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Arsenic Concentration in Groundwater Resources of the Noug Plain (Iran) and Evaluation of Influencing Factors

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Abstract: The Noug Plain, covering an area of approximately 3,600 km^2, is located in the southeast of Iran, in the western part of Kerman province. Its geographical coordinates range from 29°23' to 31°24' North latitude and from 54°10' to 57°34' East longitude. Given that arsenic concentrations are high in certain areas of neighboring plains (Anar and Rafsanjan), this plain was chosen to assess the variations in arsenic concentration. To this end, samples were collected from 23 scattered observation wells across the plain, and arsenic concentration, along with major ions and some other elements, were determined using ICP-MS. Isoconcentration maps and statistical analyses (Principal Component Analysis and Cluster Analysis) were performed on these samples. Arsenic concentrations in the plain range from 0.5 to 135.9 parts per million, with an average of 20.1 ppb, which exceeds the drinking water standard of 10 ppb. Based on this study, it appears that the source of arsenic is the Miocene red conglomerates and geothermal waters resulting from the alteration of Jurassic shales. The direct correlation between arsenic and pH suggests a role of adsorption in the release of arsenic from iron oxide surfaces. Additionally, arsenic decreases slightly toward the northwest with increasing dissolved salts in the groundwater, likely due to its minor absorption and entry into the crystalline network of aragonite, which precipitates in the northwest as evaporation increases and concentrations rise.

Keywords: Arsenic contamination, Groundwater, Geothermal waters, Environmental factors, Geochemical analysis.

I. Introduction

Groundwater has been a crucial resource for human civilization for millennia, playing an integral role in the development of cities and the advancement of societies (Li et al., 2021). Unlike surface water, groundwater is stored beneath the Earth's surface in aquifers and is often considered a more reliable and stable source of freshwater (Jia et al., 2019). In many arid and semi-arid regions, where surface water is scarce, groundwater has been the lifeblood of agricultural, industrial, and domestic needs (Freeze, 1984). Civilizations, from ancient Mesopotamia to modern cities, have relied on groundwater to sustain their populations, enabling the growth of agriculture, urbanization, and industrialization (Jia et al., 2019). With the increasing demands of the global population, especially in regions experiencing rapid urbanization, groundwater continues to be indispensable for supporting human activities and economic development (Abdel-Shafy & Kamel, 2016).

The importance of groundwater extends beyond its role in meeting basic human needs (Coyte et al., 2018). It is also essential for maintaining the ecological balance, as many wetlands, rivers, and lakes are sustained by groundwater discharge (Raj & Shaji, 2017). The availability of groundwater can regulate hydrological cycles, providing a stable source of water for both human and ecological consumption (Oyeku & Eludoyin, 2010). Furthermore, groundwater is critical for agricultural productivity, especially in areas where irrigation from surface water is not feasible (Re et al., 2017). As urban areas expand, groundwater also plays a vital role in meeting the needs of industries, ensuring that cities can function efficiently and support the diverse activities of their populations (Ahn & Chon, 1999). Given its key role in sustaining life and supporting economic development, the protection of groundwater resources is of paramount importance (Chen et al., 2010). The increasing pressures of population growth, urbanization, and industrialization have led to an intensification of groundwater extraction (Karunanidhi et al., 2021). Over-extraction can lead to a variety of environmental problems, including the depletion of aquifers, land subsidence, and the intrusion of seawater into coastal aquifers (Araya et al., 2022). Therefore, safeguarding the quality and quantity of groundwater is essential to ensure its continued availability for future generations (Nisi et al., 2014). Additionally, climate change is influencing the recharge rates of groundwater (Kumar, 2012), making it even more imperative to manage these resources carefully and sustainably (Earman & Dettinger, 2011).

Protecting groundwater from contamination is equally critical (Li et al., 2021). Pollution from agricultural runoff, industrial waste, sewage, and even household chemicals can infiltrate the soil and reach aquifers, rendering water supplies unsafe for consumption and damaging ecosystems (Jia et al., 2019). The risks associated with groundwater contamination are severe because pollutants often remain underground for extended periods, making remediation efforts costly and time-consuming (Abdel-Shafy & Kamel, 2016). In addition to the direct health risks posed by polluted water, contamination can also have long-term socio-economic consequences, such as reduced agricultural productivity and increased healthcare costs (Oyeku & Eludoyin, 2010). Therefore, preventing pollution and ensuring that groundwater remains clean is an essential aspect of sustainable water management (Karunanidhi et al., 2021).

The protection of groundwater from pollution requires a multifaceted approach, encompassing proper waste management, stricter regulations on the use of chemicals, and the promotion of sustainable agricultural practices (Al-Sudani, 2019). Monitoring and controlling pollution sources are essential for preventing contamination, as is the adoption of technology and practices that minimize environmental impacts (Kurwadkar et al., 2020). In urban areas, proper waste disposal systems and effective wastewater treatment are critical in preventing pollutants from seeping into the groundwater (Balderacchi et al., 2013). Similarly, in agricultural regions, the use of fertilizers and pesticides must be carefully managed to prevent excessive runoff that could contaminate groundwater supplies (Kurwadkar, 2017). The contamination of groundwater is a growing concern worldwide, and its implications are far-reaching (Mazac et al., 1987). One of the most significant risks associated with polluted groundwater is the potential for widespread public health issues (Liu et al., 2007). Groundwater is often the primary source of drinking water in many regions, and contamination can introduce harmful chemicals, heavy metals, and pathogens into the water supply (Rao et al., 2022). For instance, arsenic contamination, often from natural sources, has been a critical issue in many parts of the world, leading to severe health problems such as cancer and skin lesions (Adhikary et al., 2010). Similarly, nitrate contamination from agricultural fertilizers has been linked to serious health issues, particularly for infants, who are vulnerable to methemoglobinemia or blue baby syndrome (Knobeloch et al., 2000).

Another significant issue related to groundwater contamination is the persistence of pollutants in the underground environment (Azizpour et al., 2020). Unlike surface water, which can be more easily treated or flushed out, contaminants in groundwater can remain for decades or even centuries, making it challenging to restore water quality once it has been compromised (Tiwari et al., 2016). Contaminants can spread over large areas, affecting entire communities and regions. In some cases, the contamination of one aquifer can impact multiple communities that rely on the same groundwater source, creating regional water crises (Hashim et al., 2011). In addition to health and environmental risks, the economic impact of groundwater contamination can be profound (Singhal et al., 2010). The costs of cleaning up contaminated groundwater can be astronomical, especially if the contamination affects large aquifers or widespread areas (Nivetha et al., 2021). Remediation efforts may involve expensive treatments such as filtration, pumping, and bioremediation, all of which require significant financial resources and time (Baumann et al., 2006). In some cases, entire water systems may need to be replaced or abandoned, resulting in the loss of valuable water supplies (Boateng et al., 2019). Furthermore, contaminated groundwater can reduce the productivity of agriculture, as polluted water can harm crops, soil quality, and livestock health, leading to economic losses for farmers and communities (Ismanto et al., 2023).

Groundwater contamination also exacerbates the challenge of water scarcity, particularly in regions that are already facing water stress (Ullah et al., 2022). As clean water sources become increasingly limited due to pollution, the availability of safe drinking water becomes a growing concern (Saracino & Phipps, 2008). In many parts of the world, especially in developing countries, people rely on contaminated groundwater because it is the only available water source, which results in chronic health problems and a reduced quality of life (Al-Hashimi et al., 2021). Without proper measures to protect groundwater from contamination, the global water crisis will only worsen, making it even more difficult to meet the growing demand for clean water (Karthikeyan et al., 2021). Addressing groundwater contamination requires a concerted effort from governments, industries, and communities (Amin et al., 2011). Policies and regulations must be enforced to reduce the risks of pollution, and investments in water treatment and monitoring systems must be made to protect groundwater from further degradation (Kurwadkar et al., 2020). Education and public awareness campaigns are essential in informing people about the importance of groundwater protection and the consequences of contamination (Oyeku & Eludoyin, 2010). It is also crucial to invest in research and technology that can help identify pollution sources (Jia et al., 2019) and develop innovative solutions to safeguard groundwater for future generations (Kumar, 2012).

The primary objective of this study is to assess the concentration of arsenic in the groundwater resources of the Noug Plain and to identify the key factors influencing its distribution. Given the elevated levels of arsenic detected in neighboring plains, such as Anar and Rafsanjan, it is essential to investigate whether similar contamination exists in the Noug Plain and to understand the underlying geochemical processes contributing to arsenic mobilization. Through extensive sampling and advanced analytical techniques such as ICP-MS, this research aims to provide a detailed geochemical characterization of groundwater in the region. Additionally, statistical analyses, including Principal Component Analysis (PCA) and Cluster Analysis, will be utilized to identify patterns and potential sources of contamination. By understanding these factors, the study seeks to contribute valuable scientific insights into arsenic contamination in arid and semi-arid regions, aiding future research and groundwater management strategies. The necessity of this study stems from the critical importance of groundwater as a primary drinking water source for many communities in the region. Elevated arsenic levels in groundwater pose serious health risks, including long-term exposure effects such as cancer, skin diseases, and developmental disorders. Therefore, identifying the extent of arsenic contamination is essential for implementing effective water management policies and mitigating health hazards. Furthermore, the study will provide practical recommendations for sustainable groundwater extraction, such as drilling deeper wells to avoid arsenic-rich geological formations and geothermal waters. By addressing both the scientific and public health aspects of arsenic contamination, this research will support decision-makers in developing more

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effective water quality monitoring programs and pollution prevention strategies, ensuring the long-term sustainability of groundwater resources in the Noug Plain.

II. Arsenic in Groundwater

Arsenic contamination in groundwater is a significant environmental and public health concern worldwide. Arsenic (As) is a naturally occurring element found in the Earth's crust, and it can enter groundwater through both natural and anthropogenic processes (Mukherjee et al., 2006). Natural sources include weathering of arsenic-rich minerals, volcanic activity, and geothermal processes, while human activities such as mining, industrial waste disposal, and excessive use of pesticides and fertilizers contribute to its presence in water sources (Thakur et al., 2010). The mobility and concentration of arsenic in groundwater depend on various geochemical conditions, including pH levels, redox potential, and the presence of other ions that influence its dissolution and adsorption behavior (Abbasnejad et al., 2013; Shankar & Shankar, 2014).

One of the most concerning aspects of arsenic contamination in groundwater is its severe impact on human health. The British Geological Survey (BGS) has conducted large-scale studies on naturally occurring arsenic contamination, as well as in regions where mining activities have disrupted groundwater systems. Figure 1 presents the findings of BGS research on arsenic contamination across different areas. Long-term exposure to As through drinking water has been linked to severe health issues, including skin lesions, cardiovascular diseases, neurological disorders, and various types of cancer, particularly skin, lung, and bladder cancer (Rahman et al., 2009). Chronic arsenic poisoning, also known as arsenicosis, affects millions of people globally, especially in regions where groundwater is the primary source of drinking water. Figure 2 provides an example of As contamination of groundwater. The World Health Organization (WHO) has set a guideline limit of 10 parts per billion (ppb) for arsenic in drinking water, but in many areas, arsenic levels far exceed this limit, posing a significant health risk to local populations (Hamidian et al., 2019).

As contamination in groundwater is particularly problematic in arid and semi-arid regions, where reliance on groundwater is high due to limited surface water resources (Hamidian et al., 2019). Countries such as Bangladesh, India, China, Argentina, and parts of the United States have reported widespread arsenic contamination, affecting millions of people (Amini et al., 2008; Rodríguez-Lado et al., 2013). In Iran, arsenic contamination has been identified in several plains, including Anar and Rafsanjan, raising concerns about its presence in other groundwater basins such as the Noug Plain (Hamidian et al., 2019). Understanding the extent of arsenic pollution in groundwater is essential for developing appropriate mitigation strategies and ensuring safe drinking water for affected communities (Singhal et al., 2010). The geochemical behavior of As in groundwater is influenced by several environmental factors (Jia et al., 2019). In oxidizing conditions, arsenic primarily exists as arsenate (As^{5+}), which has a strong affinity for iron oxides and clays, limiting its mobility (Rahman et al., 2009). However, under reducing conditions, arsenic is often present as arsenite (As^{3+}), which is more toxic and more mobile in water (Wang et al., 2021).

Fig. 1 Global map of As contamination in groundwater (BGS, 2024)

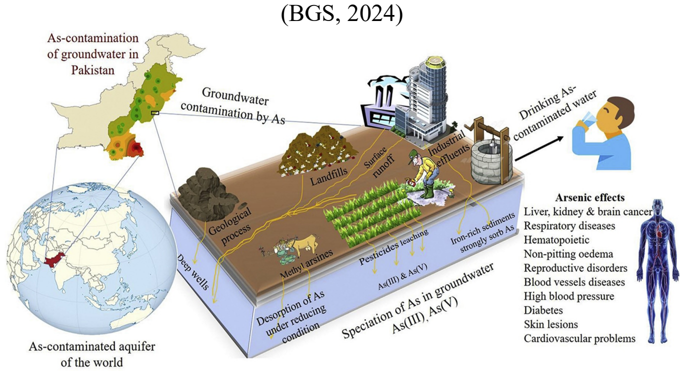

Fig. 2 An example of As contamination in groundwater (Shahid et al., 2018)

Changes in pH and redox potential, often triggered by natural geological processes or human activities such as excessive groundwater pumping, can lead to the release of arsenic into water sources (Cao et al., 2021). Additionally, competitive interactions with other anions, such as phosphate and carbonate, can enhance arsenic mobility, further increasing the risk of contamination (Rahnamarad et al., 2020; Jha & Tripathi, 2021).

One of the critical challenges in addressing As contamination is the difficulty of remediation (Dilpazeer et al., 2023). Unlike surface water, which can be treated relatively easily, groundwater contamination is more persistent because As can remain trapped in sediments and aquifers for decades or even centuries (Cao et al., 2021). Traditional water treatment methods, such as coagulation, filtration, and adsorption, are effective in removing arsenic from drinking water, but large-scale treatment systems can be costly and difficult to implement, particularly in rural and economically disadvantaged areas (Shankar and Shankar, 2014). Therefore, preventive measures such as controlling land use practices, monitoring groundwater quality, and promoting alternative water sources are essential for reducing As exposure (Azizpour et al., 2020). As contamination not only affects human health but also has significant environmental and economic consequences (Adeloju et al., 2021). In agricultural regions, arsenic-contaminated groundwater used for irrigation can accumulate in crops, leading to food chain contamination and potential health risks for consumers (Li et al., 2021). This not only affects food safety but also reduces agricultural productivity and market value. Additionally, arsenic pollution can have long-term consequences for groundwater-dependent ecosystems, affecting aquatic life and soil quality (Chandnani et al., 2022).

To prevent further groundwater contamination, stricter regulations and sustainable land-use practices must be enforced (Adhikary et al., 2010). Industries and agricultural sectors should adopt environmentally friendly practices, such as reducing the use of arsenic-based pesticides and properly managing wastewater disposal (Thakur et al., 2010). Governments and international organizations should also invest in research and technology development to improve arsenic removal methods and provide affordable water treatment solutions for affected communities (Shahid et al., 2018). Collaborative efforts between scientists, policymakers, and local stakeholders are crucial in mitigating the impact of arsenic pollution and ensuring access to clean and safe drinking water for all (Adeloju et al., 2021).

In the Noug Plain, as in other arid and semi-arid areas, arsenic presence is influenced by natural geological formations, including Miocene red conglomerates and geothermal water interactions with Jurassic shales. The mobilization of arsenic is strongly affected by geochemical factors such as pH, redox conditions, and the presence of competing ions, which can enhance its release into groundwater. Given the potential health risks associated with arsenic exposure, including cancer and neurological disorders, understanding its distribution and sources in groundwater is essential. This study aims to assess arsenic concentrations in the region, identify the factors contributing to its presence, and provide insights into effective groundwater management strategies to mitigate contamination and protect public health.

III. Geology of Studied Location

The Noug Plain, covering an area of approximately 3,653 km^2, is one of the sub-basins of the Kavir Darreh Anjir watershed, which itself is part of the larger Rafsanjan-Noug-Anar sub-watershed (Atapour & Aftabi, 2002). The Kavir Darreh Anjir sub-basin is centrally located within the Central Iran watershed and ranks as the sixth-largest internal sub-basin in the country in terms of area (Ghannadpour et al., 2017). Geographically, the Kavir Darreh Anjir sub-basin is bordered to the north by the Siah Kooh Kavir sub-basin, to the west by the Sirjan Kavir sub-basin, to the east by the Lut Desert sub-basin, and to the south by the Hamoun and Jazmourian sub-basins. It extends between latitudes 29°23′ to 31°24′ N and longitudes 54°10′ to 57°34′ E, covering an estimated area of 48,938 km^2. Within this sub-basin, there are three major plains: Rafsanjan-Noug-Anar, Kerman, and Baghain (Sedighian et al., 2024). The Noug Plain forms a basin-like depression running parallel to the Anar Plain in a northwest-southeast direction, encompassing the northern section of the Rafsanjan-Noug-Anar sub-basin. Location of the study has been illustrated in Figure 3. Out of the total 3,653 km^2 of the Noug Plain, approximately 886 square kilometers consist of mountains and foothills, while the remaining area comprises flat plains. The plain stretches approximately 72 km in a northwest-southeast direction, with an average width of about 20 km between the surrounding highlands. This unique geographical setting influences the region’s hydrology, groundwater recharge, and potential contamination risks, making it an important area for environmental and water resource studies.

The Noug Plain is located to the northwest of the Rafsanjan Plain. The average elevation of the plain is 1,400 m above sea level, with a topographical slope of 1.6% on the northern side and 1.1% on the southern side. The area of evaporative regions within the plain is 88 km^2, while the sand dunes cover an area of 129 square kilometers. The average thickness of the alluvial deposits in the plain is approximately 20 m (Barzegar, 2007). The northern boundary of the Noug Plain is marked by the northern mountain range, known as the Davaran Mountains, which extend from the northwest of the plain to the Badamu Mountains, located north of Baghain, in a northwest-southeast direction. These mountains are characterized by significant topographical relief (Shahabpour, 2005). To the south, the plain is bordered by individual hills and isolated mountain ranges. Notably, the Badbakht Kuh Mountains, part of the Central Iranian Plateau, form the boundary between the Noug Plain and the Anar Plain, extending in a northwest-southeast direction. The Badbakht Kuh Mountains are heavily eroded and fragmented, with numerous passes and corridors between the isolated hills and eroded peaks (Barzegar, 2007). These natural features serve as important communication routes, and some of them host main transportation lines, including the strategic railway route connecting Bafq to Bandar Abbas (Mohammadi, 2022).

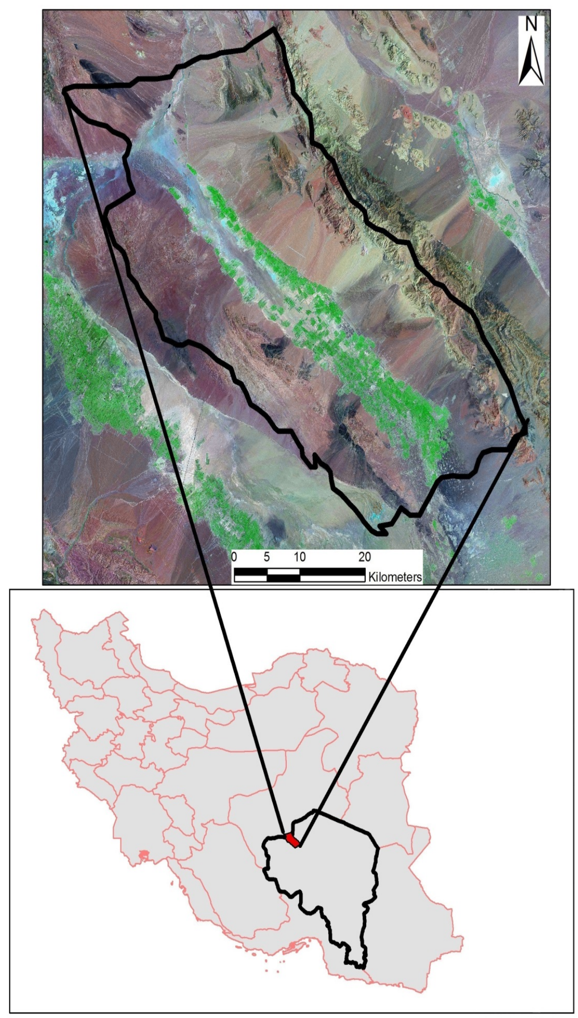

Fig. 3 Location of studied area

The Noug Plain is located between the Badbakht Kuh and Davaran mountain ranges, and it is part of the Rafsanjan Plain. The eastern mountains of the plain belong to the Central Iranian Plateau, consisting of sedimentary rocks from the Proterozoic to Neogene periods (Barzegar, 2007). In the western part, Cretaceous flysch formations are present, contributing to the Badbakht Kuh range. The surface of the Noug Plain is covered by present-day sediments and Quaternary alluvial deposits (Aghanabati, 2012). The Badbakht Kuh range exhibits a variety of geological formations, including Mesozoic flysch, which consists of metamorphosed shale, calcified pebbles, and marl (Nowjavan, 2015). The region also contains Cretaceous conglomerates composed primarily of limestone pebbles, which are disconformably overlaid on the Cretaceous flysch (Walker, 2006). Cenozoic volcanic rocks, such as andesite, basaltic lavas, and rhyodacites, are found in the area, with evidence of hydrothermal alteration (Alizadeh & Arian, 2015). In the Davaran Mountains, Proterozoic rock units, such as the Morad and Rizo series, are present but limited in distribution. These include volcanic rocks, quartzite, sandstone, and dolomite. Paleozoic units are more widespread in the northern part of the region, including formations like the Sultaniyeh limestone and gypsum-containing sedimentary units (Barzegar, 2007). The Davaran Mountains also feature volcanic rocks and numerous fault-related formations (Aghanabati, 2012). The Mesozoic units in the region are diverse, with Jurassic shale-sandstone formations dominating the Davaran Mountains. Cretaceous and Triassic sediments are less common but found in smaller outcrops. These Mesozoic formations, including the Red Shale and Shatri formations, are significant for understanding the region's geological history, as they encompass a variety of lithologies, from limestones and shales to volcanic rocks (Barzegar, 2007; Amirihanza et al., 2018).

The sediments of site consist of coarse alluvial deposits along the mountain slopes and fine-grained sediments (clay and salt) in the central plain (Noorizadeh et al., 2018). These deposits have originated from the erosion of Cretaceous flysch formations (Badbakht Kuh and Bidu Mountains) and predominantly sedimentary Paleozoic and Mesozoic formations of the Davaran Mountains (Aghanabati, 2012). These sediments, influenced by physical and chemical erosion processes, have been gradually transported by agents like water and wind to the mountain margins and central regions of the plain (Barzegar, 2007). The sediments along the mountain margins are coarser and angular, while they become finer and rounder towards the central plain. The presence of crescent-shaped and longitudinal sand dunes indicates the aeolian sediments of this period. Observed units from this era include: piedmonts and alluvial fans from the Pliocene-Pleistocene, high terraces, gravel cones, low piedmonts, young alluvial fans, clay and salt flats, floodplain alluvium, and sand dunes and plains (Aghanabati, 2012). Figure 4 provides the geological map of the studied area.

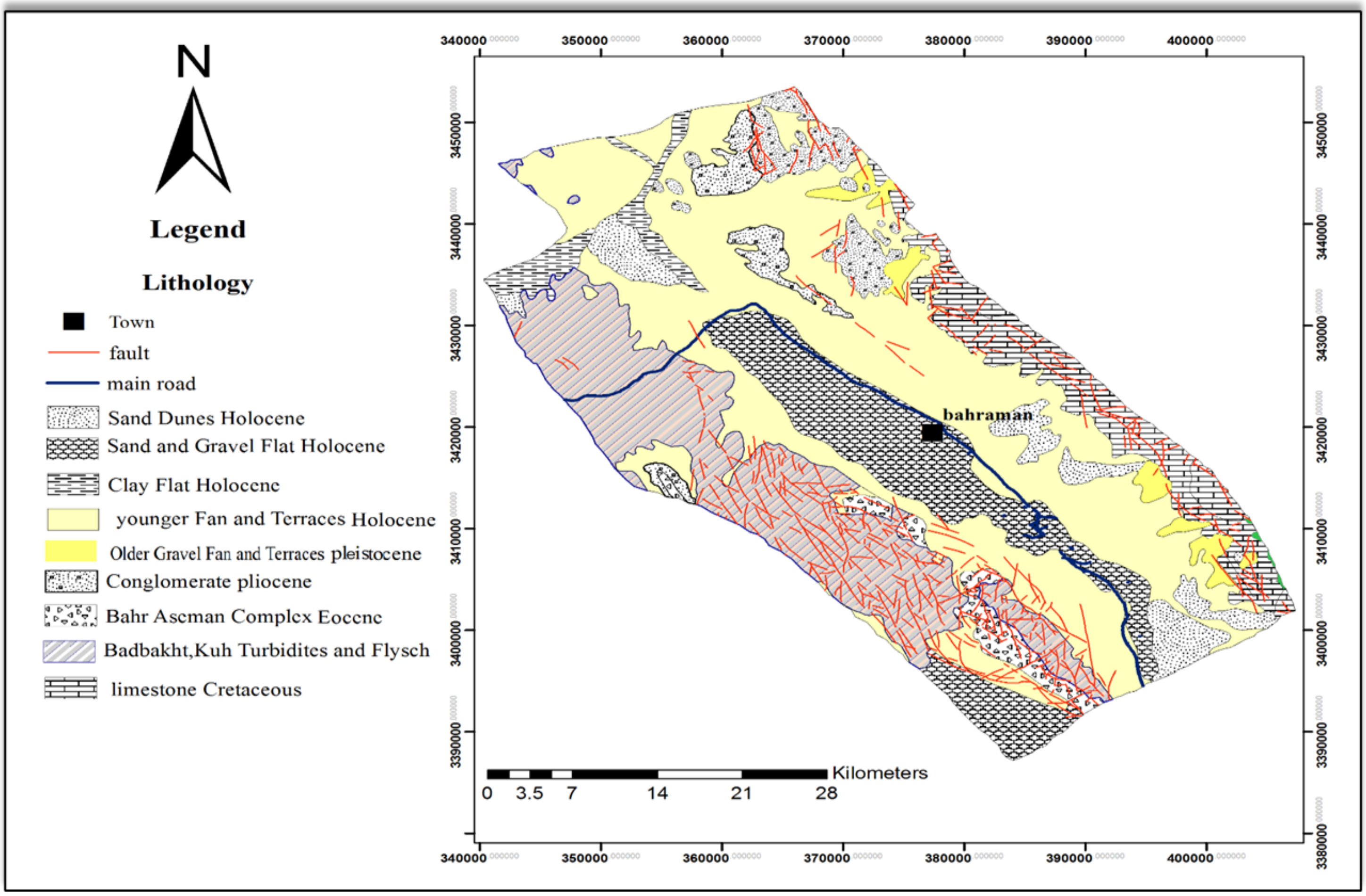

Fig. 4 Geological map for studied region (Geological Survey of Iran, 2009)

In the central areas of the Nogh Plain, particularly in the playas, fine-grained silts and clays accumulate, leading to the formation of saline soils, particularly due to intense evaporation (Beckett, 1958). These soil types in the region primarily consist of a mixture of Aridisols and Antisols, with the northern and southern boundaries of the plain containing Aridisols enriched with calcium carbonate. The northwestern part of the plain is dominated by Aridisols rich in gypsum and salts. Meanwhile, in the mountainous regions, soils are predominantly rocky, while the southeastern part features sand dunes, Dune Lands (Barzegar, 2007). The soil structure and composition vary across the plain, with the central area being characterized by soils typical of cold, dry desert climates. These soils have low to moderate potential for irrigated agriculture and are primarily made up of coarse alluvial deposits and river sediments, which remain dry for most of the year (Aghanabati, 2012). The main soil family in this area is Torri Fluevents, under the Fluvents subgroup of Antisols, with weakly developed profiles and a combination of loamy and clay textures (Alizadeh & Arian, 2015). Additionally, there are secondary soil families such as Haplosalids and Torriorthents (Nowjavan, 2015). Haplosalids belong to the Salids subgroup of Aridisols and are more developed, containing salty horizons, while Torriorthents are less developed, showing signs of weak horizon development and more loamy or clayey textures (Noorizadeh et al., 2018). The northern and southern edges of the plain contain Calsigypsid soils from the Gypsid subgroup of Aridisols, which are adapted to the dry climate and contain almost zero organic matter (Atapour & Aftabi, 2002). These soils also feature gypsum horizons, with coarse to medium texture. The Torriorthents family is also present here, with weakly developed A horizons. In the far northwestern part of the plain, soils are characterized by the presence of gypsum and salts, belonging to the Haplosalids family under the Salids subgroup of Aridisols. These soils are enriched with gypsum and salty horizons, with Torrifluvents found under the Fluvents subgroup of Antisols (Aghanabati, 2012).

Figure 5 provides the soil type and land-cover map of the studied area. Soil plays a crucial role in the transmission of heavy metals and contamination of both the soil and groundwater (Aghamolaie et al., 2019). In arid and semi-arid regions like the Nogh Plain, heavy metals from industrial activities, mining, and agricultural practices often accumulate in the soil. These metals, such as arsenic, lead, and cadmium, can become bound to soil particles, and their mobility depends on factors like soil texture, pH, and organic matter content (Sanjari & Adhami 2019). Coarse-grained soils with low organic matter, as seen in the central part of the Nogh Plain, have less ability to retain heavy metals. Over time, these metals can leach into the groundwater, contaminating local water sources and posing significant risks to public health and the environment. When soil becomes contaminated with heavy metals, it not only affects the soil's health but also compromises its ability to support agriculture and natural vegetation (Afra et al., 2023). The contamination of soil and groundwater by heavy metals is a growing environmental concern. In regions with sandy and saline soils, such as the Nogh Plain, there is a risk of heavy metals leaching into the groundwater due to the lack of adequate filtration. The fine-grained soils in playas are particularly prone to this issue because they cannot effectively trap these pollutants. Furthermore, the intense evaporation process in these areas contributes to the concentration of contaminants like salts and metals in the soil, further exacerbating the contamination of both the soil and the groundwater. This contamination not only disrupts the ecological balance but also poses a serious threat to local communities, affecting water quality and making it unsafe for drinking, irrigation, and other essential uses.

Figure 6 illustrates two key groundwater maps of the study area: (a) the groundwater isodepth contour map and (b) the groundwater level contour map. The groundwater depth map (Figure 6a) is based on data collected from 15 observational wells and represents measurements taken in September 2022. The map indicates that groundwater depth exceeds 140m near the northern highlands, with the maximum observed depth recorded at 121.55m in an observation well east of Panj Qariyeh drinking water well. The shallowest groundwater depth is observed at 19 meters in a monitoring well located north of Mehrabad. The groundwater level contour map (Figure 6a) was created using absolute elevations of observation wells and groundwater level measurements from September 2022. As shown in Figure (6b), the general groundwater flow direction in the Nogh Plain is from the southeast to the northwest. Additionally, in both the northern and southern foothills of the plain, groundwater movement is directed toward the central axis of the basin. This pattern suggests a natural groundwater recharge and discharge system influenced by topography and geological formations in the area. The groundwater flow pattern in the Nogh Plain plays a crucial role in the transport and distribution of contaminants such as arsenic. As groundwater moves from the southeast to the northwest, it can carry dissolved arsenic from natural geological sources or anthropogenic activities, leading to potential contamination in downstream areas. The variation in groundwater depth, particularly the shallower depths in the central and northern regions, increases the risk of arsenic accumulation in water supplies, as prolonged interaction between water and arsenic-bearing minerals can enhance dissolution.

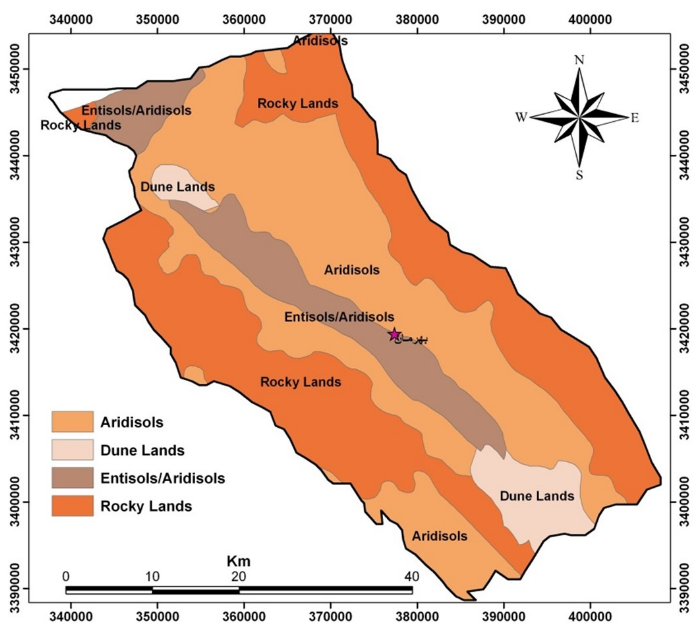

Fig. 5 Soil type and land-cover map of studied region

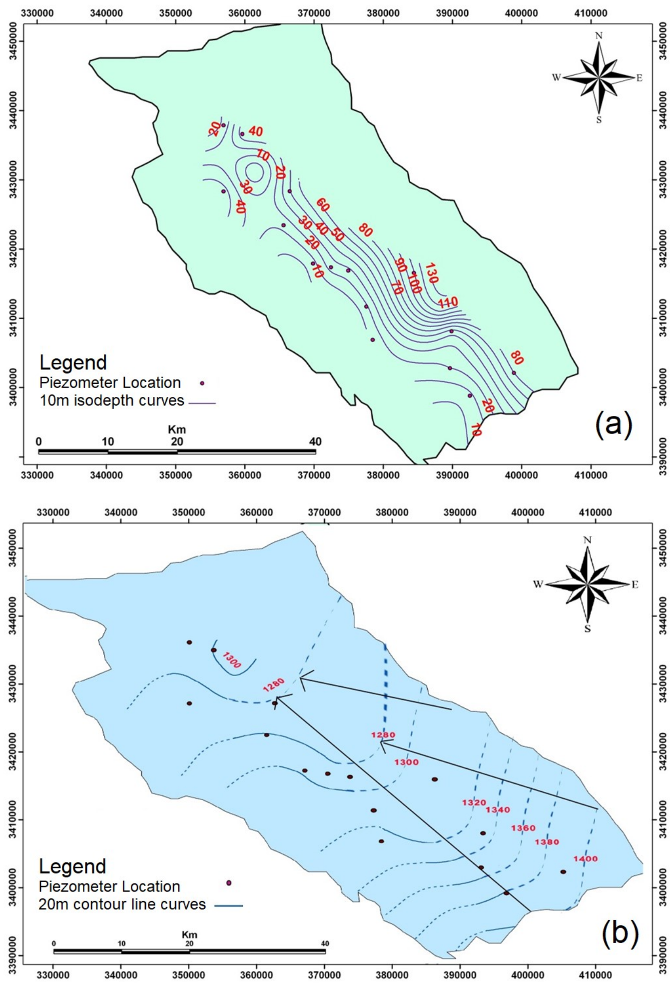

Fig. 6 Groundwater contour maps: (a) Isodepths, (b) levels

IV. Materials and Methods

A systematic methodology was designed to evaluate the groundwater quality in the study area, focusing on the concentrations of major cations, anions, and selected toxic elements such as metalloids and heavy metals. To ensure accuracy and reliability, a structured approach was followed, including precise sample collection (Figure 7), on-site measurements, laboratory analysis, and data interpretation. Given the key role of groundwater in both environmental sustainability and human health, all procedures were carefully executed in accordance with established scientific protocols. To obtain representative samples in this study, a total of 23 groundwater wells were selected across the study area, considering factors such as distribution, depth, potential contamination sources, and hydrogeological characteristics. Sampling was conducted over two consecutive days in early July 2022 to maintain consistency in environmental conditions. Water samples were collected using 1-liter polyethylene bottles, which were pre-cleaned through acid-washing and rinsed with deionized water to prevent contamination. Before sample collection, each bottle was rinsed three times with the sampled water to eliminate any residual impurities. Different preservation methods were applied depending on the type of analysis. For heavy metal analysis, concentrated nitric acid (HNO_3) was added to lower the pH below 2, preventing precipitation, microbial activity, and adsorption onto container walls. Samples for major cation and anion analysis were stored at 4°C to maintain their chemical stability until laboratory testing. In addition to sample collection, key physicochemical parameters were measured directly at each well location to provide an initial assessment of water quality. These measurements included:

- Temperature (°C) determined using a digital thermometer.
- pH measured with a calibrated pH meter.
- Electrical Conductivity (EC, µS/cm) assessed with a conductivity meter.
- Geographical Coordinates recorded using a GPS device to precisely map the sampling points.

These field measurements helped in understanding the initial hydrochemical conditions of the groundwater and provided essential data for later laboratory analysis. After collection, the water samples were carefully transported to specialized laboratories for chemical analysis. The analysis of major cations, anions, and nitrate was conducted at the Rural Water and Wastewater Company, while the detection of heavy metals was carried out at Zar Azma Laboratory in Tehran, ensuring precise results. The following analytical techniques were employed:

- Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for detecting heavy metals.
- Flame Atomic Absorption Spectrometry (FAAS) for measuring sodium (Na) and potassium (K).
- Visible Spectrophotometry for determining nitrate (NO_3^-) and sulfate (SO_4^{2-}) concentrations.
- Titration Methods for analyzing chloride (Cl^-), total hardness, calcium (Ca^{2+}), and bicarbonate (HCO_3^-).
- Digital Instruments for measuring pH and electrical conductivity (EC).

Each analysis was performed following standardized international protocols, ensuring consistency and accuracy in the results. To maintain high accuracy, strict quality control (QC) and quality assurance (QA) measures were implemented throughout the analytical process. Instrument calibration was performed before each analysis, and standard solutions were used to verify measurement accuracy. Duplicate samples and blank tests were included to detect potential contamination or systematic errors. Additionally, the ionic balance was calculated to ensure consistency between the measured cations and anions, further validating the data. To analyze groundwater movement, contour maps of water table depth and groundwater levels were created. Figure 6a presents the groundwater depth map, based on observations from 15 monitoring wells, collected in September 2022. The results indicate that groundwater depths exceed 140 meters near the northern highlands, with the deepest recorded level at 121.55m in a well east of Panj Qaryeh. Conversely, the shallowest depth was recorded at 19m in a well located north of Mehrabad. Additionally, the groundwater level map was developed using data from September 2022, incorporating absolute well elevations and measured water levels. As water moves from the southeastern part of the plain toward the northwest, it has the potential to carry dissolved arsenic and other contaminants from upstream sources toward populated and agricultural areas downstream.

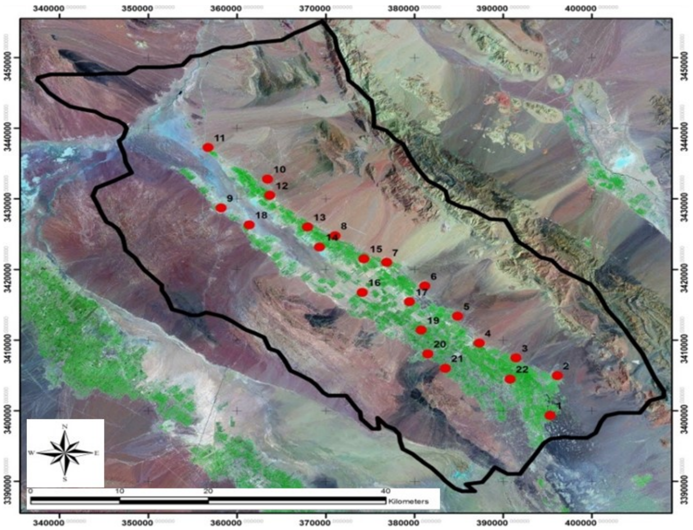

Fig. 7 Sampling locations in studied region

V. Results and Discussion

As is a primary element in over 200 minerals, including elemental As, arsenides, oxides, arsenates, and arsenides. Although these minerals are generally rare, their highest concentrations are found in mineralized areas associated with metals such as Mo, Cd, Pb, Ag, Au, Sb, P, and W. While the abundance of arsenopyrite in sulfide deposits is much lower than arsenic-rich pyrite ($Fe(S,As)_2$), the latter remains the most important source of arsenic in mineralized regions. As is capable of substituting sulfur in the structure of most sulfide minerals. For instance, during the formation of ferromagnesian pyrites, it is quite likely that As may be incorporated into their structure. In oxide and hydroxide minerals, As can also be present in high concentrations. As can often act as a substitute for elements such as Si^{4+}, Al^{3+}, Fe^{3+}, and Ti^{4+} in the crystal structure of many minerals. As a result, arsenic may be present in trace amounts in many rock-forming minerals like albite. Common silicate minerals usually contain less than 1 mg/kg of arsenic, while carbonates typically contain less than 10 mg/kg. Arsenic has four oxidation states: 3^-, 0, 3^+, and 5^+. Arsines, which have an oxidation state of 3^-, are formed through the reduction of arsenic oxides. Arsenic trioxide (As^{3+}) is a product of smelting processes and is used in the synthesis of various arsenic compounds. This compound is catalytically or bacterially oxidized to pentoxide (As^{5+}) or arsenic acid (H_3AsO_4).

As in floodplain soils and water is subject to chemical and microbiological oxidation reactions. Under high Eh conditions, similar to those in oxygen-rich waters, As^{5+} is present in forms such as H_3AsO_4, $H_2AsO_1^-$, $HAsO_2^{2-}$, and AsO_4^{3-}. In lower Eh conditions, As^{3+} species may prevail, including AsS^{2-}. In aerated soils, As^{5+} is the dominant species, while in mineralized areas, arsenite and monomethyl arsenic acid are present in smaller amounts. In anaerobic soils, As^{3+} is the dominant dissolved species. Inorganic arsenic is more mobile than organic arsenic and, therefore, poses greater risks due to leaching into surface and groundwater. According to studies conducted on rainwater, the oxidation states of arsenic vary based on the source. Arsenic emitted from smelters, coal combustion, and volcanic sources is usually in the form of As_2O_3, while organic arsenic species may be released via volatilization. Arsine (AsH_3) can be emitted from landfills and reducing soils like peat, and arsenates can be released via swamp aerosols. Reduced species in the atmosphere may be oxidized by oxygen. In aerated seawater, As(V) is predominantly present. In open ocean water, the As(V)/As(III) ratio typically differs by a factor of 10 to 100. As(V) is also the dominant species in lakes and rivers. The relative proportion of As(V) to As(III) can vary depending on changes in input sources, redox conditions, and biological activity. During summer months, biological reduction of As(V) in oxygenated waters may result in the presence of As(III). In rivers affected by geothermal and industrial activities, As(III) has been observed. The presence of iron and manganese oxides affects the arsenic speciation ratio. Organic arsenic species in surface and groundwater are generally rare. In groundwater, the relative proportion of As(V) to As(III) can vary due to widespread changes in redox conditions, the redox gradient, and historical factors. As(III) is typically abundant in iron- and sulfate-reducing aquifers. In arsenic-rich groundwater in Bangladesh, the As(III)/As(V) ratio varies from 0.1 to 0.9, but is typically around 0.5 to 0.6.

Figure 8 shows the arsenic concentration map for the region's water sources. The arsenic concentration ranges from 0.5 ppb in sample number 9 to 135.9 ppb in sample number 18, with an average of 20.1 ppb in the region's groundwater. This average concentration exceeds global standard limits for arsenic. The concentration of arsenic in samples 18 and 20 is 135.9 ppb and 132.8 ppb, respectively. The high arsenic concentration in these two samples is likely due to the bedrock of the region (the Miocene red series), which has high arsenic content. The cemented surface of the rock's precipitates iron oxides, which absorb arsenic. As the pH increases and the environment becomes more alkaline, arsenic is released from the oxides, resulting in higher arsenic concentrations in groundwater. Additionally, the dissolution of gypsum and salts in the red series contributes to higher concentrations of parameters like EC, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, and Mg^{2+}, while HCO_3^- concentrations are low. The concentration of sample number 1 is 75.1 ppb, primarily fed by limestone bedrock.

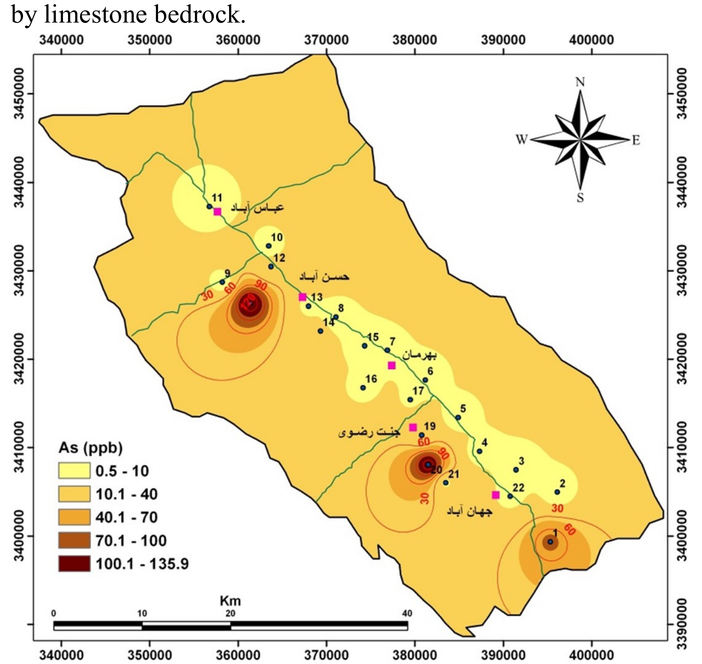

Fig. 8 Arsenic concentration map for the study area

VI. Conclusion

In conclusion, arsenic contamination in the groundwater of the studied region is a significant concern, with concentrations often exceeding global safety standards. Arsenic is present in various minerals, particularly in arsenic-rich pyrite, which is the main source of contamination in the area. The Miocene red series bedrock, rich in arsenic, plays a crucial role in the mobilization of arsenic into groundwater. Iron oxides precipitated on the surface of these rocks adsorb arsenic, which is later released into groundwater as the pH increases and the environment becomes more alkaline. Additionally, the dissolution of gypsum and salts from the red series contributes to elevated concentrations of ions like chloride, sulfate, sodium, calcium, and magnesium, while bicarbonate levels remain low. The concentration of arsenic in the region's groundwater varies significantly, with values ranging from 0.5 ppb to 135.9 ppb. This variation suggests that specific areas, particularly near fault zones and arsenic-rich bedrock, have higher arsenic concentrations. These levels surpass the global standards for arsenic in drinking water, presenting potential health risks for local populations. Given the significant arsenic contamination in the groundwater, addressing the source of pollution and mitigating its impact is critical. Effective water treatment systems, such as the oxidation of As(III) to As(V), should be implemented to reduce arsenic concentrations. Continuous monitoring of arsenic levels is essential to ensure public health safety. Overall, targeted interventions and a thorough understanding of the region's geological and hydrological conditions are key to managing arsenic contamination in the long term.

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Authors' contributions

Batoul Hassanzadeh conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Ahmad Abbasnejad assisted in the development of the methodology and performed validation checks, provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors have not disclosed any competing interests.

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