the groundwater. **Manganese (Mn):** Identified as a naturally occurring element in the groundwater. **Fluoride (F^-):** Identified as a naturally occurring element in the groundwater.	**Smelter/Mining Processes:** Linked to contamination by various PTEs (except Fe, Mn, F^-) including: Copper (Cu) Zinc (Zn) Cadmium (Cd) Chromium (Cr) Lead (Pb) Nickel (Ni) Mercury (Hg) Arsenic (As) Cobalt (Co) Vanadium (V) **Agricultural Activities:** Linked to nitrate (NO_3^-) contamination.	**Non-cancer and Cancer Risks:** Geospatial mapping identified hotspots with potential health risks from ingestion. **Arsenic:** Identified as the most significant health risk contributor among the studied PTEs. **Source-Specific Risks:** Accidental leakage from metallurgical wastewater and open mine pits pose the most significant risks. **Human Health Effects:** The study suggests potential health risks but doesn't specify the exact health problems.	Vesković *et al*., 2024 [48]
China	Coal-Grain Area (Anhui Province)	**Limited Data:** The study doesn't explicitly assess water quality for drinking or other uses. It focuses on the sources of sulfate and spatial variations in river water chemistry. **Sulfate (SO_4^{2-}):** Stable isotope analysis is used to identify soil sulfate and mine drainage as the main sources.	**Water-Rock Interactions:** Identified as a major influence on the overall river water chemistry, likely contributing to the presence of sulfate (SO_4^{2-}). **Stable Isotope Analysis:** The study uses isotopes of hydrogen (δ^2H-H_2O, $\delta^{18}O$-H_2O) and sulfur ($\delta^{34}S$-SO_4^{2-}, $\delta^{18}O$-SO_4^{2-}) to help identify sources but doesn't explicitly differentiate natural from anthropogenic contributions.	**Coal Mining:** Identified as a contributor to sulfate (SO_4^{2-}) levels in the river water, likely through mine drainage. **Agricultural Activities:** Manure release is suggested as a potential contributor, but the study doesn't quantify its impact. **Sewage Discharge:** Sewage discharge is mentioned as a potential source, but the study doesn't quantify its impact.	The study focuses on understanding sources rather than potential health risks associated with water quality.	Li *et al*., 2024 [49]

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and other Risk	Author and year
			Natural sources	Anthropogenic sources		
China	Coal mine (Caojiatan, Shaanxi Province)	The study observed a significant change in groundwater composition after mine drainage entered the upper aquifers.	The study focuses on existing groundwater in the Anding and Zhiluo aquifers**.**	The inflow of mine drainage water from the underlying Yan'an aquifer. The study highlights mine drainage's impact on groundwater's hydrochemical evolution in overlying aquifers.	**Not directly assessed:** The study focuses on the process of water quality changes, not the specific risks associated with the altered water chemistry.	Qu *et al*., 2023 [50]
Ghana (southwestern)	Gold mining (artisanal)	The study doesn't explicitly state current water quality but assesses the risk of pollution through the sustainability index.		Illegal gold mining (galamsey) activities are polluting water sources.	Potential for surface water pollution caused by illegal mining to seep into the groundwater resource.	Nti *et al*., 2024 [53]
China	Coal mining (Northern Ordos Basin)	The research doesn't explicitly state water quality parameters but focuses on changes in hydrochemical properties due to mining.	Minerals containing Rare Earth Elements (REEs)	Coal mining activities (potentially altering water-rock interaction and leading to changes in groundwater chemistry)	The focus is not on direct health risks but on using REEs as tracers to understand the impact of mining on groundwater chemistry. High levels of some REEs can be harmful, but the abstract doesn't assess this.	Liu et al., 2024 [54]
China	Coal mining (Xinglong Zhuang)	The study focuses on changes in hydrogeochemistry over time, not absolute water quality. Changes in ion concentrations (Na^+ increase, Ca_2^+ decrease) suggest potential alterations in water quality.	Groundwater in multiple aquifers (Permian and lower Quaternary)	Coal mining activities	The focus isn't on immediate health risks but on understanding how mining impacts groundwater quality over time. Increased Na+ can be a concern for some people with health conditions.	Qiao *et al*., 2019 [55]
China	Coal mining (Hancheng, Guanzhong Basin)	89% of the groundwater samples were classified as freshwater. The dominant water type is $SO_4{\cdot}Cl^{-}Ca{\cdot}Mg$, suggesting a mix of mineral dissolution and potential sulfate contribution.	Minerals: Dolomite, calcite, gypsum, halite (source of Na^+ and Cl^-) Pyrite (source of sulfate, SO_4^{2-}) - Potentially affected by natural weathering processes.	Mining activities in the area could potentially influence weathering processes and pyrite oxidation.	High sulfate levels can be a concern for some people with health conditions. The research suggests pyrite oxidation as a factor affecting sulfate but doesn't quantify the risk level.	Kou *et al*., 2024 [29]
Ghana	Illegal small-scale gold mining (galamsey)	Slightly acidic (33% of samples below pH 6.5) - may require treatment for some uses. Total dissolved solids (TDS) within acceptable range for drinking water according to WHO (<500 mg/L). Nitrates (NO_3^-) - Levels varied widely. High nitrate levels can be a health concern, especially for infants. Other parameters (Na^+, Ca^{2+}, Mg^{2+}, Cl^-) within acceptable ranges for drinking water according to WHO (specific limits not mentioned in the abstract). Water quality index analysis: 61% of samples considered optimal for domestic use.	Rock weathering and dissolution processes (main influence on groundwater chemistry)	Illegal mining activities (galamsey) - Likely polluting surface water (not directly mentioned as a source for groundwater contamination in this study, but indirectly influencing the shift to groundwater use)	Slightly acidic water can be corrosive to pipes and may cause health effects with long-term consumption. High nitrate levels in some samples can be a health risk, especially for infants. Overall, the abstract suggests a need for further evaluation of some samples before relying solely on groundwater.	Kazapoe *et al*., 2024 [25]

Table 2. Different types of mining activities in India and their groundwater pollution source

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and other Risk	Author and year
			Natural sources	Anthropogenic sources		
India	Coal mine (Korba)	**Groundwater**: Slightly acidic, indicating potential for mineral leaching. **River Water & Mine Water**: Mildly alkaline.	**Silicate Weathering**: Interaction of water with rocks releases ions like Ca^{2+}, Na^{+}, HCO_3^-, and SO_4^{2-}	**Mine water**: High levels of Pb, Mn, Fe	**Water samples**: Excellent for the permissible category for irrigation. Suitable for drinking purposes. Adverse effects on soil quality and crop yields in the long term if these metals accumulate in the soil.	Singh *et al.*, 2017 [15]
India	Coal Mine (Jampali)	**Overall:** The water quality index classified 79% of the samples as excellent and 18% as good, indicating generally good water quality. However, some treatment might be necessary for some uses. **Spatial Distribution:** Water quality worsens (higher parameter values) closer to the coal mine. **Specific Concerns:** Nitrate (NO_3^-) exceeded the permissible limit in one sample (GW-8). Fluoride (F^-) exceeded the limit in two samples (GW-4 and GW-11).	**Rock Dominance:** The study suggests rock formations are the major contributor to the water's chemical composition, based on the Gibbs plot analysis.	**Coal Mining:** While not explicitly stated as a source of contamination, the study is conducted near an opencast coal mine, suggesting a potential anthropogenic influence.	**Potential health risks:** Elevated nitrate and fluoride levels in some samples could pose health risks if consumed without treatment.	Ahmed *et al.*, 2022 [33]
India	Coal mine (Korba)	HPI and HEI suggest low to medium pollution levels. MI suggests very pure to slightly affected water. Some locations exceed WHO and BIS limits for specific metals (Al, Mn, Ni, Zn). The study concludes that the groundwater quality is generally adequate for drinking (except for a few locations with high metal concentrations).		Open-cast coal mining and leachate from overburden dumps are identified as the primary source of heavy metal contamination.	**Elevated metal concentrations:** Al, Mn, Ni, and Zn exceeded acceptable limits in some areas, posing potential health risks for humans and animals. **Health effects:** The study mentions various health problems that can arise from exposure to high metal concentrations but doesn't specify the specific diseases.	Dheeraj *et al.*, 2024 [2]
India	Coal Mines (Dipka, Chhattisgarh)	**Poor quality:** Water samples from the area exceed acceptable contamination levels for the listed heavy metals. **Groundwater downstream:** Significantly high levels of heavy metals detected in groundwater used by settlements located downstream of the mining waste facilities.		Mining waste facilities (coal extraction and washeries) are identified as the primary source of contamination. Metalloids and heavy metals like Lead (Pb), Zinc (Zn), Cadmium (Cd), Copper (Cu), and Nickel (Ni).	**Environmental risk:** The close proximity of mining waste facilities to residential areas, agricultural land, and surface water creates a high environmental risk. **Health risks:** Contaminated groundwater is used for drinking by humans and animals, posing potential health risks. Agricultural impact: Contaminated water is used for irrigation, potentially impacting agricultural products.	Pandey *et al.*, 2023 [30]
South India	Inactive mines (Cuddapah Basin)	Several heavy metals (Arsenic (As), Cadmium (Cd), Nickel (Ni), Lead (Pb), Strontium (Sr)) exceeded permissible limits in both pre-monsoon and post-monsoon seasons. Heavy Metal Pollution Index (HPI) suggests high pollution in 17.5% and 10% of samples during pre- and post-monsoon seasons, respectively. Degree of Contamination (DOC) suggests low contamination in all samples.		Trace metal leachate from inactive mine reservoirs in the study area is identified as the primary source of contamination.	**Ecological Risk:** The study suggests an extreme to high ecological risk based on ecological risk classification (90% of samples in both seasons). **Health Risk:** The study suggests non-carcinogenic health effects for both adults and children.	Reddy *et al.*, 2023 [51]

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and other Risk	Author and year
			Natural sources	Anthropogenic sources		
India	Coal mine (pristine streams)	**Water Quality Index (WQI):** Confirms the poor quality in impacted streams and good quality in the unimpacted stream. **Comprehensive Pollution Index (CPI):** Indicates "Severely Polluted" status in impacted streams and "Clean to Sub-Clean" in the unimpacted stream. **Principal Component Analysis** (PCA) identified higher levels of free CO_2, Lead (Pb), Sulfate (SO_4^{2-}), Electrical Conductivity (EC), Iron (Fe), and Zinc (Zn) in AMD-impacted streams.		Coal mining is identified as the main culprit for water quality degradation.	**Environmental Damage:** Coal mine waste is causing severe environmental issues, particularly impacting stream water quality. **Public Health Risk:** Contamination by Acid Mine Drainage (AMD) makes stream water unsuitable for drinking in most areas. This is a major concern as these streams are the primary water source for local communities.	Das *et al*., 2023 [31]
India (South)	Coal mine (Neyveli)	**pH:** Moderately acidic to slightly basic. **Major ions:** **Calcium (Ca) and Magnesium (Mg):** Likely come from natural sources (halite and dolomite dissolution). **Phosphate:** Possible influence from agricultural practices (fertilizers). **Water types:** Mixed $CaNaHCO_3$, mixed CaMgCl, CaCl (based on Piper diagram). Salinity: Most samples fall under "high salinity - low sodium hazard" category.	Halite and dolomite dissolution (contributing to Ca and Mg).	Agricultural practices (possible source of phosphate).	**Salinity:** High salinity might limit some irrigation uses or require special management practices. **Limited data:** The study doesn't assess potential trace element contamination or long-term impacts of using mine water for irrigation.	Anjali *et al*., 2023 [32]
India Sukinda ultramafic valley, Odisha	Chromite Mining	**78% of water samples** exceeded chromium (VI) drinking water standards. **82% of water samples** exceeded drinking water standards for iron. **Entropy water quality index classified:** 50% of samples are average to bad 44.29% as unsafe for drinking.	Mineralization of ultramafic rocks (high in chromium) Leaching of chromium and iron from soil overburden	Mining activities (discharge of Cr (VI) and iron)	Increased cancer risk, especially for children (1.5 times higher than adults) Metal concentrations are the most influential factor for increased risk	Kumari *et al*., 2024 [52]

Table 3. Different types of mining activities in the state of Jharkhand and their groundwater pollution source

Country	Mining Type	Water quality	Source of contamination		Health, Ecological, and Other Risks	Author and year
			Natural sources	Anthropogenic sources		
India, Jharkhand	Coal mines	High levels of Total Dissolved Solids, Fluoride, Nitrate, Total Hardness, Turbidity, Iron, Manganese Exceedance of the Bureau of Indian Standards (BIS 2012) acceptable drinking water limits at many locations	Dissolution of minerals Weathering of rocks	Agriculture Coal mining Other mining-related activities	Human health risks via the drinking water pathway. The **Estimated Hazard Index (HI)** indicates a higher potential health risk for the child population compared to the adult population. **The Heavy Metal Pollution Index (HPI)** indicates that 41% of water samples belong to the medium class, suggesting a moderate pollution level. The **Water Quality Index (WQI)** suggests that a few locations are not suitable for drinking purposes.	Neogi *et al.*, 2023 [85]
Eastern India	Coal Mines Jharia Coalfield	Increase in common water quality indicators in the Fire Impact (FI) zone. The presence of different ions in the water, including Heavy metals and Other inorganic ions Considerable changes in water level based on seasonal variation Efficient mixing of ions in the groundwater	Leaching of ions through porous lithography. Seasonal variation in water level.	Coal mine fire	Long-term health impacts for both adults and children due to the presence of heavy metals in the FI zone Increased levels of water quality indicators Health risk assessment study indicates a higher risk in the FI zone compared to the Non-Fire (NF) zone Potential health impacts may include Cancer, Neurological damage Other health problems associated with heavy metal exposure	Prasad *et al.*, 2022 [35]
India	Lalmatia, open-cast mining, Godda, Jharkhand	The highest concentration of chromium and uranium was found to be 0.092 ppm and 0.00733 ppm. Arsenic concentration in groundwater was 0.004 ppm.	Mobilization of metals from uranium ores (like uraninite and autunite). Diffusion from arsenic- and chromium-bearing ores.	Pollution from nearby dyeing industries and other industrial effluents. Along with the direct impacts of mining activities	The groundwater in the region is polluted with heavy metals and is unfit for drinking and agricultural use, which can pose certain health risks, especially in children.	Jha *et al.*, 2023 [34]
Charhi and Kuju, Jharkhand, India	Open-cast coal mining	Elevated concentrations of: Arsenic (up to 0.09 mg/L in summer); Selenium (up to 0.29 mg/L in summer); Physical and chemical parameters exceeding acceptable limits. Water quality indicate unsuitability for drinking water.	Geogenic sources (arsenic and selenium-rich rocks and soil)	Coal mining activities (active and abandoned sites)	Health risks associated with long-term consumption of arsenic and selenium-contaminated water include Cancer, Neurological damage, and other health problems. Irrigation indices indicate suitability for irrigation but potential risks to crops and soil quality due to elevated arsenic and selenium levels.	Prathap *et al.*, 2019 [38]

Table 4. Summary of Groundwater hydrogeochemical characteristics in mining areas.

Location and type of mine	WHO (2008) and BIS (2012)	pH	EC (µS/cm)	TDS	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	SO_4^{2-}	NO_3^{-}	Cl^{-}	F^{-}	CO_3^{2-}	HCO_3^{-}	References
		Parameters (mg/L)													
	Desirable	6.5	500	500	50	12	75	30	250	50	200	1	300	300	
	Permissible	8.5	2500	2000	200	-	200	150	600	100	400	1.5	600	600	
Basundhara **coal mining** area Ib Valley coalfields Sundargarh district of Odisha	Groundwater	7	787	503	42	20	43	34	92	28	65	0.57	183	247	Samal *et al*., 2022 [8]
Sukinda **chromite** mines Jajpur district of Odisha	Groundwater	6.37	305.23	211.67	23.57	3.10	25.39	19.84	3.589	6.418	54.00			144.47	Kumari *et al*., 2024 [25]
	Surface water	6.85	193.63	138.46	5.08	1.54	21.65	12.30	8.98	2.78	39.33			95.44	
Neyveli **coal mine region** Tamil Nadu, India	Ground water	7.30	1243	791.6	114.50	8.57	34.86	29.14	0.53	19.15	184.2				Anjali *et al*., 2023 [32]
Fengfeng **Coal Mining** Area, China	shallow pore water (SPW)	7.24		936.13	99.30	2.80	298.13	46.71	611.40	107.60		0.50		347.67	Zhang *et al*., 2023 [47]
	deep karst water (DKW)	7.81		452.24		1.25	110.17	26.61	122.74	33.33	16.86	0.27		262.24	
Jampali **Coal Mining** Chhattisgarh, India	Groundwater	7.43	317	160.04	17.83	13.38	14.07	8.68	11.17	7.86	24.14	0.61		31.16	Ahmed *et al*., 2022 [33]
Handan **Coal Mining**, China	Groundwater	7.55	1252	626	84.7	1.94	142	37.4	254	28	107			301	Hussain *et al*., 2019 [45]
	Surface water	7.27	2010	1005	136	15.85	192	95.2	637	18.1	143			323	
Xishan **coalfield,** Taiyuan, China	Groundwater			1253.33	92.79	3.05	205.93	63.33	504.01	42.94	100.20	0.51	1.57	343.02	Chen *et al*., 2023 [43]
	Surface water			790.80	83.05	3.29	86.29	31.11	216.83	7.11	80.10	0.62	9.89	236.21	
Shendong **Coal Mine**, China	Mixed (Surface, ground, coal seam roof water, inlet & outlet of underground reservoirs	7.90		1023.57	354.11	4.36	54.56	12.92	234.36	0.64	140.82	2.29		508.82	Guo *et al*., 2023 [41]
Nsuta **Manganese Mine**, Ghana	Groundwater	6.63	38.8	34.2	13.4	0.69	52.1	8.74	23.3	0.98	12.2	0.11		14.9	Ewusi *et al*., 2022 [40]
	Surface water	6.80	21.8	19.2	6.06	2.62	17.4	10.35	41.8	3.65	7.01	0.10		15.8	
	Pit water	7.54	84.2	74.1	8.00	3.73	96.6	42.9	324	25.3	3.86	0.10		23.1	

Table 5. Summary of various heavy metals in the groundwater of mining areas

Location and country	Source	Heavy metals													References
		As	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**	**Se**	**Sb**	**Mn**	**Al**	**Fe**	
Shendong Coal Mine, China	Drinking water(mg/L)	5.69×10^{-3}	1.36×10^{-4}	4.39×10^{-4}	-	2.61×10^{-5}	-	2.02×10^{-3}	-						Guo *et al*., 2023 [41]
Coal mining, **Yulin**, China	Drinking water (mg/L)	-	0.10	2.25	0.77	-	0.45	0.06	8.35						Zhou *et al*., 2020 [74]
Basundhara Coal Mining, Odisha, India	Groundwater (µg/L)	-	0.6	1.1	4.1	-	8.6	2.4	425			90	391	1618	Samal *et al*., 2024 [75]
Neyveli coal mine region Tamil Nadu, India	Groundwater (mg/L)	-	-	0.004	0.007	-	0.009	0.359	0.061						Anjali *et al*., 2023 [23]
Korba Coalfield, Chhattisgarh, India	Groundwater (µg/L)	-	0.107	0.936	3.973	-	10.046	0.908	401.761						Dheeraj *et al*., 2024 [2]
Handan Coal Mining, China	Groundwater (µg/L)	1.47	0.011	2.59	0.33	0.024	3.21	0.022	26.3						Hussain *et al*., 2019 [45]
	Surface Water (µg/L)	0.005	0.029	2.49	1.39	0.023	5.2	0.079	13.71						
Nsuta Manganese Mine, Ghana	Groundwater (mg/L)	0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.62	0.05	0.98	Ewusi *et al*., 2022 [40]
	Surface water (mg/L)	0.005	0.0001	0.001	0.001	0.0001	0.003	0.0011	0.016	0.01	0.0004	1.53	0.15	2.05	
	Pit water (mg/L)	0.38	0.0004	0.00	0.002	0.0001	0.22	0.0006	0.01	0.01	0.10	1.74	0.08	0.10	

5. Human health effects associated with Mining

Many researchers have explored the health impacts associated with mining activities; some have identified the sources of groundwater contamination, and additional inputs from anthropogenic activities have also been stated. Research on mining areas in Joghatai, Iran, by Shams *et al.*has investigated heavy metal pollution like chromium, arsenic, and cadmium in drinking water near mining zones of Sabzevar, Iran. It is evident that the presence of these metals has exceeded the WHO guidelines; the Cancer risk values for both adults and children were above the USEPA limits, particularly with arsenic pollution posing a carcinogenic risk. His findings suggest that improper management in mining has led to environmental degradation and risk to human health [58].

Environmental contamination due to mining can affect other economic activities like agriculture and the fishery sectors, as it may transfer the pollution load to the surrounding environment, impacting the soil, air, and water bodies. Mining near the settlement area of the population, basically the marginalised people, is usually affected by such activities. Such people are unaware that mining greatly impacts those residing near the mining zone due to a lack of awareness and knowledge [59]. Mining processes usually lack appropriate strategies for managing the environmental impacts on air, water, soil, biodiversity and forest structure. Hazardous wastes generated during mining are released into the environment, degrading the overall environment nearby and affecting soil, air, and water (Figure1). It can pose various health issues for the public working in the mines and people living near colliery regions. Quality of life and physical, mental, and social well-being of local communities can be severely impacted by the sudden onset of adverse effects from mining operations. Establishing makeshift mining towns and camps can compromise food security and safety. Furthermore, mining activities can have indirect consequences on public health, leading to a higher incidence of diseases such as tuberculosis, asthma, chronic bronchitis, and gastrointestinal disorders [59].

Table 6. Heavy metals and their effect on human health

Heavy Metals	Acute	Chronic	Reference
Arsenic	nausea, vomiting, colicky abdominal pain, profuse watery diarrhoea, and excessive salivation. skin rash, toxic cardiomyopathy, and seizures Haematological abnormalities renal failure, respiratory failure, and pulmonary oedema	Arsenicosis, melanosis, keratosis, and Leucomelanosis, skin, lung, kidney and bladder cancer, coronary heart disease, bronchiectasis. hyperkeratosis, Arsenicosis, hyperpigmentation of the palm and sole, hypertension, myocardial damage, liver damage, Bowen's disease and diabetes	Saha et al., 2019 [60] Ratnaike, 2003 [61]
Mercury	skin rashes, and eye irritation, increases in blood pressure or heart rate	Minamata disease, permanently damages the brain, kidneys, and developing foetuses, lung damage	Martin et al., 2009 [62] Zafar et al., 2024 [63] Parida et al., 2023 [64]
Chromium	skin allergies, swelling, redness in the skin, and problems related to the respiratory, gastrointestinal systems	Itai Itai, ulcers, Anaemia, damage to the male reproductive system, cardiovascular, haematological, hepatic, renal and neurological effects	Li Chen et al., 2009 [65] Reif, 2024 [66] Nishijo et al., 2017 [67]
Cadmium	Bronchitis, chemical pneumonitis, pulmonary edema, and gastrointestinal symptoms	Tubular cell necrosis, renal failure characterized by proteinuria, anaemia, impairs lung function, osteoporosis, and bone fractures	WHO 2010 [68] Orlowski et al., 2003 [69] HPA, 2010 [70]
Lead	Hemolytic anemia, hypertension, cardiovascular disease, Fanconi's syndrome	Encephalopathy, Hemolytic anaemia, hypertension, and cardiovascular disease Reproductive issues, Kidney damage, cardiovascular risks, neurological effects	Gidlow, 2015 [71] Sankhla et al., 2016 [72] Raj et al.,2023 [73]

6. Modern tools for Groundwater quality management in mining areas

Mining activities, which involve coal, metals, rare earth metals, and uranium, can cause serious threats to groundwater quality. The groundwater pollution increases due to acid mine drainage (AMD), leaching of heavy metals, and mobilisation of radioactive nuclides. To combat the issues with mining activities in managing groundwater, various emerging techniques involve in-situ treatment techniques like phytoremediation, bioremediation, adsorption, passive treatment systems, pump and treat system and application of biochar from wastes provide a clear and efficient remediation in managing the groundwater resources [87,89]. Traditional monitoring techniques can be resource-intensive, frequently reactive and time-consuming methods for evaluation of resources. On the other hand, artificial intelligence, machine learning techniques can provide real-time prediction, risk classification, and geospatial mapping by using non-linear and multi-dimensional datasets from satellite observations [90]. Some of the techniques like Artificial Neural Network (ANN) for predicting the groundwater quality, Random Forest (RF) for feature selection, classification of contaminated zones, Support Vector Machine (SVM) for quality classification (safe/Unsafe), K-means Clustering for identification of pollution hotspots, Genetic Algorithms (NSGA-II) for optimization of monitoring network, Fuzzy Inference System (FIS/MANFIS) for handling uncertainty in predictions and CHIO models can provide insights for optimization of water level forecasting, are some of the methods to manage the groundwater resources [91,93].

7. Summary

Many researchers have explored the field of hydrogeochemistry and water quality assessments to comprehend the changes in groundwater chemistry caused by mining activities. These analyses provide insights into the significant impacts of mining operations, the hydrogeochemical features of groundwater affected by mining, and the variations in water characteristics due to both natural processes and human activities. Mining activities commonly face challenges such as acid mine drainage, metal contamination, and sediment buildup from unstable materials. Different mining activities have been proven to influence varying levels of groundwater quality and its hydrogeochemistry. Heavy metals in the aquatic, terrestrial, and social environments pose significant concerns due to their toxicity and bioaccumulation potential in the ecosystem. Studies worldwide indicate that mining has influenced acidification, metal contamination and high concentrations of total dissolved solids. Mining regions in developed and developing nations are facing challenges in remediating these unwanted changes, but advancements in the hydrogeochemical characteristics studies, particularly with emphasis on the mining environment, could help in understanding the mechanism of mobilization of unwanted contamination, which would lead to improvement in mining practice for sustainable mining. Studies show groundwater contamination in the states of Jharkhand, Odisha, Chhattisgarh, and Meghalaya, which is the primary mining sector of coal, iron, bauxite, copper, etc., which also show alteration in groundwater quality, such as high levels of fluoride, nitrate, sulphate, and heavy metals are common in groundwater. In Jharkhand, states like Dhanbad, Hazaribagh, and Ramgarh are key coal-producing districts that fulfil the nation's requirement for electricity. The seasonal variation also affects the groundwater quality. Research findings have shown seasonal changes in higher concentration levels of unwanted substances. The problems with mining activities are heavy metals pollution, acid mine drainage, loss of groundwater recharge and decline in groundwater quality for drinking and agricultural purposes. The challenges include a lack of comprehensive hydrogeochemical data, the impact of seasonal variations, making it difficult to monitor, and poor enforcement of environmental regulations. Implementation of sustainable mining techniques, real-time groundwater monitoring system, lime neutralization to reduce sulphate from AMD treatment, rehabilitation, and afforestation could help restore the mining area and the groundwater. To overcome these challenges, advanced techniques and methods have been employed, such as expanding monitoring networks, utilising geochemical modelling, implementing risk assessment and management strategies, employing innovative sampling techniques, integrating data fusion and machine learning, promoting collaboration and capacity building, adapting to climate change, and raising public awareness and education. Encouraging collaboration between researchers, policymakers, and local communities is imperative to ensure sustainable groundwater management and responsible water use.

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بررسی ویژگی‌های هیدروژئوشیمیایی و ارزیابی کیفیت آب‌های زیرزمینی در مناطق معدنی

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چکیده

فعالیت‌های معدنی بر کیفیت آب‌های زیرزمینی تأثیر منفی می‌گذارند. سلامت انسان نیز متعاقباً به دلیل خطرات زیست‌محیطی و اکولوژیکی فراوان ناشی از تحرک آلاینده‌ها و تغییر فرآیندهای هیدروژئوشیمیایی تحت تأثیر قرار می‌گیرد. این بررسی، ویژگی‌های هیدروژئوشیمیایی و کیفیت آب‌های زیرزمینی در مناطق معدنی را با تأکید بر فرآیندهای حیاتی مانند برهمکنش سنگ-آب، تشکیل زهکشی اسیدی معدن و آلودگی فلزات سنگین ارزیابی می‌کند. این فرآیندها بر کاربردهای نهایی کیفیت آب‌های زیرزمینی مانند آشامیدن، آبیاری و مصارف صنعتی تأثیر می‌گذارند. برای درک علل آلودگی و در دسترس بودن و مناسب بودن آب، بررسی آب‌های زیرزمینی مانند ارزیابی پارامترهای فیزیکوشیمیایی و چهره‌های هیدروژئوشیمیایی مورد نیاز است. با استفاده از تکنیک‌های ایزوتوپی و ادغام تغییرات مکانی و زمانی با استفاده از سنجش از دور و کاربرد GIS، می‌توان بار آلودگی را بر منابع آب ارزیابی کرد. تجزیه و تحلیل کتابشناختی، پیشرفت تحقیقات فعلی در بخش معدن را با تمرکز بر مطالعات جهانی و منطقه‌ای و تأثیر آنها بر منابع آب برجسته می‌کند. آلودگی ناشی از فلزات سنگین مانند آرسنیک، کروم، کادمیوم و سایر عناصر سمی، بیماری‌های جدی را برای سلامت انسان و اکوسیستم اطراف ایجاد کرده است. این بررسی همچنین شکاف‌های تحقیقاتی و چشم‌اندازهای بهبود منابع آب زیرزمینی را از طریق استراتژی‌های کاهش مناسب مانند شیوه‌های پایدار معدن‌کاری و فناوری‌های تصفیه آب برجسته می‌کند.

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