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Arsenic concentration in the unique Rift Valley Lake-Beseka: Sources, impact, and suggested technological interventions: A systematic review

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ABSTRACT

Both natural and human activities have contributed to the depletion of water resources. As a result, large levels of contaminants like heavy metals and arsenic have been found in both surface and groundwater. This comprehensive study cautiously analyzed both public and unpublished sources to get detailed information on the sources, levels, impacts, and removal of arsenic in Lake Beseka. High levels of arsenic have been found in water sources in the Main Ethiopian Rift Valley, such as Lake Beseka (96.3 µg/L), boreholes (278 µg/L), and surface water (405 µg/L). After blending with the Awash River, downstream users are exposed to and are using the water for washing, irrigation, and livestock watering, and also sometimes people living downstream, particularly pastoralists, use it for drinking purposes directly without treating it. The findings also demonstrate that human activity, such as industrialization and the use of agrochemicals, as well as geogenic processes, such as rock weathering, volcanic ash, groundwater-surface water interactions, and maybe the presence of hot springs, are the cause of the increased levels of arsenic in Lake Beseka and in the Main Ethiopian Rift Valley. Due to its toxic nature, arsenic has detrimental effects on ecosystems and human well-being. If this problem is not resolved, it may have detrimental consequences for the local ecosystems as well as downstream implications for soils, water bodies, and human health. The main aim of this systematic review was to investigate the sources, extent, and impact of arsenic (As) in Lake Beseka, a unique lake in the Rift Valley, and effective technologies to remove arsenic from drinking water, such as ion exchange, coagulation/flocculation, and membrane technologies like ultrafiltration and electrodialysis, helping to deal with the adverse effects caused by arsenic exposure. Electrocoagulation, adsorption, and phytoremediation are the most efficient and cost-effective technologies. In fact, recent research has predominantly focused on arsenic removal technologies from aqueous solutions (groundwater, surface water, and wastewater) through coagulation-flocculation-microfiltration, adsorption, and phyto remediation in individual ways or in combined forms with phytoremediation and constructive wetlands. Notably, the paper also reviews how locally available adsorbents have become a promising material for arsenic removal from water bodies.

1. Introduction

Water pollution has been progressively rising as a result of pollutants that have been drained into water resources. The water quality degradation problem is particularly high in sub-Saharan Africa, particularly in East Africa, due to urbanization and industrialization (Salomons et al.,

1995; Masindi and Muedi, 2018; Musilova et al., 2016; Goerner and Gloaguen, 2009). Heavy metals (HMs) and meatloids sourced from human activities and geogenic sources can harm aquatic ecosystems (Hameed et al., 2020). Arsenic is the first known toxic element to have been investigated in different countries (Sevak and Pushkar, 2024). Globally, significant level of arsenic are introduced into environment

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from anthropogenic sources including metal mining and smelting, coal mining and burning, agricultural runoff, industrial wastes (Jin et al., 2023; Moore and Woessner, 2003; Oyarzun et al., 2004; Filippi et al., 2004; Bech et al., 1997; Patinha et al., 2004; Modabberi and Moore, 2004). Arsenic (As) occurs naturally in more than 200 mineral forms, of which approximately 60 % are arsenates, 20 % sulfides and sulfosalts, with the remaining 20 % comprising arsenides, arsenites, oxides, silicates, and elemental arsenic (Norton et al., 2009). The WHO provisional guideline value for As in drinking water is $10\,\mu\text{g/L}$ (Rajeswari, 2015).

Approximately 60% of groundwater sources worldwide are poisoned at levels higher than those advised (Mukherjee et al., 2024). For example, countries like Bangladesh, Nepal, India, and Pakistan suffer greatly from pollution (Aryan et al., 2024). In addition to these countries, certain other countries, such as Mexico, the US, Saudi Arabia, and China, also had levels over the WHO limit of As (Dilpazeer et al., 2023). Consequently, it also impacts and jeopardizes the health of millions of individuals in the countries stated above. Because of the severity of the issues, nations like India (West Bengal, Bihar, Uttar Pradesh) have identified their areas as arsenic-prone zones (Kundu and Naskar, 2021). For instance, in China, the population affected by high-As groundwater contamination was estimated to be about 19.6 million (Rodríguez-Lado et al., 2013). Thus, between 300 and 500 million people are thought to be at risk for serious As health problems and premature mortality (Mukherjee et al., 2024).

As illustrated in Fig. 1, approximately 108 nations were impacted by groundwater As contamination, and reports of extremely high levels of As have been made in many parts of the world (Shaji et al., 2021). In addition to Fig. 1, the global scenario of arsenic contamination showed that very high levels of arsenic were found in several nations, surpassing either the WHO guideline of 10 µg/L or certain countries' limits of 50 µg/L. For example, approximately 14,969 µg/L was found in Argentina's Santiago del Estero province due to volcanic ash (Bhattacharya et al., 2006); 4730 µg/L of As was found in Bangladesh's Noakhali surface water, which may have been eroded by the flood plain river (Chakraborti et al., 2010); 2330 µg/L was found in China's Jianghan Basin because of 850 µg/L in Vietnam's Mekong Delta surface water (Wang et al., 2021). Similar findings were found in Africa: 2100 µg/L in Egypt from sources based on arsenic-sulphide (Murcott, 2012); 1760 µg/L in South Africa's groundwater and 119 µg/L in its surface water (Poshiwa, 2024); 2000 µg/L in Ghana's southwest due to gold-arsenic mineralization (Murcott, 2012); 188 µg/L in Botswana from geogenic sources (Poshiwa, 2024); and 96 µg/L in Eastern Zimbabwe.

In Sub-saharan Africa, high levels of As and associated

contamination were observed in the Okavango Delta and Rift Valley in Botswana and Ethiopia, respectively (Reimann et al., 2003; Huntsman-Mapila et al., 2006; Rango et al., 2010, 2013; Dsikowitzky et al., 2013; Yirga et al., 2019). In the Rift Valley countries like Ethiopia, Kenya, Tanzania, and Botswana, the concentration of As was found to range from 2.39 to 566 μ g/L (Rango et al., 2013), 3.26 to 22.7 μ g/L (Yang et al., 2017), less than 1-82 µg/L (Nyanza et al., 2014), and less than 1–188 µg/L (Mladenov et al., 2014), respectively. Similar to this, significant levels of As above WHO guidelines were found in both the surface water (Rango et al., 2013; Nyanza et al., 2014) and groundwater (Rango et al., 2010; Nwankwo et al., 2020; Abiye and Bhattacharya, 2019) in Eastern Africa, but also in Botswana, Tanzania, Ethiopia, and South Africa. The groundwater samples from Ethiopia, Tanzania, Botswana, and South Africa also showed elevated concentrations of As, ranging from 21.4 to 278 $\mu g/L$ (Filippi et al., 2004), 0.5 to 123 $\mu g/L$ (Nwankwo et al., 2020), 87 to 185 µg/L (Mladenov et al., 2014), and 20 to 253 µg/L (Abiye and Bhattacharya, 2019), respectively. Elevated levels of As exceeds the WHO limit (10 µg/L) were observed in both surface water and groundwater samples from Ethiopia, Togo, Zimbabwe, and Tanzania (Rango et al., 2010; Abebe et al., 2024; Irunde et al., 2022; Ouédraogo and Amyot, 2013; Serfor-Armah et al., 2006; Rezaie-Boroon et al., 2011). Arsenic has been found in low concentrations in some parts of Tanzania and Burkinafaso (Dilpazeer et al., 2023; Dsikowitzky et al., 2013). In fact, the extent of arsenic pollution varies spatially and temporally due to factors like geology and human activities (Demissie et al., 2024). For instance, in Africa, even within the same continent, there are significant regional variations in the content of arsenic.

In actuality, the salinity, depth, and size of saline lakes naturally vary with the seasons (Melese and Debella, 2024). However, Lake Beseka showed a significant change in salinity, while it was one of the Rift Valley lakes in Ethiopia and was severely saline (74,000 $\mu S/cm$). The lake has shown extreme dynamics, both in water quality and quantity, over the past six decades. The lake volume change is sometimes abrupt (in 1978 and 2007) and mostly gradual (WWDSE, 2011; Belete et al., 2015a). Disasters surrounding the lake catchment, such as the loss of human life, irrigable and grazing areas, people displacement, shifting of the railroad and asphalt road and the destruction of residential and institutional structures (submerged), occurred as a result of the lake's expansion or volume change. The Awash River has experienced uncontrolled expansion and releases of Beseka's water that have impacted the water quality of the receiving river, downstream hydrochemistry, soil chemistry (sodicity and salinity effects), aquatic ecosystems

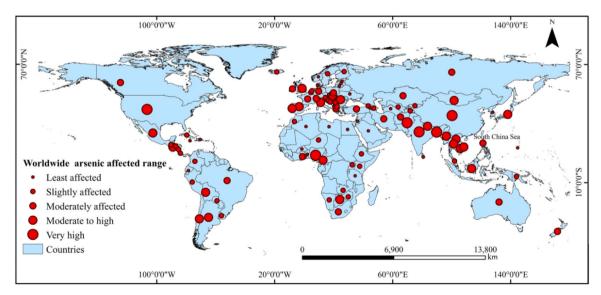


Fig. 1. Countries affected with arsenic (Reprinted following Shaji et al., 2021 under an open access, creative commons license).

(Ayenew and Legesse, 2007), the severity of flooding issues (Alemayehu et al., 2006; Dinka, 2017), groundwater flooding, and saline intrusion (Melkamu et al., 2022). If it is not controlled and properly managed, it will also affect and continue to affect Methara Town, the area of sugar plantations (Ayenew and Legesse, 2007; Awulachew, 2020), and fertile lands both near and downstream of Lake Beseka, particularly the Amibera cotton and sugar plantations.

Likewise, the geochemistry and associated environmental and health risks of As, and their associated toxicity have not yet been studied or are not perceived in the study area (Ethiopian Rift Valley). Therefore, exposure to As has been recognized as a major public health concern over the past three decades. Nonetheless, long-term exposure to As, either in drinking water or food, harms human health and can cause cancer (Zemedagegnehu et al., 1999). It's a growing problem and is becoming the number one threat. Thus, the purpose of this review effort was to examine the likelihood of the issue, the degree to which it exists, and the origin of the As and Mo concentrations in the Lake Beseka by evaluating both published and unpublished works. Since the 1960s, there has been a change in the lake's surface area, which was continuous expansion (Belay et al., 2019), which had a negative impact on the surrounding area. But some measures have been put in place to address the issue, particularly the impact of the rising lake level. However, the LULC (Melese and Debella, 2023) and the impact of water quality, particularly the concentration of heavy metals, need to be focused on. In fact, there is a change in the physicochemical parameters of the lake water (Bramer et al., 2018; Abebe et al., 2023a), and it is also not expanding at the rate of its history (Melkamu et al., 2022).

This systematic review examines the water quality of Lake Beseka, focusing on the changes in water quality and quantity, sources of pollution, and the lake's expansion. Key questions addressed include the sources of heavy metals and arsenic, their impact on water quality, and recommendable solutions for remediation. The review utilizes search phrases related to water quality sources and arsenic extent and impact. It employs PRISMA methods (Kapaj et al., 2006; Özerol et al., 2018; Moher et al., 2009) to gather relevant data and aims to summarize Lake Beseka's condition, along with recent advancements in cost-effective removal techniques for heavy metals and arsenic. Among the techniques discussed are the uses of locally available materials, such as termite mounds and clay-based adsorption, as well as phytoremediation strategies.

In this systematic review, the PRISMA checklist guided the selection criteria to evaluate existing research on arsenic and technological interventions. Databases such as Google Scholar, Scopus, PubMed, and Web of Science were utilized to identify and categorize relevant literature, capturing both quantitative and qualitative characteristics. This comprehensive approach aimed to highlight the main current issues in the field. The main sources of heavy metals and arsenic in the area of focus are also well discussed, with a focus on arsenic pollution in surface water and the human health problems associated with arsenic toxicity and accumulation. Not only these, but also the important issues surrounding arsenic pollution and its effects are also reviewed, along with the necessary remedies for lowering the amount of As in water bodies including rivers, lakes, and boreholes.

The study specifically addresses the issue of arsenic removal from Lake Beseka, highlighting its environmental and health impacts. It reviews current remediation methods, emphasizing the emerging technologies like clay-based adsorption and advanced oxidation processes (AOPs). The research notes that conventional treatment methods fall short of reducing arsenic levels to the WHO-recommended standard of $10~\mu g/L$. It also suggests that combining adsorption with phytoremediation, AOPs, and conventional techniques may enhance the effectiveness of arsenic remediation, improving water security for multiple uses in developing nations such as Ethiopia. In general, this comprehensive article aims to give a detailed understanding of the effects arsenic has on the environment and provide suggestions for practical ways to control its presence in surface water (Lake Beseka) and

other crucial areas (Rift Valley boreholes). This assessment seeks to support international efforts to lessen the negative effects of arsenic contamination on public health and ensure that impacted populations have access to clean surface water or lake water by addressing the complex issues it presents.

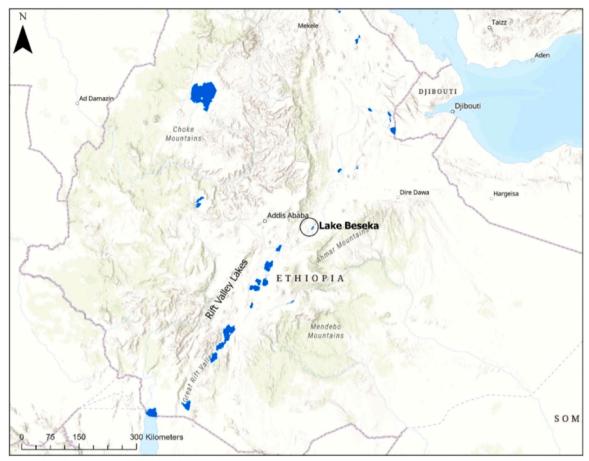
2. Methods

2.1. Study area

This study is primarily focused on Rift Valley lakes in the middle valley of the Awash sub-basin, called Lake Beseka (Fig. 2). In the study, the term Rift valley stands for the middle part of the Awash basin (Awash-Awash sub-basin) and some parts of the Zeway Shalla sub-basin. The lake is bordered by Abadir Farm in the south, Metehara Town and Metehara Farm in the east, and Fentalie Mountain in the north. Ethiopia's rift lake is located in Ethiopia's main rift valley, and Lake Beseka has a unique character. Lake Beseka is an endoreic lake located at the northern extreme of the Main Ethiopian Rift (MER) just south of the Fentale volcano, with a semi-arid climate and an elevation of 953 m a.s.l (Melkamu et al., 2022; Megerssa, 2017b; Dinka, 2020). The nature of the catchment is characterized by diverse relief displacements, including undulating plateaus, narrow valleys, and flat plains (Melese and Debella, 2023). The lake was a naturally closed lake from 1957 to 2009 that has been dammed by volcanic activity. However, currently, it is an open basin-type lake. Because channels created by AwBA, MoWE, OWWDSE, and EWWDSE have made it an open lake since 2010, The lake's watershed covers 505 km², of which 10 % of Beseka's water shade is occupied by Lake Beseka.

2.2. Search strategy

The bibliographic study of research trends on Lake Beseka, the total number of documents collected, and the temporal evolution of annual scientific production in Google Scholar sources are all visually illustrated, as can be seen in Fig. 3. Actually, there were two distinct periods identified. The first one spans the years 1961-1990. Before 1990, there had only been four publications in the first thirty years (1961-1990) (a PhD dissertation research), totaling only one paper. With a linear growth in annual production from 25-130 to 311-244 articles, the second phase ran from 1991 to 2025. The results showed that there were 714 papers on changes in abundance, expansion, causes of expansion, consequences, and societal issues. In fact, of the reviewed 1192 articles, approximately 71 papers were directly chosen for further examination. An additional 4076 additional records were searched; of these, 150 papers related to the mitigation and impacts of arsenic on global trends were reviewed and selected. In general, of the total of 5268 searched records from the database, the study conducted a systematic review on Lake Beseka and heavy metals using the PRISMA checklist. After removing or screening duplicate records, less significant papers, conference papers, and non-English articles, a total of 221 published articles on volcanic ash, weathering rocks, and removal technologies were selected for review (Fig. 3). This systematic review of databases, including Google Scholar, Web of Science, Scopus, and Science Direct, was used. In addition, relevant unpublished works were extensively utilized. Therefore, in order to obtain trustworthy information, we extracted a total of two hundred twenty-one articles on the following topics: (1) Lake Beseka's expansion and its sources of volume change; (2) Lake Beseka's physicochemical and heavy metal water quality change; (3) The effects of volcano eruptions on Lake Beseka's concentration of heavy metals, including arsenic. (4) Impacts on human health and the environment; and (5) Further implications (remediation and technologies) and similar topics.



Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community, Esri, USGS

Fig. 2. Study area (The main Ethiopian Rift and Lake Beseka).

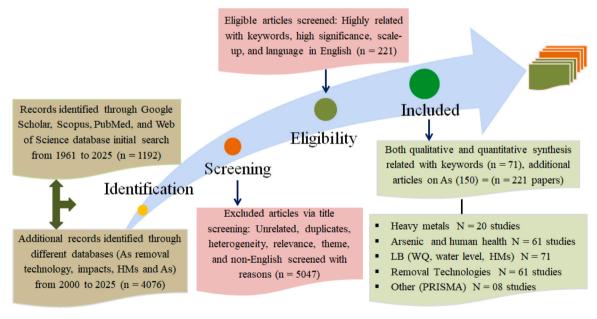


Fig. 3. Schematic representation of flowchart of study selection or inclusion process (PRISMA flow diagram/steps).

3. Results and discussion

3.1. Geological processes and lake chemistry

The Ethiopian Rift Valley (MER) is part of the East African Rift system, or the uppermost part of MER (Dinka, 2017), the largest active continental rift valley on Earth (Davies, 2008). The MER is part of the East African Rift Valley system, and is characterized by extensive volcanic and tectonic activities that have led to formation of volcanic rocks and their weathered products, partially remobilized and redeposited as fluvio-lacustrine sediments (WoldeGabriel et al., 1990; Peccerillo et al., 2007). Several studies indicate that there is an ongoing geological process in the basin. In an inert geological process, fissures change from time to time, allowing groundwater and surface water interactions within the basin core, in addition to the exchange of subsurface materials (Furi, 2011). The Young Ignimbrites and various volcanic domes are tectonic products of young volcanoes found on the rift floor of the Awash Basin (Aregu, 2018; Williams et al., 2004). The sources of As in the environment might be due to the occurrence of young volcanic rocks such as ignimbrite, pumice, rhyolite, trachybasalt, and fragmentation of basalt (Reimann et al., 2003; Melese and Debella, 2023). The origins of Mo in the Ethiopian Rift Valley, especially in Lake Beseka, have been linked to the presence of rhyolitic ash within the loess silt-sand deposits and its maintenance in soluble form by the oxic (presence of oxygen) and alkaline conditions (Smedley and Kinniburgh, 2017). The hydrological cycle is regulated by tectonic activity that could influence the drainage systems at various temporal/spatial scales modifying the basin input/output, and also by volcanism and associated geothermal processes that provide significant geochemical fluxes (Goerner and Gloaguen, 2009). The lake's expansion and unregulated discharge are causing a decline in the water quality of the River Awash and potentially causing salinity issues downstream of the Lake. The chemistry of Besekas water might be affected by geochemical processes. For instance, dissolved particles have been drained or washed into Lake Beseka as a result of volcanotectonic activity and the weathering of volcanic rocks. This hydrochemical and geochemical process has an impact on the lake's quality, especially on the amount of heavy metals (Belete et al., 2015b).

3.2. The source of lake expansion

There are three ways that lakes and groundwater interact; some get influxes across the bed. It takes a hydro-geo-ecological framework to comprehend these interactions (Belay et al., 2019). However, studies on Lake Beseka, suggest several explanations were rose for rising lake levels (Megerssa, 2017b; Gichamo et al., 2022), including Abadir and Nura Hera farms, Matahara Sugar Estate, Fentalie Irrigation, hot springs, and ground-surface interactions. In fact, quite a lot of studies have paid attention to the source of lake expansion and volume rise, as well as lake physicochemical characteristics and salinity. The level, extent, and sources of As in lake water have been investigated (Rango et al., 2010; Abebe et al., 2023a, 2023b). Ethiopia's rift lake, Lake Beseka, with unique characteristics, has been investigated using hydrological, geochemical, isotopic, and geophysical methods. Piezometric and geophysical survey results suggest increased inflow from submerged springs (Belay et al., 2019; Workie et al., 2024). Consequently, it has been expanding due to a rise in the net groundwater flux into the lake, and over half of the overall inflow into Lake Beseka comes from groundwater (Alemayehu et al., 2006; Dinka, 2017, 2010; Ayenew, 2004; Dinka et al., 2014; Belay, 2009; OWWDSE, 2014).

The assumptions regarding lake level rise tend to combine natural activities, including open fissures and fractures that allowed hot springs to emerge on the lake's southwest side (Davies, 2008), with anthropogenic influence, like the northeastern groundwater rise from excessive irrigation recharge creating a hydraulic barrier that crosses the direction of groundwater outflow (Alemayehu et al., 2006). For instance, the Metehara Sugar Estate's north farm and the Abadir farms recorded the

largest groundwater level rises, 6.03 m and 4.0 m, between November 1998 and November 2010, respectively (Alemayehu et al., 2006; Ayenew, 2004). Unexpectedly, a groundwater level change was noticed in the lake catchment; this could be related to both irrigation practices. The presence of fissures, basaltic rocks, faults, and non-porous natures, as well as the climatic variables and anthropogenic activities, volcano-tectonic forcing's control the dynamic of Lake Beseka's lake level and size and potentially increase the depth and volume of the lake.

Over the past 60 years, a large number of new earthquake-induced crack swarms have occurred (Kebede and Zewdu, 2019). This process increases the hydraulic conductivity of the aquifer, suggesting that groundwater is stored in abundantly buried and uncovered bubble caves in the region. The δ^{18} O, δ^{2} H, and δ^{222} Rn isotopes are established tools for tracing the movement of water around lakes and detecting the specific site of groundwater discharge to open water bodies in quantifying the groundwater inflow to lakes without the need to revert to detailed hydrological measurements of groundwater flow into lakes (Aregu, 2018; Yi et al., 2008; Cook et al., 2008; Kebede et al., 2010a). The extraction of water from shallow aquifers directly connected to the southwestern waters could have a significant impact on water movements between these two bodies of water (Bramer et al., 2018). Perhaps, a climatic, non-climatic, and meteorological process has also influenced the present lake rise and expansion in addition to the tectonic effects, which are the major causes (Alemayehu et al., 2006). Research also indicates that the lake level experienced a sudden increase at two specific time periods: the first being from 1976 to 1980 and the second from 2008 to 2009 (Alemayehu et al., 2006; OWWDSE, 2014; Gebremichael et al., 2022).

However, during the periods from 1980 to 2008 and from 2009 to 2013, the rise in lake level was gradual, although with varying rates of increase. Lake water level rise and expansion are partly man-made and partly natural, with groundwater-surface water interaction expected (Megerssa, 2017b). Surface water is hydraulically connected to groundwater, but interactions are difficult to observe and measure. However, these interactions can have significant implications for both water quantity and quality management. The water isotope analysis was applied to determine the flow, velocity, age, and origin of the lake water in the aquifer systems of Lake Beseka and its surroundings (Kebede et al., 2010a). The water chemistry of the lake is extremely complicated because of the intricate relationship between Lake Beseka and the water sources, as well as their interactions with surfacewater-groundwater. This may be due to the basin sedimentary characteristics of the catchment, where water transfer between groundwater and surface water provides an important pathway for chemical transfer between terrestrial and aquatic systems (Lamontagne et al., 2005; Kalbus et al., 2006; Schmidt and Schubert, 2007; Haile and Shishaye, 2018).

Depending on the amount and direction of flow, the concentrations of dissolved substances, and the biotic activity, the river-groundwater interface can either operate as a source for dissolved substances including heavy metals and As. Surface undercurrents are a characteristic of the majority of rivers. It is mostly regulated by groundwater discharge and denotes the bare minimum of water flow within a single river system. Indeed, considering the interdependence of the Awash River, Lake Beseka, springs, and groundwater (borehole) ecosystems as interconnected parts of a hydrological continuum for the transport of heavy metals and arsenic. As previously mentioned, the Lake Beseka was in the Fentalie active rift system, and its water quality and lake water quality were dominated by Na⁺ and HCO₃-ions with varying salinities (Yimer and Geberekidan, 2020; Yimer and Jin, 2020). The high salinity of the lake might be due to groundwater recharge and geology, while other stations have high concentrations of dissolved solids due to anthropogenic sources derived from industrial and domestic waste and agricultural runoff.

Accordingly, the water chemistry of the lake, how continuous the water quality of HM concentrations is, and the impact of groundwater in contributing to the rise in the level of HMs such as As, Mo, Hg, V, and the like in the surface water of Awash after the discharge of the lake water.

Most of the water sources that were analyzed in Zeway Shall sub-basin (Main Ethiopian Rift Valley) were dangerous to human health and were not suitable for human consumption in the area under study (Demissie et al., 2024). Fortunately, the lake's physicochemical characteristics have been getting better (Abebe et al., 2025). The water is more or less safe for a variety of uses just downstream of Lake Beseka, and the concentration values of TDS, EC, Na, K, sulphate, bicarbonates, and alkalinity, as well as pH, will be below the maximum threshold year-round in the upcoming year (assuming heavy rains appear) or two years. However, some users (humans, animals, and fish) and uses, such as drinking water and livestock watering, hook the observed dangerous heavy metals and arsenic levels above the limits undesirable. These users are not tolerant of excessive arsenic and heavy metals. Likewise, the river water is dangerous due to the high levels of heavy metals and arsenic found in the specified river reach.

3.3. Sources of arsenic in Lake Beseka

3.3.1. Anthropogenic sources of arsenic

Pollution from urban, rural, mining, agricultural, and natural processes can transport suspended and dissolved materials, as well as heavy metals, into water bodies. The use of chemicals continues to grow basinwide, particularly in Awash River Basin (Abebe et al., 2022). This is likely to result in greater negative effect on health if sound chemicals management is not ensured (Garelick et al., 2008). In addition to these, high rates of erosion, magmatism and associated hydrothermal activity, and active plate tectonics are all highly correlated with arsenic distribution (Masuda, 2018). Various studies clearly show that major tributaries including Atibela, Little and Big Akaki, and Mojo rivers flow through the cities Addis Ababa, and Mojo (Workie et al., 2024; OWWDSE, 2014). These major tributaries receive and also carry pollutants from the aforementioned urban towns. These potential sources of HMs are untreated and might be from urban waste, industrial wastewater and agricultural runoff (agrochemicals, including fertilizers and pesticides) reached in the surface water of the basin, including the Awash River and drained into Lake Beseka in the form of Abadir, Nura-Era, and Fentalie drainages. Arguably, the potential source of As in Lake Beseka might be geogenic.

The lake is to some extent impacted by human activities (Ayenew, 2004). In fact, water-soluble arsenic species existing in natural water are inorganic As (iAs) and organic As (oAs) species. Arsenic species exhibit

different toxicity (Issa et al., 2011). The investigation of As species and their behavior in various samples, especially in natural waters and the environment, is important for chemistry and environmental protection (Rajakovic and Rajakovic-Ognjanovic, 2018). From the value of the chemical equilibrium constants for each molecular or ionic form of As in water, the present species can be recognized (Rajaković et al., 2013). High As concentrations have recently been documented in the Middle Awash close to large-scale agroindustry and Methara Sugar Cane fields, both in surface water (Lake Beseka) and groundwater (boreholes) (Abebe et al., 2024, 2023a, 2023b). Similar investigations have presumably been conducted in the northern Egyptian delta lake close to agricultural locations and have been linked to industrial wastewater flows and pesticides containing As (El-Badry and Khalifa, 2017). Despite this, the significant concentration of As was linked to the lithology and geology in addition to agricultural runoff (Rango et al., 2013). Different studies also revealed that as might enter in to water bodies from discharge and use of certain substances including paints, cosmotic, sopas and detergents, dyes, drugs, electronic materials, agrochemicals and metals (Rao et al., 2024; Nduka et al., 2016; Higgins et al., 2022; Saadatzadeh et al., 2019) (Fig. 4).

3.3.2. Geogenic sources of arsenic

Meanwhile, the lake potentially polluted by geogenic activity including volcanic ash and the weathering effects of sedimentary rocks (Ayenew, 2004; Rajaković et al., 2013; Abduro, 2017). Arsenic may be transported into surface water by hot springs that are submerged in Lake Beseka and surround the lake catchment (Masuda, 2018). The presence of As in the lake may be caused by magmatic activity, particularly that of volcanoes, as evidenced by volcanic ash. Due to the complexity of the surface water and groundwater (aquifer) systems in the Lake Beseka catchment, the water-rock interactions and hydro-geochemical evolution may really be highly complicated to assess the possible sources. Studies also indicate that about 60 % of As come from natural activities (Abduro, 2017).

Studies conducted in the Southern Poopó Basin, Bolivian Altiplano shallow hydrological system, revealed that the groundwater in the Lake Beseka area had somewhat similar water types and hydrochemistry, primarily of the Na–Cl–HCO $_3$ type with a slightly alkaline pH and oxidizing character (Munoz et al., 2013). Additionally, there may be comparable paths for arsenic in both regions' shallow groundwater and surface water systems. The study area may be distinguished by its high

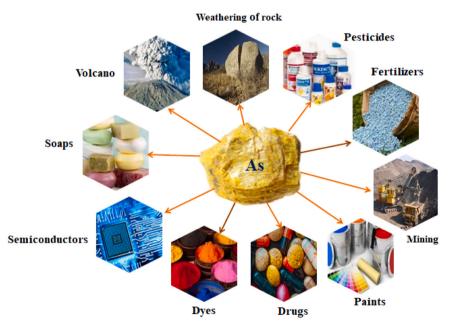


Fig. 4. Sources of arsenic drained into water bodies.

agroindustry, semi-arid environment, primarily volcanic geogenic formation, and high rift features in the MER valley. Heavy metal concentrations, such as fluoride and arsenic, may be carried from fundamental rock minerals to aquifer sediment (Hug et al., 2020), and the interplay between water resources' high As, F, bicarbonate, salinity, and pH were recorded (Rango et al., 2010; Abebe et al., 2023a, 2025; Belete et al., 2015b; Yimer and Geberekidan, 2020; Yimer and Jin, 2020). Rift floor groundwaters typically have high mineral contents (high F, U, As, and salinity). The MER's waters exhibit a broad spectrum of geochemical diversity, including bicarbonates, chlorides, and sulphate (Kebede et al., 2010a; Bianchini et al., 2020; Gizaw, 1996; Alemayehu, 2000a; Shishaye and Asfaw, 2020). Elevated levels of As, U, V, Mo, Mn, and other heavy and physicochemical elements, were noted. The waters of the MER show a wide range of geochemical variations (Alemayehu, 2000b), including alkali metals. The area is enriched with volcanic ash and active volcanos. Volcanic ash is dispersed over great distances during a volcano eruption. Tiny fragments of magma that have solidified following volcanic explosions make up volcanic ash (Table 1). Depending on the structure of the ash particles, pollutants from volcanic eruptions permeate into the water at varying rates.

High volcanic activity and volcanic ash may be the cause of the heavy metal and arsenic concentrations in Lake Beseka (Eisenstadt, 2019). In the southwest region of the Awash River Basin, particularly in the middle Main Ethiopian Rift Valley (MER Valley), common rhyolite weathering and dissolving processes may grow as concentrations (Reimann et al., 2003; Rango et al., 2013; Alemayehu et al., 2006). Rhyolite weathering can lead to the production of fulvio-lacustrine deposits, high pH (8.5–10.4), free fluorides, and weathering particles such as arsenic due to the dissolution processes of volcanic glasses containing these elements (Bianchini et al., 2020). Accordingly, the central part of the MER region showed high values of As, U, V, Mo, B, and F (Tekle-Haimanot et al., 2006). The presences of this oxyvalent material in the same area and their positive association or linear nature suggest that they may be due to the same geological source and aquifer (Smedley and Kinniburgh, 2017; Bianchini et al., 2020).

3.4. Arsenic chemistry (mobility and speciation) in water bodies

Particulate or dissolved arsenic are the most prevalent types found in natural waterways (Patel et al., 2023). For example, the most common forms of arsenic in natural waters are arsenite (As(III)) and arsenate (As (V)) (Patel et al., 2023). Research indicates that trivalent arsenite and inorganic pentavalent arsenate are produced by the interaction of arsenic and oxygen, primarily in groundwaters. Arsenic can be mobilized in both oxidizing and reducing conditions, as well as at pH values that are typically seen in surface and groundwaters (pH 6.5–8.5) (Baeyens et al., 2007). As the salinity and alkalinity of natural waters increase, so do the solubility and environmental mobility of As (Patel et al., 2023). Removal of arsenic from water bodies is not an easy task; it needs knowing several factors, including pH, For instance, removal of As

Table 1Types of volcanoes expected near the study area.

71		,		
Volcanic name	Location	Last Eruption	Primary volcanic type	Distance from LB
Boset - Bericha	Oromia	Unknown- evidence credible	Stratovolcano (es)	Less than 100 km
Dofan	Afar	Unknown- evidence credible	Shield	Less than 100 km
Fentale	Oromia- Afar	1820	Stratovolcano	Study area
Sodore	Oromia	Unknown- evidence credible	Pyroclastic cone (s)	Less than 100 km
Yangudi	Afar	Unknown- evidence credible	Complex	Less than 200 km

(Source: Ethiopia Volcanoes-Global Volcanism program, EV-GVP, 2013).

(III) is one of the most difficult. The main protonation equilibrium in which H_3AsO_3 is involved, at the pH values of natural waters (Cassone et al., 2018). Redox potential (Eh) and pH are the most important factors controlling arsenic speciation (Baeyens et al., 2007).

As shown in Table 1, di-hydrogen arsenate ($H_2AsO_4^-$) represents the most stable species for $3 \le pH \le 6$, whereas, for pH > 6, the other two species, hydrogen arsenate ($HAsO_4^{2-}$) and arsenate ion (AsO_4^{3-}), are produced (Cassone et al., 2018). In fact, when choosing and analyzing the most dominant form of As in water, the most present is inorganic As (V). If As (III) is present, there are two important things that need to be taken into account. As (III) is more poisonous (even at low concentrations) than As (V) (Rajakovic and Rajakovic-Ognjanovic, 2018). Besides the severe toxic effect, As(III) is easily oxidized. Due to different reasons, the formation of complex solutions between As oxyanions and other elements is limited; however, even such limited interactions still influence As speciation (Redman et al., 2002). Arsenic species can be transformed into insoluble compounds in combination with other elements, such as iron and sulfur (Mandal and Suzuki, 2002).

The adsorption of arsenate As (V) and arsenite As (III) to mineral surfaces is reduced in the presence of natural organic matter (NOM) (Grafe et al., 2001, 2002). Surface complexation models suggest that dissolved carbonate should interfere with As adsorption on mineral surfaces at carbonate concentrations typically measured in ground and soil waters (Appelo et al., 2002). Complex thermodynamic calculations that assume specific subterranean conditions are required to trace the sequence of events from the original GW to lake water and back again. Some studies used sediment samples from surface waters to determine concentrations of HM (Temesgen Eliku Bosset, 2018). Nowadays, heavy metals are considered to be a serious threat to the environment and human health all over the world (Briffa et al., 2020). A number of studies have revealed that As has an effect on human health (Ashan et al., 2006; Chen et al., 2007, 2011; Sohel et al., 2010; Dauphiné et al., 2011; Lin et al., 2013; Srivastava et al., 2013; Mundey et al., 2013). As shown in the Fig. 5, under oxidizing conditions, H₂AsO₄ is dominant at low pH (less than about pH 6.9), whilst at higher pH, HAsO₄²⁻ becomes dominant (H₃AsO₄⁰ and AsO₄³⁻ may be present in extremely acidic and alkaline conditions respectively) (Baeyens et al., 2007).

3.5. Concentration of arsenic in lake Beseka

Arsenic, a metalloid, can exist in different forms, such as III or V states. Since As (III) is less firmly adsorbed on most mineral surfaces than the negatively charged As (V) oxyanions (H₃AsO₄), it is actually more mobile than As (V) and found in most natural water as As (OH)₃, Table 2 shows that GW from rhyolitic/volcanogenic sedimentary rocks from the same region had high concentrations of As in the range of 0.53-446 µg/L (Rango et al., 2010) in parts of the Ethiopian Rift Valley, specifically in the Methara and Zeway Shala sub-basins (Aryan et al., 2024). In addition, in some parts of Ethiopia, such as in the Awetu watershed, the south-western part, elevated levels of arsenic (> 184.5 µg/L) were found. The As concentration range in all sampled stations exceeding the limit of $10 \mu g/L$ specified by WHO (Astatkie et al., 2021). Overall, the lake water's influence was evaluated and determined to be unsuitable for this level of use (Mladenov et al., 2014). With the exception of watering livestock, the lake's water quality has not been suggested for any domestic, drinking, or irrigation uses. As species can exist in water in solution or as precipitates, and they can also adsorb or desorb from the precipitates that are already there, depending on a number of driving factors, such as redox conditions and the microbiological environment (Issa et al., 2011, 2010). Both inorganic and organic forms of As species are possible when they are soluble in water. Both As (III), arsenite, and As (V), arsenate, may be found in iAs species (Rajakovic and Rajakovic-Ognjanovic, 2018).

According to some studies conducted in the Main Ethiopian Rift Valley, which includes the middle section of the Awash Basin, surface water, and boreholes, the findings of As in water bodies were above the

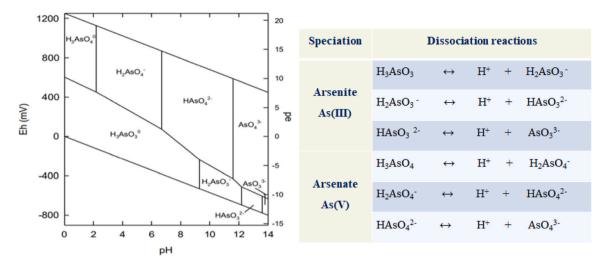


Fig. 5. Eh/pe-pH diagram for arsenic speciation (Chaudhary et al., 2024) and dissociation reactions.

Table 2The concentration of arsenic in the rift valet water bodies including Lake Beseka.

Basin (Sub-basin)	Water bodies	No. of samples	Conc. Range in µg/L	Sources	Ref.
Rift valley	Surface	10	0.90-405	Human activities	(Rango et al., 2010)
(including Awash-Awash sub-basin, Zeway-Shall sub-	Water	09	0.2100	Human activities	(Dsikowitzky et al., 2013).
basin)	(Lake, Rivers)	11	2.39-266	Human activities	(Rango et al., 2013)
		05	0.02-96	Human activities	(Chen et al., 2008)
		44	184.5	Human activities	(Astatkie et al., 2021)
		20	2.14–61.2	Human and natural activities	(Abebe et al., 2023a)
		21	0.4–95.2	Human and natural activities	(Abebe et al., 2023b)
		21	BDL-25	Industrial wastewater	(Jin et al., 2023)
	Groundwater	-	0.016-96.2	Natural actvities	(Norton et al., 2009)
	(Boreholes)	-	21.4–278	Natural actvities	(Huntsman-Mapila et al., 2006)
		-	0.60-190	Natural activities	(Rango et al., 2013)
		34	0.60-73.4	Natural activities	(El-Badry and Khalifa, 2017
		16	0.90–210	Natural and human activities	(Abebe et al., 2024)
	Sediment (SW)	46	ND-67.42	Human actvities	(Dirbaba et al., 2018)

NB: NA stands for natural activities, including weathering of rocks, volcanic ash, and climate change, whereas HA stands for human activities, including agricultural runoff, municipalities, and industrial wastewaters. BDL means below detection limits. ND stands not detected. The bold figures exceeded the values of the standards limit of As and Mo with $10 \, \mu g/L$ and $70 \, \mu g/L$ respectively.

Table 3
The concentration of heavy metals in the Awash River and LB: Date of sampling: A: Jun 16, 2021 and B: Nov. 9, 2021.

Sample ID	DoS	Tur	pН	EC	U	As	Mo	Fe	Al	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	Ge	Rb
LB1	A	36.4	9.2	2520.0	7.3	95.6	94.1	404.4	518.6	36.9	68.6	1.0	21.9	0.2	1.3	25.0	23.1	1.1	27.7
	В	41.4	9.5	2111.0	5.8	18.8	83.7	858.2	1113.4	64.2	71.1	1.9	24.0	0.5	1.7	83.6	19.6	1.1	26.6
	Av.	38.9	9.4	2315.5	6.5	57.2	88.9	631.3	816.0	50.6	69.9	1.4	22.9	0.3	1.5	54.3	21.4	1.1	27.2
LB2	Α	17.4	9.2	2480.0	9.8	67.6	96.2	298.2	377.2	25.6	73.7	0.9	12.4	0.2	1.3	20.5	9.9	1.3	29.0
	В	56.8	9.5	2180.0	5.9	19.1	85.8	899.1	1140.3	64.9	71.9	1.9	25.7	0.4	1.8	78.6	13.1	1.2	27.1
	Av.	37.1	9.4	2330.0	7.9	43.4	91.0	598.7	758.8	45.2	72.8	1.4	19.0	0.3	1.5	49.6	11.5	1.2	28.0
LB3	Α	4.7	9.5	3650.0	15.2	51.1	146.7	76.9	42.0	8.5	72.7	0.4	3.5	0.2	1.0	24.9	4.4	0.9	34.9
	В	58.4	9.5	2210.0	6.6	19.1	86.6	842.0	1070.3	61.9	70.0	1.8	22.0	0.4	1.6	66.1	11.9	1.2	27.8
	Av.	31.5	9.5	2930.0	10.9	35.1	116.7	459.4	556.2	35.2	71.3	1.1	12.7	0.3	1.3	45.5	8.1	1.0	31.4
LB4	Α	8.2	9.3	2800.0	11.2	66.5	108.5	21.4	36.7	3.1	66.9	0.5	3.1	0.1	1.0	20.1	6.5	1.2	30.7
	В	56.0	9.7	2290.0	9.9	24.7	114.9	196.0	231.7	16.6	57.0	0.8	11.9	0.4	1.3	96.6	9.6	1.0	28.3
	Av.	32.1	9.5	2545.0	10.5	45.6	111.7	108.7	134.2	9.9	62.0	0.6	7.5	0.2	1.2	58.4	8.1	1.1	29.5
LB5	Α	20.8	9.2	2410.0	10.7	61.2	91.9	150.7	188.5	14.4	94.2	1.9	7.9	0.1	0.8	15.6	8.2	1.5	31.8

(Source: Abebe et al., 2023a, 2023b).

threshold (Tables 4 and 5). Almost all discussed studies in the study area used advanced analytical methods such as ICP-MS, GF-AAS, and HG-AAS, which can be used to determine the quantity of heavy metals and arsenic in drinking water (Abebe et al., 2022; Grafe et al., 2001). However, due to a number of factors, including a lack of advanced instrumentation, not much research has been done on the concentration, causes, and effects of heavy metals in Ethiopia's Awash Basin. According to the reviewed paper found, the sampling stations reviewed in Lake Beseka and the surrounding catchment boreholes mentioned in Tables 3 and 4 are represented as follows: GW1: Borehole near Addis Ketma Mosque site; GW2: Borehole at Merti near cow shelter (Berret House); GW3: Borehole at Merti camp near employee shelter (Barack House); GW4: Borehole at Merti camp near Abattoir-Awash River site; GW5: Borehole at Merti slaughter and abattoir area; GW6: Borehole at Abadir 4th camp; LB1: Lake Beseka at Canal; LB2: Lake Beseka at Intake; LB3: Lake Beseka at the right side of old Road; LB4: Lake Beseka at the left side of old Road; LB5: Lake Beseka near new lodge. The units of turbidity, pH, EC, TDS, alkalinity, bicarbonates, carbonates, total hardness (TH), and heavy metals are in NTU, unitless, µS/cm, mg/L, mg/L, mg/L, mg/L, and µg/L, respectively.

The lake has been improving because of relatively fresh water drained into the lake from agricultural runoff from big farms, including Nura Era, Abadir, and Fentalie projects. The saline levels of Lake Beseka water changed with the seasons and climate, which had an adverse influence on the water level and quantity. Despite this, the lake has been a significant source of water for their livestock, especially during the dry seasons. The study carried out Abebe et al. (2024, 2023a, 2023b, 2023c), which provided data for over 42 parameters for Lake Beseka and boreholes in the lake catchment, has the most exhaustive and thorough inventory of data on heavy metals (or trace elements) in surface water and groundwater of Lake Beseka. Studies on the groundwater, particularly in the rift valley, showed a high positive correlation of As with Na, HCO₃, U, B, V, and Mo (Rango et al., 2013; Abebe et al., 2023b; Dirbaba et al., 2018).

According to these authors (Abebe et al., 2024, 2023b, 2023c; Bramer et al., 2018), a typical geological (impact of volcanism) and hydrothermal geochemical signal was discovered to be the relative enrichment of numerous species, including pH, EC, TDS, alkalinity, carbonates, bicarbonates, chlorides, As, Cs, F, Ge, K, Li, Mo, Na, Rb, Sb, Se, Tl, and W. Additionally, they discovered unexpectedly high natural concentrations of some elements (such as Be, Br, Co, Li, Nb, Si, Sr, Te, and Th) for which is no WHO (Rajeswari, 2015) values have been established. In general, as seen in Table 3 and Table 4, the heavy metals and arsenic pollution of Lake Beseka and boreholes near to Lake Beseka of the Ethiopian Rift Valley's lake and boreholes were shown to be influenced by both human activities and natural sources, with volcanic activity having the greatest impact (Abebe et al., 2024, 2023a, 2023b). Geogenic pollutants associated with tectonic and geologic settings have contaminated the lake water (Abebe et al., 2023a, 2023b, 2023c; Bussi et al., 2021; Dirbaba et al., 2018; Yimer et al., 2020; Jin et al., 2021). Because of the interactions and/or percolations between surface water and groundwater, this impact is not restricted to bodies of surface water but also affects groundwater (Hailu and Haftu, 2023).

The current main concern is heavy metal pollution of surface waters because of its toxicity, persistence in the ecosystem, and bio-accumulation effect (Sin et al., 2001). The lake area has an unconfined aquifer type, with groundwater temperatures ranging from 36 to 40 °C. Of the various hot springs south of the lake, the Tone and Chelelektu springs are the most significant. The springs' surface temperature can rise to 43 °C. In addition to this, hot seepage and submerged springs can be found southwest of Lake Beseka, and these sources are deemed unsuitable for irrigation and domestic use. Lake Beseka's chemical makeup is comparable to that of the springs along the eastern coast, with high sodium ion content and a low divalent ion content, similar to the rocks of the Fentale Mountains region. It has also been reported that geothermal springs are one of the causes of arsenic contamination in river water on

Heavy concentration in groundwater (boreholes near LB) Date of sampling A: June 1, 2014) and B:October 10, 2021.

neavy co	niceiman	on m grom	idwalei (I	orenores n	וכמו דים) המ	reavy concentration in groundwater (borenoies near ED) Date of surpring, A.	omic 1	, 2014) and B.October	p.October 10	, 2021.									
SID	DoS	Turb.	hН	EC	U	As	Мо	Fe	Al	Ti	Λ	\mathbf{Cr}	Mn	Co	Ni	Cu	Zn	Ge	Rb
GW1	A	0.57	8.81	4960	37.24	170.18	147.89	5.40	49.27	0.75	399.69	9.31	0.91	0.28	1.14	36.44	12.12	0.25	19.85
	В	0.61	6.39	6460	50.82	62.03	197.50	16.96	46.91	1.41	427.34	12.18	3.83	0.67	2.10	226.36	8.11	0.19	26.89
	Av.	0.59	9.10	5710	44.03	116.11	172.69	11.18	48.09	1.08	413.52	10.75	2.37	0.48	1.62	131.40	10.11	0.22	23.37
GW2	A	1.55	7.97	1757	37.26	160.03	163.72	BD	29.57	0.32	153.92	1.33	1.36	0.04	0.49	23.23	47.65	0.29	10.02
	В	1.78	8.84	1800	9.75	6.23	45.53	25.90	84.82	2.07	40.01	1.87	79.41	0.87	2.82	201.84	199.48	0.56	14.18
	Av.	1.67	8.41	1779	23.51	83.13	104.62	ВD	57.20	1.20	96.96	1.60	40.38	0.46	1.66	112.53	123.57	0.42	12.10
GW3	V	0.79	8.00	1564	9.40	57.37	38.21	7.00	28.45	0.35	96.51	0.19	992.24	0.24	1.08	128.27	95.39	0.34	9.02
	В	0.73	99.8	1350	7.14	11.13	29.16	103.02	228.74	3.41	88.06	0.51	824.78	0.44	1.50	224.61	39.36	0.39	8.69
	Av.	0.76	8.33	1457	8.27	34.25	33.68	55.01	128.59	1.88	92.29	0.35	908.51	0.34	1.29	176.44	67.38	0.36	8.85
GW4	A	3.08	7.97	2070	22.39	14.76	23.09	BD	22.35	0.31	30.51	1.80	48.59	0.02	0.38	21.95	26.85	1.05	36.81
	В	2.98	8.90	1840	14.58	3.29	18.52	98.73	261.78	4.60	31.06	1.97	112.15	0.42	1.10	206.88	25.47	1.07	33.15
	Av.	3.03	8.44	1955	18.48	9.02	20.80	BD	142.06	2.46	30.78	1.89	80.37	0.24	0.74	114.41	26.16	1.06	34.98
GW5	¥	1.07	7.86	2390	18.32	30.22	19.85	BD	18.98	0.27	98.09	1.23	16.00	0.09	0.41	19.74	47.18	0.46	16.97
	В	1.27	8.56	2110	13.14	90.9	15.31	22.06	74.82	1.40	52.24	1.34	13.82	0.30	0.97	170.13	26.12	0.49	14.80
	Av.	1.17	8.21	2250	15.73	18.14	17.58	BD	46.90	0.83	56.55	1.29	14.91	0.19	69.0	94.93	36.65	0.48	15.88
9M9	A	3.93	8.70	1653	14.86	68.65	65.44	BD	15.55	0.15	77.72	2.34	2.67	BD	0.27	12.75	17.99	1.09	28.85
	В	3.43	60.6	1550	10.80	15.15	44.80	88.69	178.83	2.81	65.91	1.95	12.57	0.28	0.64	98.70	15.66	1.11	24.32
	Av.	3.68	8.90	1602	12.83	41.90	55.12	ВD	97.19	1.48	71.82	2.14	7.62	BD	0.45	55.72	16.82	1.10	26.58

Table 5
Removal of As (V) using adsorption processes using different adsorbents by batch experiment.

Forms	Water type	pН	Concentration	Removal efficiency	Adsorbent used	Ref.
As(v)	Groundwater	7	96 μg/L	80–90 %	Fertile soil	(Bhattacharyya et al., 2003)
As(v)	Aqueous soln.	10	500 μg/L	99 %	Bio char	(Hung et al., 2004)
As(v)	Groundwater	3-9	$0.21-10 \ \mu g/L$	99 %	Termite mound	(Fufa et al., 2014)
As(v)	Aqueous soln.	3	5000 μg/L	97 %	Feldspar	(Yazdani et al., 2016)
As(v)	Aqueous soln.	3-9	0.25 mg/L	99.7 %	Cerium-loaded volcanic rocks	(Asere et al., 2017)
As(v)	Aqueous soln.	3	1-10 mg/L	78 %	Kaolinite	(Mohapatra et al., 2007)
As(v)	Aqueous soln.	3	1–10 mg/L	53 %	Illite	(Mohapatra et al., 2007)
As(v)	Aqueous soln.	3	1-10 mg/L	53 %	Montmorillonite	(Mohapatra et al., 2007)
As(III)	Aqueous soln.	4–8	1 mg/L	-	Concrete-based adsorbent	(Mondal et al., 2020)
As(III)	Aqueous soln.	5	1-2500 mg/L	-	Algerian natural montmorillonites	(Zehhaf et al., 2015)
As(III)	Aqueous soln.	4–7	50 mg/L	95 %	hydroxyapatite-bentonite clay-nanocrystalline cellulose	(Hokkanen et al., 2019)
As(III)	Aqueous	2-12	10 mg/L	90 %	Rice straw	(Wu et al., 2018)
As (III)	Aqueous	2–12	10 mg/L	100 %	Fe3O4 modified rice straw	(Wu et al., 2018)

the southern Tibetan Plateau (Li et al., 2014). Geological conditions produce tectonic movements, sedimentations, and hydrological cycles are the tree important factors affecting the movement and transformation of arsenic in surface water and groundwater (Mukherjee et al., 2014).

A high value of arsenic is found in hot springs (Zhang et al., 2023). Similar studies also revealed that, hot springs can be found in the area with no $\rm H_2S$, high As level with a positive correlation to Fe level (Kikawada, 2025). According to a study done on Lake Beseka, a number of hot springs on the lake's southwest shoreline are a major contributor to both the lake's water chemistry and its level rise. Even though, scarcity of data on hot springs, the hot springs submerged or/and found near the lake might have a source for high levels of Arsenic in the lake water. Perhaps the basin wide groundwater flow paths, hydrogeochemical evolution may play a crucial role in determining the fate of As in lake (Mukherjee et al., 2014). Similarly, as Fig. 6 illustrates, more than 90 % of samples had an As value over the WHO guidelines (10 μ g/L), which could be caused by geology, hydrogeology, rock weathering, and certain human activities.

3.6. Toxicity of arsenic and environmental implications

Arsenic is known for its toxicity, particularly in inorganic forms, and its ability to form various compounds with metals, halogens, and organic molecules. The issue of aquatic environment poisoning by arsenic is a global concern (Mojiri et al., 2024). The toxicity of As to humans is well studied and well documented, and its presence at elevated concentrations in the public water supply will be a great contemporary concern (Welch et al., 2000; Berg et al., 2001; Smedley and Kinniburgh, 2002) globally as well as regionly. Human health and the environment are being harmed by the introduction of heavy metals and As into water bodies through hydrogeology and geochemical processes, as well as presence of hot springs (Kikawada, 2025), agricultural runoff (agrochemicals) and other natural sources (volcanic ash, and weathering of rocks). Arsenic, a naturally occurring element in the environment, forms compounds through its interaction with oxygen, chlorine, and sulfur. Rock and soil contain harmful inorganic arsenic chemicals linked to cancer, while organic substances have lower levels. Aquatic species absorb and transform arsenic. Studies indicate that those who consume drinking water containing high concentrations of arsenic are highly

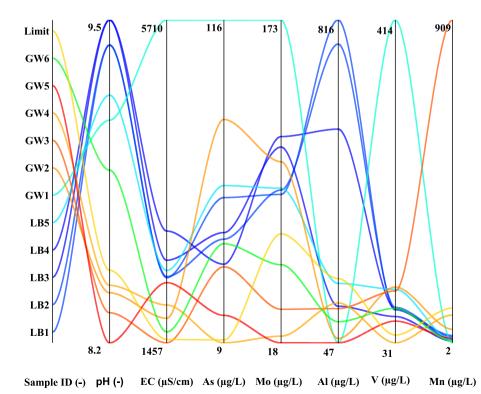


Fig. 6. The concentration of arsenic and some heavy metals in the lake catchment.

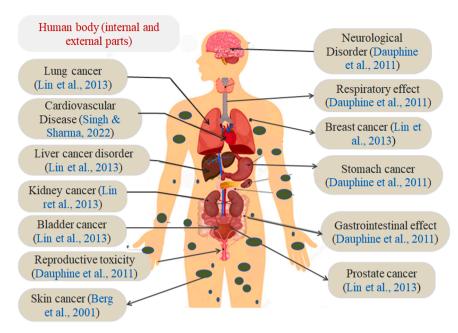


Fig. 7. Effect of long term exposure of arsenic on various body parts (internal and external parts).

affected by different types of cancer (Singh and Sharma, 2022; Palma-Lara et al., 2020; Huang et al., 2015; Shridhar et al., 2023).

As seen in the Fig. 7, similar studies revealed that, a long-term effect of chronic expose to inorganic arsenic causes skin, lung, liver, kidney, prostate, breast, stomach, and urinary bladder cancer (Nail et al., 2023; EFSA Panel on Contaminants in the Food Chain (CONTAM) et al., 2024; Ganie et al., 2024; Rahmani et al., 2023), and diabetes mellitus (Shridhar et al., 2023; Hashim, 2023), cardiovascular effect (Singh and Sharma, 2022), and neurological disorders and reproductive toxicity (Hashim, 2023). Although severe health disasters linked to arsenic poisoning in Ethiopia have not yet occurred, arsenic poses a progressive health concern. In fact, because of its moderate effects, it might not be immediately identified as the cause of health issues. Aquatic species can absorb, retain, and alter various forms of arsenic in their bodies when they come into touch with As through their diet and other sources, like water (Azizur Rahman et al., 2012). Water quality and safety may be

significantly impacted by the mobility, speciation, and chemical interaction of heavy metals including arsenic, which are known for their high toxicity, persistent presence, and bioaccumulation. To reduce the threat that heavy metals and arsenic cause to the environment and public health, it is actually essential to comprehend their sources, chemical changes, leaching procedures, and modes of deposition in water bodies. There doesn't seem to be any As present in high concentrations that cancer and other non-cancer producing disorders directly endanger the health of the vulnerable people.

3.7. Further implication (remediation and technologies)

In order to remove pollutants such as As from water bodies various technologies have been implemented (Nicomel et al., 2016). Some additional activities including the implementation of pollutant removal from water media (groundwater, wastewater, surface water, synthetic

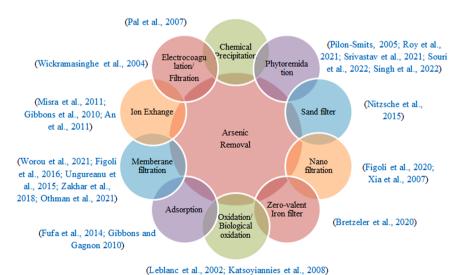


Fig. 8. Removal of arsenic from water using different removal techniques (Bretzler et al., 2020; Figoli et al., 2019; Katsoyiannis et al., 2008; Leblanc et al., 2002; Nitzsche et al., 2015; Wickramasinghe et al., 2004; Xia et al., 2007).

water, and boreholes) will solve the problem of water scarcity as well water quality deterioration downstream of Lake Beseka. For instance, as shown in Fig. 8, the removal of As from an aqueous solution was carried out using co-precipitation, coagulation, and ion exchange (Misra et al., 2011), chemical precipitation, and adsorption (Afkhami et al., 2010). Consequently, researchers have been using different methods for the removal of heavy metals (Aziz et al., 2025), and arsenic (Dilpazeer et al., 2023), from wastewater, real water, or an aqueous solution, including ion exchange (Orrego et al., 2019), coagulation (Zhang and Ma, 2016), solvent extraction (Pradhan et al., 2020), precipitation, and adsorption (Verbinnen et al., 2012; Lian et al., 2018).

3.7.1. Coagulation and flocculation

To achieve effective coagulation in water treatment, a high-energy, rapid-mix process is necessary to disperse coagulants and encourage particle collisions. Both groundwater and surface water contain dissolved and suspended particles, which are separated by flocculation a gentle mixing process that enlarges particles from microfloc to visible sizes. Coagulants with opposite charges to the suspended solids are added to neutralize negative charges on non-settlable substances like clay and organic materials (Han et al., 2002). Even though it might be difficult to use in the lake because of the generation of secondary pollution and also to apply on a large scale, the application of combining coagulation-filtration-adsorption was potentially viable for real application of As removal (Chiavola et al., 2019). For instance, ferric chloride (FeCl₃) was used as a coagulant in a lake investigation. The coagulation was used in field studies for lake water with volumes of $1 \times 10(4)$ m³ and 25 × 10(4) m³, where arsenic was also successfully eliminated (Chen et al., 2015). By using microscopic techniques to investigate molecular As surface complexes on the freshly formed Fe flocs and compare the performance of ferric(III) sulfate (FS) and polyferric sulfate (PFS), similar studies were also conducted in groundwater on the removal of As from groundwater. Ultimately, a workable solution was provided in As-geogenic areas. Fig. 9 illustrates that oxidants (KMnO₄ and H₂O₂) and coagulants (FeSO₄, Fe₂(SO₄)₃, and FeCl₃) show promise (Teh et al., 2016; Habuda-Stanić et al., 2015) on As removal. The removal efficiency was also encouraging, and there was evidence of improved As removal efficiency in coagulation and coagulation/filtration (Cui et al., 2015).

3.7.2. Adsorption

Although the physicochemical characteristics of the lake's water are improving (Abebe et al., 2025), mitigation measures and a thorough follow-up are still required in order to use the lake water for a variety of

purposes. Removing heavy metals and arsenic from surface water is challenging due to its chemical features and speciation complexes. In fact, several heavy metals (Bhattacharyya et al., 2003), removal including Mo and As (Metaloid) removal techniques have been tested to develop efficient and effective adsorbents at a low cost. As seen in Table 5, a wide range of adsorbents have previously been investigated in multiple studies for the removal of arsenic.

A few of these are zeolites, coal, fly ash, chicken feathers, red mud, activated carbon, kaolinite, montmorillonite, goethite, zero-valent iron, chitosan, and cation-exchange resins. There are increasing experimental efforts to look into improved removal methods for various contaminants, including arsenic, from various types of water. Arsenic (V) is removed more efficiently than As (III) by both conventional and nonconventional methods (continuously recyclable natural process). Pretreatment of As (III) with As (V) is an essential step for better removal (Issa et al., 2011). Most of the aforementioned techniques are capable of removing As from water and wastewater, but the adsorption technique is one of the most chosen methods because of its simplicity, nontoxicity, and low cost (Yadanaparthi et al., 2009; Kwon et al., 2010) to remove As from aqueous medium. Among the aforementioned techniques, the removal of oxyanion from metals, As, by the adsorption technique is getting more popular. For instance, Fe has a high affinity for Mo, which is why elemental iron has been extensively used as an adsorbent for the removal of Mo (Lian et al., 2018; Chen and Lu, 2014). Arguably, due to its simplicity, low cost, and locally available adsorbent materials, adsorptive technology is a frequently used and promising technology for removing As (and Mo) from water. Various chemical methods have been applied from classical to contemporary analytical techniques for the determination of heavy metals and their species in water (Rajakovic and Rajakovic-Ognjanovic, 2018).

As illustrated in Fig. 10, adsorption may start with the transfer of arsenic As species (As (III) and/or As (V)) (reduction and oxidation) from the aqueous solution or lake water to the surface of adsorbents. These ions, in both the pentavalent and trivalent form, then bind to the surface through physical or chemical interactions; therefore, adsorbents need to have a large accessible surface area in order to facilitate this process, ensuring the presence of numerous exposed active sites for efficient and selective binding with heavy metal ions (Fei and Hu, 2023). In fact, physisorption happens when van der Waals forces bring the absorbent and adsorbate together, chemisorption happens when the adsorbate forms chemical bonds with the adsorbent surface, and surface complexation, electrostatic attraction, ion exchange, and surface complexation happen when heavy metals and As exceed available sites (Mojiri et al., 2024). Therefore, it is crucial to make sure that control

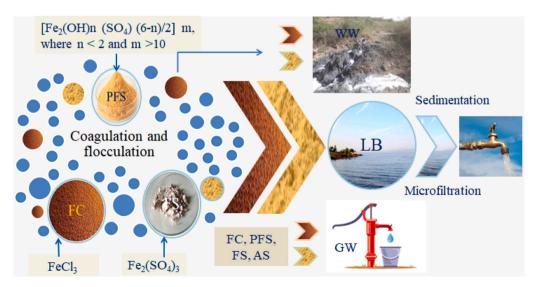


Fig. 9. Removal of As using coagulation, flocculation, and sedimentation/microfilteration.

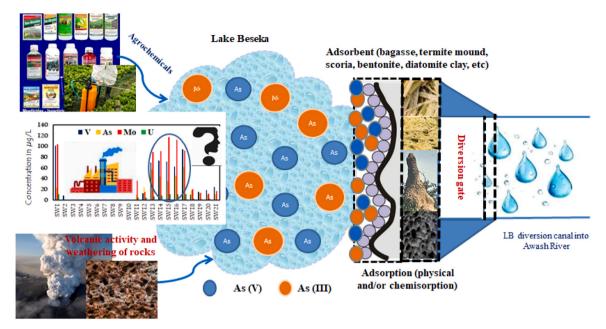


Fig. 10. Suggested removal technology for arsenic removal from Lake Beseka by adsorption processes.

gates that are operated at high quality of operational efficiency, either manually or automatically, have the necessary provisions and supporting technologies to enhance the removal of arsenic from lake water outflow. Adsorption is a comparatevely inexpensive and eco-friendly technology (Kareem et al., 2025). It is also a very promising technique to implement on its own or perhaps in conjunction with other technologies. For instances a combined technology such as adsorption with ultra filtration memberane processes has been implemented for the removal of arsenic from surface water (River) (Hao et al., 2018).

3.7.3. Memberane technology

Nowadays, membrane technology is becoming more and more significant due to its numerous uses. This is because membranes are inexpensive, simple to operate, and need relatively little energy. Due to its multidisciplinary nature, it is utilized in many different sectors. A membrane is a thin layer or film that separates a liquid or gas into two phases. The membrane's capacity to control chemical species' penetration is one of its most important characteristics. Membranes, such as reverse osmosis, microfiltration, and ultrafiltration, have been extensively employed in water treatment technologies and are a promising method in the removal of arsenic (Worou et al., 2021). Studies indicate that, nanofiltration (NF) and reverse osmosis (RO) (Figoli et al., 2016) are the most promising technologies for the selective removal of arsenic

from contaminated water (Ungureanu et al., 2015; Zakhar et al., 2018; Othman et al., 2021). Despite this, the recommended membrane technologies are advantageous since they are easy to scale, have tunable membrane properties, use less energy, and are more efficient (constant effluent quality). The cost of large-scale membrane water treatment systems is still one of the key obstacles, though, particularly for Ethiopia and the majority of poor nations.

3.7.4. Phytoremediation

Over the last thirty years, a new technology called phytoremediation has emerged that uses plants and related soil bacteria to lower the levels of pollutants in the environment or their harmful effects. It is an affordable, non-invasive substitute or addition to engineering-based remedial techniques. Pollutants can be stabilized, extracted, degraded, or volatilized using plants (Pilon-Smits, 2005; Roy et al., 2021; Srivastava et al., 2021; Souri et al., 2022; Singh et al., 2022). In fact several studies revealed that, the contaminated water bodies may be remediated with the help of high biomass aquatic plants including Lemna gibba (Mkandawire et al., 2004). As per their findings, Lemna gibba has been demonstrated to accumulate As up to 1022 mg/kg dry biomass in 21 d from contaminated surface water containing 41.37–47 µg/L As (Srivastava et al., 2021; Mkandawire et al., 2004). As shown in Fig. 11. I-.III), not only Lemna gibba, but also, Ceratophyllum demersum (Weis

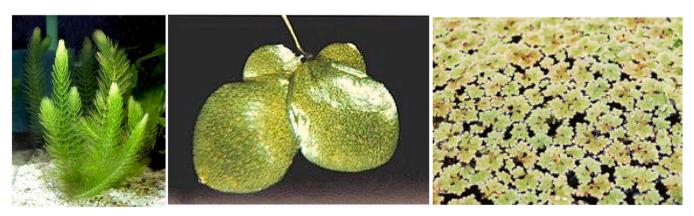


Fig. 11. i. Ceratophyllum demersum (hornwort). ii. Lemna gibba. iii. Azolla caroliniana.

and Weis, 2004). Azolla caroliniana (Zhang et al., 2008), Pistia stratiotes (Farnese et al., 2014), and the like are a promising plants for removal of arsenic from water. Due to subsurface flow, the lake has recently appeared behind or after the Addis Ketema to Methara road during rainy seasons, consuming a portion of the land. Previously, it used to a grazing land, this area could be appropriate for the application of phytoremediation techniques and adsorption.

In order to reduce the negative effects on human health and the environment, in placing adsorption-phytoremediation technologies could strengthen the removal of As and other heavy metals from lake water that has been drained into Awash River. In fact, phytoremediation is a promising, affordable, and sustainable plant-based remediation technique. Plants are indeed one of the primary species that lead the treatment processes, but they also require a conjunction with other technologies, such as adsorptive artificial wetlands. Not only the aforementioned technologies, but also the electrocoagulation techniques (Kobya et al., 2015), chemical precipitations (Pal et al., 2007), and ion exchange (Misra et al., 2011; Gibbons and Gagnon, 2010; An et al., 2011), are a very promising technologies for the removal of arsenic from water, wastewater, and groundwater. However, due to several reasons and driving factors, the adsorption, phytoremediation, and memberane technology could be or relatively very recommendable for removal of arsenic from the lake water.

3.7.5. Advanced oxidation processes (AOPs)

An advanced oxidation process (AOP) is a very promising method for heavy metal and As removal from surface water and wastewater, despite the fact that there are various methods to remove arsenic and heavy metals from water. Through oxidation and interactions with hydroxyl radicals (•OH), it is a wide term for a group of chemical treatment techniques intended to eliminate organic (and sometimes inorganic) contaminants from surface water and wastewater. Heavy metals and arsenic have been removed from water and wastewater using a variety of AOP techniques, as indicated in Fig. 12. These techniques include Fenton and Fenton-like, sulfate and persulfate-based UV/peroxide, UV/ ozone, ozone/peroxide, UV/peroxide/ozone, sonochemicals, electrochemical (Shu et al., 2023), and non-thermal based (Ansari et al., 2023), AOP systems. For example, the oxidation of arsenic is significantly increased by UV-activated persulfate with adsorption, and the oxidation phase under ideal pH 3 yielded an As removal effectiveness of up to 96 % (Salehi et al., 2020). As(III) can be electrooxidized to As(V) in an electrochemical reactor equipped with a dimension stable anode (DSA) and an iron plate electrode. As(V) can then be removed using an

electro-coagulation technique (Zhao et al., 2010).

Studies revealed that the oxidation of non-ionic As(III) to negativelycharged As(V) is of crucial importance to achieve the optimum As removal efficiency (Liu and Qu, 2021). However, AOPs have some drawbacks, including a high energy consumption, oxidant toxicity, pH sensitivity, byproduct production, and difficulties scaling up, despite their effectiveness in eliminating heavy metal complexes from wastewater being very promising (Aziz and Mustafa, 2024). In general, techniques including membrane filtration, ion-exchange, adsorption, and electrocoagulation can be applied to improve the removal of metal and arsenic ions either concurrently or following AOPs. As seen in Fig. 12, treating complex water resources, including wastewater, groundwater, and surface water (like Lake Beseka) that contains arsenic and heavy metals, may need the use of a combination of removal technologies (Aziz et al., 2023). For instance, combining AOPs with adsorption or electrocoagulation, or membrane filtration, or ion exchange can enhance the removal of arsenic from the aforementioned water resources.

4. Conclusion and future prospects

Actually, the primary focus of this study is on regional issues, such as the causes of pollution, the prevalence and effects of arsenic, and the techniques for removing arsenic from water (surface water, groundwater, and wastewater). The findings demonstrated that the levels of heavy metals and arsenic (As) in surface water samples from Lake Beseka and boreholes around the lake were significantly higher than the WHO's recommended limits. Rapid population increase, industrialization, and the use of agrochemicals upstream, as well as natural elements like volcanic ash, rock weathering, and the existence of hot springs in the basin, are the sources of this contamination, which had a negative effect on the lake's water quality. Although severe health disasters linked to arsenic poisoning in Ethiopia, particularly in the Awash Basin, have not yet happened, arsenic poses a progressive health risk. Because of its moderate effects, it might not be immediately identified as the cause of health issues. Ethiopia and many other African countries are still far behind in effectively addressing the harmful health impacts of arsenic, despite the fact that extensive research has been conducted globally to reduce this issue. Therefore, the sources of As and heavy metals, their concentrations, and remedial measures were all carefully assessed in this review study.

In fact, a great deal of research has been done all over the world to remove arsenic and heavy metals from surface water, wastewater, and

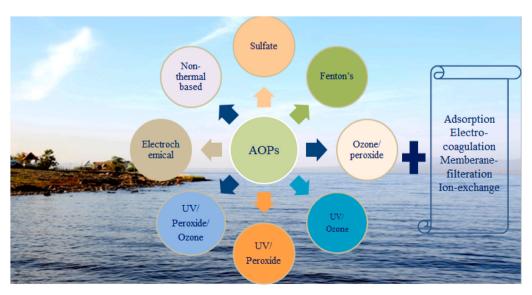


Fig. 12. Advanced oxidation processes (AOPs) for the removal of arsenic and heavy metals.

groundwater. However, efforts to remove heavy metal and arsenic pollution were inadequate in developing nations, such as Ethiopia, especially in the study area. It is essential and needs to be paid attention to As even if it is extremely complex and movable throughout the water and surroundings. In the study location, no treatment was used, and there was comparatively little research on the removal of heavy metals and arsenic in both batch and continuous forms. By increasing usable water through locally accessible, reasonably priced, and ecologically friendly materials in water treatment systems, this systematic review should provide information for the implementation of water treatment and removal technology in the study area and the region. A review is conducted of recent developments in heavy metal removal technologies, including those related to arsenic. Potential techniques for removing arsenic from surface water and wastewater, particularly from Lake include adsorption. phytoremediation, coagulationflocculation-sedimentation/microfiltration, and advanced oxidation processes (AOPs), which might protect human and environmental health before serious pollution happens.

Current studies were carefully reviewed for knowledge and experience input on the removal of As and heavy metals for future study and application on a regional, national, and basin-wide level to enhance water security and advance sustainable development. Selectivity, costeffectiveness, compatibility, and integration with current treatment systems all require more investigation. Universities and nongovernmental groups must work together with regulatory agencies like the Environmental Protection Authority and the Ministry of Water and Energy. They should also work together to address the community's vulnerability and water security downstream of Lake Beseka. To address the environmental and public health concerns, future research should focus on technological solutions and the assessment of practical and viable technologies for the removal of arsenic. Field-scale restoration methods, such as adsorption, phytoremediation, and combination approaches (adsorptive constructive wetlands), are advised because the lake's water quality declined from brackish to moderately saline, resulting in a decline in the water chemistry. In sum, methods that don't result in secondary environmental issues, make use of locally available materials, are cost-effective, use less energy, and show promise for sustainable and probably recyclable technologies need to be given consideration to reduce arsenic contamination.

CRediT authorship contribution statement

Yosef Abebe: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Tena Alamirew: Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. Behailu Birhanu: Writing – review & editing, Visualization, Methodology, Investigation, Data curation. Esayas Alemayehu: Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. Andualem Mekonnen: Writing – review & editing, Supervision, Methodology, Data curation.

Declaration of Competing Interest

Hereby, I Yosef Abebe consciously assures that for the manuscript entitled Arsenic Concentration in the Unique Rift Valley Lake-Beseka: Sources, Impact, and Suggested Technological Interventions.

- This material is the authors' own original work, which has not been previously published elsewhere.
- > The authors declare no conflict of interest
- > The paper is not currently being considered for publication elsewhere.
- > The paper reflects the author's own research and analysis in a truthful and complete manner.

- > The paper properly credits the meaningful contributions of coauthors.
- > The results are appropriately placed in the context of prior and existing research.

I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

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Conflict of interest

The authors declare that there is no conflict of interest in this review paper.

Data availability

Data will be made available on request.

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