Pollution and probabilistic human health risk assessment of potentially toxic elements in the soil-water-plant system in the Bolkar mining district, Niğde, south-central Turkey

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Abstract
Globally, potentially toxic elements (PTEs) are regarded as an important group of pollutants for the wider environment because of their intrinsic toxicity and probable accumulation in the soil-water-plant system. In this regard, this study assessed the pollution levels and probable human health risks of PTEs in the soil-water-plant system in the Bolkar mining district of the Niğde Province in south-central Turkey. Pollution assessment using contamination factor, enrichment factor, index of geoaccumulation, and soil pollution index reveals moderate to extremely high pollution of PTEs in the soil, exposing the soils to extreme toxicity levels. The areas that fall under the toxic to extremely toxic categories are in proximity to the ore slags and agricultural lands towards the central and southern domains of the study area. The water hazard index (WHI) values indicate that 100% of the samples collected in both winter and fall seasons are of extreme toxicity (WHI > 15). Arsenic is the dominant contaminant among the PTEs in the soil and water samples. The bioconcentration factor values of the PTEs in most of the fruit plants are > 1, indicating very high levels of element transfer from the soil and water to the plants. The probabilistic human health risk assessment involved exposure to arsenic in groundwater (a major pathway to humans) since it is the only carcinogenic element in this study. The estimated daily intake of arsenic-contaminated water exceeds the safe limit of $5 \times 10^{-8}$ mg/kg/day. About 33.3% and 55.6% of the groundwater samples have higher hazard quotient and carcinogenic risk values of arsenic in the winter and fall seasons, respectively. This implies that the people are more exposed to the carcinogenic effects of drinking arsenic-contaminated water.

Keywords Anthropic activities • Human health risk assessment • Ore slags • Pollution assessment • Potentially toxic elements • Arsenic contamination

Highlights
- Pollution assessment reveals moderate to extremely high pollution of PTEs in the soil.
- Water hazard index values indicate that 100% of the samples are of extreme toxicity.
- Bioconcentration factors show high levels of element transfer from the soil and water to the plants.
- About 55.6% of the samples have high carcinogenic risk values of arsenic in drinking water.

Introduction
Potentially toxic elements (PTEs) are naturally dispersed through various environmental media with acceptable concentrations. However, due to the increasing rate of anthropogenic activities, the PTEs are being re-dispersed resulting in elevated concentrations (Elnazer and Salman 2020). Globally, it is well documented that the main anthropogenic sources of PTEs in the soil-water-plant system are mining activities, agricultural activities, sewage disposal, and industrial and vehicular emissions (Lermi and Ertan 2019; Zango et al. 2019; Kovacheva et al. 2020; Liu et al. 2020; Nganje et al. 2020; Çiner et al. 2021). Among these, mining activities are the dominant routes of PTEs in the soil-water-plant system in metallogenic provinces. Ore slags left after mining can weather thereby releasing PTEs into the soil, which can in turn be

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leached into surface and groundwater resources and then become available for plant uptake. Excessive exposure to PTEs, especially Mn, may lead to mental retardation and in extreme cases, Parkinson’s disease (Li and Yang 2018; Rahman et al. 2021). Over exposure to Cu through industrial and mining activities can lead to liver damage and impairment of the central nervous system, and in some cases, it can lead to lung cancer (Giri and Singh 2017). In addition, most of the non-essential PTEs like Pb, As, Hg, and Cd act as carcinogens and are the cause of many diseases, especially those involving the heart, nervous system, kidney, and bones (Järup 2003; Chiang et al. 2011; Zhan et al. 2014; Sunkari and Danladi 2016; Çiner et al. 2021).

A typical agricultural system involves the soil-water-plant nexus, which is essential for survival of the human race on earth. In this regard, the quality of the soil-water-plant system has become a global concern in the past decades. Although many published works were focused on soil, water, and plant quality, there is paucity of research on assessment of the soil-water-plant system pollution as well as the associated human health risks. A few studies considered the pollution of potentially toxic elements (PTEs) in the soil-water-plant system in some countries like Morocco (El Azhari et al. 2017), Egypt (Salman et al. 2017; Elnazer and Salman 2020), Bangladesh (Alam et al. 2020), Bulgaria (Kovacheva et al. 2020), and Nigeria (Nganje et al. 2020). The significance of these studies in national development is the use of models such as pollution and human health risk assessment indices to understand the sustainability of the soil–water–plant system in food production, to determine the sources and dispersion mechanisms of PTEs.

Human beings can be exposed to PTEs through consumption of water and food, inhalation of soil particles, and ingestion of soil (geophagia) (Elnazer and Salman 2020). Among all these routes, dietary intake of polluted food happens to be the principal route of PTEs in the human system (Ji et al. 2013). Pollution of foodstuff with PTEs is mostly due to soil pollution, which is a major setback to agricultural productivity in many parts of the world (Chauhan et al. 2018). Therefore, considering the intrinsic toxicity of PTEs and their potential accumulation in the soil-water-plant system, they are globally regarded as an important group of pollutants for the wider environment and thus the need for human health risk assessment (Ngole-Jeme 2016). The potential human health risks from PTEs are generally assessed by carcinogenic and non-carcinogenic risk assessment methods such as lifetime exposure level (ADDlife) and hazard quotient (HQ) (Chen et al. 2018). By the use of these methods, the level of pollution loading can be ascertained, which will provide useful constraints to scale and determine potential health risks. In terms of the effect of the PTEs on plants, the bioconcentration factor (BCF) also referred to as biological adsorption coefficient (BAC) is widely used to determine the accumulation levels of PTEs from soil to plants (Kabata-Pendias 2011; Jiang et al. 2020; Luo et al. 2020; Nganje et al. 2020). However, contamination factor (CF), enrichment factor (EF), index of geoaccumulation (Igeo), and soil pollution index (PI) have been effectively used to estimate the extent of soil contamination by PTEs (e.g., Darwish and Pöllmann 2015; Kowalska et al. 2018; Dan-Badjo et al. 2019; Kabala et al. 2020; Lermi and Sunkari 2020; Nganje et al. 2020).

The Bolkar mining district is an ancient metallogenic province that has been under exploration since the 1880s. The ore deposits in this area are mostly chromite and Sb-W-Hg-Au deposits (Akçay 1995), Mn deposits (Öztürk 1997; Lermi et al. 2016), MVT- and CRD-type Pb and Zn deposits (Hanilçi and Öztürk 2011; Hanilçi 2019), Fe-Zn skarn deposits Kusçu (2019), and bauxite, Al, and Fe-rich laterite deposits (Hanilçi 2013; Hanilçi 2019). Exploration and mining of these deposit types have left abundant ore slags (Fig. 1) in the area that are continuously being weathered and dispersed. Despite this threat to the soil-water-plant quality and human health, no study has documented the pollution levels and human health risks of PTEs derived from the ore slags to the soil-water-plant system. Therefore, this study is aimed at assessing the pollution levels of PTEs in the soil-water-plant system in the Bolkar mining district of the Niğde Province in south-central Turkey by using pollution indices like contamination factor, enrichment factor, index of geoaccumulation, soil pollution index, water hazard index, and bioconcentration factor. The current study is also aimed at appraising the probabilistic human health risks associated with the exposure of PTEs in the groundwater resources within the soil-water-plant system since they are the major pathways of PTEs to humans residing in the study area. The soil and plants were not assessed for human health risks because the contaminated water is what is used to irrigate plants, which also reaches the soil, and thus, water was considered the major pathway for transfer of PTEs from the environment to humans.

Materials and methods

Study area

The study area is located in Gümüş village of the Niğde Province in the Central Anatolian Part of Turkey (Fig. 1). The climatic conditions prevailing in this area reflect that of continental climate where there is a period of dryness in the summer season and wetness in the winter season. The study area is bounded by high altitude mountains up to 3200 m above sea level. The highest average precipitation is about 58 mm and mostly occurs in May, whereas the least average precipitation is about 5 mm and occurs in August. Temperatures are usually low to about −5°C in January, whereas relatively high temperatures up to 22°C are usually
recorded in July. The main rocks in the area are metamorphic rocks such as marble and schist and volcano-sedimentary rocks like pyroclastics, pillow lavas, andesite, basalt, limestone, and dolomite, which are intruded by granitoids in some places (Fig. 1; Clark and Robertson 2002; Alpaslan et al. 2006; Lermi and Sunkari 2020). There are abundant ore slags in most parts of the study area, which are remnants of the ancient mining activities and the numerous active mines in which polymetallic deposits are being explored and exploited (Fig. 1).

Sample collection

A total of 40 composite samples were collected from the A and B horizons of the soil profile in the area because these horizons appear to be the most contaminated from a preliminary survey. The collected samples were sent to the ACME Analytical Laboratories, Vancouver, Canada, for analysis of PTEs using ICP-MS method. One control soil sample from Lermi and Sunkari (2020) was used in this study. A total of 20 groundwater samples (10 samples each from the winter and summer seasons) were collected in 500-ml polyethylene bottles, acidified with nitric acid to a pH < 2 (Lermi and Ertan 2019) and then sent to the ACME Analytical Laboratories, Vancouver, Canada, for analysis of PTEs using Ultra trace ICP-MS method. For the plants, leaves of fruit plants were used in the analysis because the leaves reflect 1 year of element absorption and thus, they are the best sample medium for geochemical prospection and analysis (Kabata-Pendias 2011). In this regard, leaves of the fruit plants were collected in paper bags, washed, dried, ground in agate mortar, and filtered with a 100 mesh sieve (Dan-Badjo et al. 2019; Wang et al. 2019). About 1 g of the ground samples was acidified and analyzed in aqua regia by means of Ultra trace

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Pollution assessment

Contamination factor (Cf)

Contamination factor (Cf) is mostly used to assess the extent of soil pollution by PTEs, especially the metallic PTEs. In this study, the Cf was calculated from the equation (1) after Hakanson (1980):

\[
Cf = \frac{C_{PTE}}{C_{BV}}
\]

where Cf is the contamination factor, \( C_{PTE} \) is the concentration (ppm) of each PTE, and \( C_{BV} \) is the background value (ppm) of each PTE, which is the world average crustal value. The Cf values calculated from the above equation were interpreted according to the four classes of contamination of Hakanson (1980); Cf < 1 (low contamination), 1 ≤ Cf ≤ 3 (moderate contamination), 3 ≤ Cf ≤ 6 (considerable contamination), and Cf > 6 (very high contamination).

Enrichment factor (EF)

The EF was calculated by comparing the concentrations of the individual PTEs in the soils against average crustal values or unpolluted soil using data from Bowen (1979). Aluminum was used as the normalization element because of its conservative nature even under extreme pedogenic processes (Ettler et al. 2006). The EF values of the studied soils were calculated from Equation 2:

\[
EF = \frac{(C_i/C_{Al})_s}{(C_i/C_{Al})_b}
\]

where \( C_i/C_{Al}s \) is the PTE/Al ratio in the samples and \( C_i/C_{Al}b \) is the PTE/Al ratio in the background sample (unpolluted soil). For assessing the enrichment levels of the individual PTEs, five classes have been suggested by Andrews and Sutherland (2004); EF < 2 (minimal pollution), EF 2–5 (moderate pollution), EF 5–20 (significant pollution), EF 20–40 (high pollution), and EF > 40 (extreme pollution).

Index of geoaccumulation (Igeo)

The level of anthropogenic influence of each PTE on the soil was assessed using the index of geoaccumulation (Igeo) by Müller (1979), Equation 3:

\[
I_{geo} = \log_2 \left( \frac{C_n}{1.5B_n} \right)
\]

where \( C_n \) is the PTE (n) concentration (ppm) and \( B_n \) represents the background concentration (ppm) of that PTE (n) in the average shale. The factor 1.5 permits assessment of the fluctuations of the natural content of the PTE in the environment (Wei et al. 2009). The interpretation of the calculated Igeo values was based on the classification scheme of (Müller 1979); Igeo < 0 (no pollution), 0 ≤ Igeo ≤ 1 (no to moderate pollution), 1 ≤ Igeo ≤ 2 (moderate pollution), 2 ≤ Igeo ≤ 3 (moderate to heavy pollution), 3 ≤ Igeo ≤ 4 (heavy pollution), 4 ≤ Igeo ≤ 5 (heavy to extreme pollution), and Igeo > 5 (extreme pollution).

Soil pollution index (PI)

The contamination of PTEs in soil, especially in mining areas is usually a combination of several contaminants rather than a single element (Lee et al. 2006). In this regard, the concept of soil pollution index (PI) has become an effective way of assessing the combined influence of multi-elements on soils (Dan-Badjo et al. 2013, 2019; Nganje et al. 2020). The PI is a criterion for assessing the overall toxicity of PTEs and its computation varies among different workers but the basic concept is the same. In this study, the PI of the soil was computed as the average ratio of metal concentration in the soil samples to background values of the metals (Bowen 1979) from Equation 4:

\[
PI = \left\{ \frac{As}{5} + \frac{Cd}{0.06} + \frac{Co}{29} + \frac{Cu}{30} + \frac{Hg}{0.03} + \frac{Mo}{2} + \frac{Ni}{40} + \frac{Pb}{20} + \frac{Zn}{50} \right\}/9
\]

where As, Cd, Co, Cu, Hg, Mo, Ni, Pb, and Zn are the concentrations (ppm) of these PTEs in the soil samples, whereas the denominators are their background values (ppm) in unpolluted soil (Bowen 1979; Lindsay 1979). PI > 1 indicates that the soil is polluted by several PTEs owing to anthropogenic input. Generally, PI values < 5 indicate low toxicity, PI values between 5 and 10 indicate slight toxicity, PI values between 10 and 20 indicate moderate toxicity, and PI values > 20 indicate extreme toxicity (Chon et al. 1996).

Water hazard index (WHI)

The water hazard index (WHI) was used in assessing the overall impact of the PTEs on water resources in the study area.
area. It was computed as a ratio of the concentration of the individual PTEs to their maximum guideline values for drinking water in Turkey (TSE-266 2005). Equation 5 below was used for the computation of the WHI:

\[
\text{WHI} = \sqrt[5]{\left(\frac{\text{As}}{0.01}\right) + \left(\frac{\text{Cu}}{3}\right) + \left(\frac{\text{Sb}}{0.01}\right) + \left(\frac{\text{Pb}}{0.05}\right) + \left(\frac{\text{Zn}}{5}\right)}
\]

where As, Cu, Sb, Pb, and Zn are the concentrations (ppm) of these PTEs in the water samples, and the denominators are their standard guideline values (ppm) in drinking water obtained from the Turkish Standards Institute (TSE-266 2005). The following categories of interpretation of the computed WHI values (Nсанje et al. 2020) were used: WHI < 5 (low to minimal toxicity), 5 \(\leq\) WHI \(\leq\) 10 (slightly toxic), 10 \(\leq\) WHI \(\leq\) 15 (moderately toxic), and WHI > 15 (extremely toxic).

**Bioconcentration factor (BCF)**

The bioconcentration factor (BCF) is used to evaluate the accumulation levels of plants for the PTEs (Wang et al. 2019). It was calculated using Equation 6:

\[
\text{BCF} = \frac{\text{CMIP}}{\text{CMIS}}
\]

where CMIP is the concentration (ppm) of the metal in the plants and CMIS is the concentration (ppm) of the metal in the soil.

**Probabilistic human health risk assessment**

**Exposure assessment**

The exposure assessment reveals the routes and pathways through which humans are exposed to contaminants and estimates the amount, frequency, and duration of exposure. In this study, the exposure assessment was limited to the water medium since the people largely depend on groundwater for drinking and irrigation purposes. The PTEs considered in this assessment include As, Cd, Ni, Pb, and Zn based on their elevated concentrations in groundwater. The average daily dose (ADD) of the contaminant in the water was computed using the model of the United States Environmental Protection Agency (USEPA 1997; 2004).

\[
\text{ADD} = \frac{C \times \text{IR} \times \text{ED} \times \text{EF}}{\text{BW} \times \text{AT}}
\]

where C is the concentration of the PTE in the water (mg/L), IR represents the ingestion rate (2 L/day) taken from (USEPA 2004), ED is the exposure duration (years) to the PTEs and according to the archives of the USEPA (USEPA 1997), 30 years is used, EF denotes the exposure frequency (days/year) taken as 365 days/year (USEPA 2004), BW is the average body weight (kg) (61.75) from Çiner et al. (2021), AT is the average time of exposure (d), and in this study, for the non-carcinogenic risk, AT = ED \times 365 and for carcinogenic risk, AT = 77,434 \times 365 since 77,434 is the average life expectancy of people living in Turkey (Karacan et al. 2020).

**Non-carcinogenic risk assessment**

Non-carcinogenic risk refers to toxic risks that are not up to the extent of causing cancers but cause harm to consumers due to exposure to PTEs. It is mostly computed in terms of hazard quotient (HQ):

\[
\text{HQ} = \frac{\text{ADD}}{\text{RfD}}
\]

where RfD is the reference dose, which is taken from the United States Integrated Risk Information System for the individual PTEs (USEPA 2011). The RfD for As, Ni, Pb, Zn, and Sb are \(3 \times 10^{-4}, 2 \times 10^{-2}, 3.5 \times 10^{-3}, 3 \times 10^{-1},\) and \(4 \times 10^{-4}\) mg/kg/day, respectively. In assessing the non-carcinogenic risk, if the computed HQ exceeds 1, then it is interpreted that there is a potential health risk with respect to the particular element.

**Carcinogenic risk assessment**

Among the PTEs detected in the water samples in the study area, only arsenic is a carcinogen. Therefore, the carcinogenic risk (CR) associated with exposure to the intake of arsenic through the water samples collected from the study area was computed using the model of the USEPA (1989):

\[
\text{CR} = \text{ADD}_{\text{life}} \times \text{SF}
\]

where ADD_{life} is the lifetime exposure level and is calculated by estimating the exposure suffered during the exposure duration over the life expectancy of the individual. SF (mg/kg/day) is the slope factor, which indicates the probability of having cancer due to exposure to arsenic. The SF for arsenic according to USEPA (2011) is 1.5 mg/kg/day. Computed CR values above \(1 \times 10^{-4}\) suggest that there is a carcinogenic risk with respect to exposure to arsenic for both children and adults (Zhang et al. 2019).

**Results and discussion**

**Soil pollution levels with PTEs**

Statistical summaries of concentrations of PTEs in the soil and the pollution assessment are given in Tables 1 and 2, respectively. The PTEs vary in the order Au < Th < U < Co < Bi < Mo < Ag < V < Sr < Sb < Ni < Cu < Mn < Zn < Hg < Cd < Pb.
As (Table 1), indicating that As is the most dominant potentially toxic element in the soil samples. In terms of contamination factors (CF), only Mn and Co are in the class of low to moderate contamination, whereas As, Cd, Cu, Mo, Pb, Zn, and Sb fall in the class of low to very high contamination. However, Ni is in the class of moderate to very high contamination. The computed enrichment factor (EF) values also show that Mn is in the class of moderate to significant pollution, Co in the class of moderate to high pollution, and As, Cd, Cu, Mo, Pb, Zn, and Sb in the class of minimal to extreme pollution. But the EF values of Ni show significant to extreme pollution. Accordingly, EF values of soil that ranges from 0.5 to 1.5 indicate that PTEs in the soil are mostly coming from crustal or geogenic sources, whereas EF values higher than 1.5 reflect large input from anthropogenic sources (Zhang and Liu 2002; Lermi and Sunkari 2020). In the current study, the mean EF values for the investigated PTEs are all above 1.5, indicating that contribution from slag piles in the area and agricultural activities, which are the main anthropogenic sources of PTEs, is intense. For the Index of geoaccumulation ($I_{geo}$) values, Mn and Co fall in the class of no to moderate pollution; Mo is in the class of no to heavy pollution, whereas As, Cd, Cu, Pb, Zn, and Sb are in the class of no to extreme pollution. Nevertheless, Ni is distinctly within the moderate to heavy pollution class. This suggests that the results of the CF, EF, and $I_{geo}$ assessments corroborate with each other. Thus, it is clear that the soil samples have varied levels of pollution with regard to Mn, As, Cd, Co, Cu, Mo, Pb, Zn, and Sb.

The values computed from the soil pollution index (PI) assessment revealed that the PI values ranged from 2.51 (low toxicity potential) to 407 (extreme toxicity potential) (Table 1). All the samples have PI values > 1 (Table 1), suggesting that relatively high contents of PTEs are mobilized in the soils of the historical Bolkar mining area, rendering them extremely toxic. The lowest PI values are around the areas without mines and uncultivated for crops. These areas do not have ore slag piles, which accounted for the low accumulation of the PTEs (Fig. 2). However, the areas that fall under the toxic to extremely toxic classes are in proximity to the ore slag piles and agricultural lands towards the central and southern domains of the study area (Fig. 2). This confirms the fact that the proximity of the ore slags to the soil sampling sites is a contributory factor to the pollution of the PTEs in the soil.

### Water pollution levels with PTEs

Statistical summary of the concentrations of PTEs in the water samples is given in Table 3. Among the PTEs, arsenic (As) has the highest concentration ranging from 0.80–287 μg/L with a median of 2.90 μg/L in the winter season, whereas the concentration varied from 1.20 to 373 μg/L with
am e d i a no f9 μg/L in the fall season (Table 3). The water hazard index (WHI) values indicate that 100% of the samples collected in both seasons are of extreme toxicity (Fig. 3). The combined effect of multi-PTEs is therefore very evident in the studied water samples. During the winter season, the WHI values varied in the range of 35.9–6334 (Fig. 3), whereas in the fall season, the WHI values significantly increased from 42.6 to 8805 (Fig. 3). Certainly, the water in the vicinity of the ore slags is highly polluted and thus detrimental to human health.

Bioaccumulation effect of PTEs in plants

Table 4 contains statistical summary of the concentrations of PTEs in plants in this study. The average concentrations of the PTEs in the fruit plants vary in the order of Zn < As < Pb < Fe, implying that Fe is the most enriched element in the plants. Plants can only absorb some of the elements in the soil through cation exchange. Accordingly, the most suitable amount of elements for biological nutrition is equivalent to the amounts in groundwater (Nguyen et al. 2005). In this regard, to clearly understand the bioaccumulation capacities of the plants, the bioconcentration factors (BCF) were computed. The BCF is a factor that indicates the degree of the plant to absorb PTEs from the surrounding water resources (Nguyen et al. 2005). The results indicate that the fruit plants in the region copiously absorb Fe, Pb, Zn, and As and act like bio-accumulators (Table 4). Moreover, the BCF for most of the fruit plants are > 1 (Table 4), indicating very high levels of element transfer from the soil and water to the plants. This is attributed to the high solubility of most secondary minerals in the area under alkaline conditions (Kabata-Pendias qo11). Bioaccumulation of PTEs by plants is potentially detrimental to the organisms that feed on the leaves and fruits of these plants and may cause undesirable disorders in the long term. Essentially, the high BCF values suggest that human health and plant growth in the region are under jeopardy. Therefore, the stakeholders in the area should take necessary measures to curtail the menace.

Constraints from probabilistic human health risk assessment

In terms of the computed estimated daily intake (EDI) values for the various PTEs, arsenic (As) appears to be the element dominant in groundwater in both seasons and the people are more exposed to the intake of arsenic-contaminated groundwater than the other PTEs (Tables 5 and 6). The EDI values of As range from 0.00003 to 0.00929 mg/kg/day in the winter season (Table 5), whereas they range from 0.00011 to 0.01206 in the fall season (Table 6). All the samples in both seasons have EDI values exceeding the safe limit of 5 × 10⁻⁸ mg/kg/day indicating that the inhabitants of the study area are all exposed to the health implications emanating from the intake of As-contaminated water (Zhang et al. 2019). The results obtained in this study can be compared with that of Zhang et al. (2019) and Barzegar et al. (2019) who reported higher EDI values of As in groundwater in China and Iran, respectively.

The USEPA (1989) indicated that when the hazard quotient (HQ) values of groundwater in any environment exceeds the threshold of 1, then there is a potential health risk associated with the consumption of water contaminated with PTEs. This study reports higher HQ values for As in the winter season (0.08637–30.97436; Table 5) and fall season (0.12955–40.21592; Table 6). About 33.3% of the water samples have higher HQ values of As in the winter season, whereas 55.6% of the water samples have higher HQ values of As in the fall season. Comparing this with the EDI values in both seasons, it can be concluded that the residents of the study area...
drink more water in the fall season due to the high temperature conditions and are thus more exposed to the non-carcinogenic effects of drinking groundwater enriched in arsenic. Apart from As, in the winter season, one sample representing...
11.1% of the total samples has HQ value with respect to Pb > 1 and 2 samples representing 22.2% of the total samples also have HQ values with respect to Sb > 1 (Table 5). However, in the fall season, only 2 samples have HQ values with respect to Sb exceeding the safe limit of 1 (Table 6).

The carcinogenic risk (CR) is expressed in terms of the probability that one is likely to have cancer owing to the intake of arsenic-contaminated water during a lifetime exposure of approximately 77 years, since that is the life expectancy age for people living in Turkey (Karacan et al. 2020). The CR of being exposed to As by the drinking water is in the range of 0.00002 to 0.00540 in the winter season (Table 5). This suggests that some of the samples have high CR values in view of the safe limit of $1 \times 10^{-4}$. Just like the HQ values for As, approximately 33.3% of the samples have CR values above the safe limit (Table 5). Moreover, the CR values are relatively higher in the fall season varying in the range of 0.00002 to 0.00701 (Table 6). It is also worth mentioning that the CR values exceed the safe limit of $1 \times 10^{-4}$ in almost 55.6% of the samples in the fall season, similar to the trend shown by the HQ values with respect to As in the fall season (Table 6). Definitely, the As concentrations in the water samples are extremely high exposing the people to the risk of carcinogenesis or keratinization of the skin (Çiner et al. 2021). This calls for a great deal of attention by the government and key stakeholders in the historical Bolkar mining area within the Niğde Province. The results of this study have provided evidence for a nexus among soils, plants, and water in the area.

**Conclusion**

This study was conducted to assess the pollution levels and probable human health risks associated with the dispersion of
| Fruit plant type | Walnut | Cherry | Pear | Plum | Grape |
|-----------------|--------|--------|------|------|-------|
| PTEs            | Min    | Max    | Mean | Median | Min    | Max    | Mean | Median | Min    | Max    | Mean | Median | Min    | Max    | Mean | Median | Acceptable limit | Toxic level | BCF |
| Fe              | 150    | 3380   | 752  | 240   | 160    | 11270  | 1432 | 245    | 180    | 380    | 325  | 335    | 250    | 380    | 325  | 335    | 200    | 3.80–4.50    |
| Mn              | 48.0   | 205    | 124  | 113   | 19.0    | 90.0   | 37.1 | 38.0   | 27.0   | 205    | 69.1 | 48.0   | 26.0   | 54.0   | 39.0 | 36.0   | 3.20   | 2.40–3.20    |
| Ni              | 0.70   | 7.10   | 2.80 | 2.25  | 0.70    | 4.60   | 2.61 | 2.10   | 1.50   | 15.7   | 6.09 | 5.50   | 1.60   | 6.50   | 2.93 | 2.60   | 1.00   | 0.10–3.70    | 10.0   | 2.20–2.70    |
| Co              | 0.10   | 0.30   | 0.20 | 0.13  | 0.07    | 0.26   | 0.14 | 0.20   | 0.07   | 1.71   | 0.57 | 0.43   | 0.08   | 0.31   | 0.17 | 0.15   | 0.07   | 0.28–0.15    | 0.13   | 2.20–2.70    |
| Mo              | 0.20   | 2.30   | 1.00 | 0.64  | 0.02    | 2.46   | 0.37 | 0.23   | 0.12   | 6.16   | 0.97 | 0.24   | 0.01   | 1.17   | 0.50 | 0.41   | 0.07   | 0.70–1.75    | 0.13   | 2.20–2.70    |
| Cu              | 3.30   | 31.6   | 8.90 | 4.65  | 6.14    | 33.6   | 10.1 | 11.0   | 6.00   | 106    | 19.4 | 9.97   | 3.07   | 10.2   | 7.42 | 7.65   | 4.77   | 8.98–6.70    | 6.53   | 5.00–10.00   | 20.0   | 2.80–3.30    |
| Pb              | 1.70   | 1185   | 221  | 28.9  | 2.68    | 1150   | 135  | 65.1   | 1.61   | 4443   | 490  | 21.62  | 2.98   | 195    | 32.7 | 32.6   | 2.76   | 62.8–32.7    | 32.6   | 5.00–10.00   | 30.0   | 3.30–4.50    |
| Zn              | 9.40   | 257    | 66.1 | 27.0  | 8.50    | 206    | 37.1 | 32.4   | 11.7   | 846    | 119  | 37.7   | 8.60   | 62.5   | 25.3 | 25.9   | 13.2   | 35.3–25.1    | 25.9   | 2.50–3.10    |
| Ag              | 0.00   | 0.29   | 0.05 | 0.01  | 0.00    | 0.29   | 0.03 | 1E-05  | 0.00   | 0.96   | 0.10 | 0.00   | 0.00   | 0.03   | 0.01 | 0.01   | 0.00   | 0.02–0.01    | 0.01   | 2.20–2.70    |
| As              | 0.60   | 192    | 37.2 | 7.00  | 0.70    | 181    | 21.2 | 17.0   | 0.30   | 527    | 59.7 | 3.70   | 0.50   | 27.4   | 7.08 | 6.00   | 0.40   | 4.60–2.40    | 4.50   | 0.009–1.50   | 5.00   | 1.80–3.00    |
| Cd              | 0.01   | 0.07   | 0.03 | 0.02  | 0.01    | 0.07   | 0.02 | 0.02   | 0.01   | 0.46   | 0.14 | 0.08   | 0.01   | 0.05   | 0.02 | 0.02   | 0.01   | 0.03–0.02    | 0.02   | 1.50–2.50    |
| Sb              | 0.05   | 21.7   | 4.09 | 0.48  | 0.07    | 22.1   | 24.1 | 1.25   | 0.04   | 60.6   | 6.71 | 0.29   | 0.05   | 2.76   | 0.67 | 0.47   | 0.05   | 0.87–0.46    | 0.45   | 2.60–3.80    |
| Cr              | 0.90   | 2.90   | 1.42 | 1.15  | 1.00    | 2.30   | 1.41 | 1.80   | 1.00   | 7.10   | 1.94 | 1.30   | 1.00   | 1.70   | 1.32 | 1.30   | 1.10   | 2.20–1.50    | 1.35   | 2.20–1.50    |
| Ti              | 9.00   | 19.0   | 12.3 | 11.5  | 9.00    | 17.0   | 11.1 | 12.0   | 10.0   | 37.0   | 15.5 | 13.0   | 11.0   | 41.0   | 16.7 | 14.0   | 11.0   | 19.0–13.8    | 12.5   | 11.0–13.8    |
| Se              | 0.20   | 0.50   | 0.32 | 0.30  | 0.10    | 0.50   | 0.28 | 0.30   | 0.10   | 0.50   | 0.32 | 0.30   | 0.20   | 0.40   | 0.31 | 0.30   | 0.10   | 0.40–0.28    | 0.30   |                  |
| Au              | 3.30   | 91.5    | 29.4 | 16.1  | 3.70    | 31.8   | 12.7 | 15.0   | 3.40   | 115    | 30.2 | 10.2   | 4.10   | 54.6   | 18.7 | 12.6   | 4.00   | 9.70–6.85    | 6.85   |                  |
| B               | 95.0   | 277    | 179  | 176   | 29.0    | 91.0   | 54.9 | 29.0   | 23.0   | 83.0   | 37.5 | 34.5   | 30.0   | 67.0   | 42.7 | 42.0   | 28.0   | 54.0–39.8    | 38.5   |                  |
| Hg              | 13.0   | 28.0   | 20.2 | 20.5  | 9.0     | 32.0   | 19.8 | 32.0   | 9.00   | 41.0   | 21.2 | 21.0   | 12.0   | 19.0   | 15.9 | 15.0   | 6.00   | 20.0–13.0    | 13.0   | 0.002–0.086   |
potentially toxic elements (PTEs) into the soil-water-plant system of the Bolkar mining district in south-central Turkey. The soil samples have soil pollution index values > 1, suggesting that relatively high contents of PTEs are in the soils of the historical Bolkar mining area, exposing the soils to extreme toxicity levels. Other pollution assessment indexes such as contamination factor, enrichment factor, and index of geoaccumulation reveal that the soils are moderately to extremely polluted with respect to the PTEs. For the water samples, 100% of the samples collected in both winter and fall seasons show extreme toxicity (WHI > 15) for the PTEs. The fruit plants also show high levels of bioaccumulation in terms of their Fe, Pb, Zn, and As concentrations. The human health risk assessment indicates that the water poses significant cancer risks due to the high arsenic content. The carcinogenic risk is associated with 55.6% of groundwater in the area, raising an alarm for the vulnerable population. In all, this study has provided significant data for the monitoring and management of mine waste in the historical Bolkar mining district.

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### Availability of data and material (data transparency)

All data used in the study will be readily available to the public.

#### Table 5  Health risk assessment of groundwater in the winter season

| Sample | As   | Ni   | Pb   | Zn   | Sb  | As   | Ni   | Pb   | Zn   | Sb  | As   |
|--------|------|------|------|------|-----|------|------|------|------|-----|------|
| GS1a   | 0.00003 | 0.00020 | 0.0001 | 0.0059 | 0.0001 | 0.008637 | 0.00130 | 0.02128 | 0.01965 | 0.01296 | 0.00002 |
| GS1b   | 0.00006 | 0.00011 | 0.0002 | 0.0025 | 0.0002 | 0.21592 | 0.00324 | 0.06570 | 0.00837 | 0.03887 | 0.00004 |
| GS2    | 0.00011 | 0.00008 | 0.0005 | 0.0003 | 0.0001 | 0.37787 | 0.00567 | 0.15639 | 0.00111 | 0.01457 | 0.00007 |
| GS3    | 0.00029 | 0.00009 | 0.0001 | 0.0010 | 0.00095 | 30.97436 | 0.46462 | 0.02313 | 0.00342 | 2.36761 | 0.00540 |
| GS4    | 0.000736 | 0.00030 | 0.0044 | 0.0017 | 0.00069 | 24.52901 | 0.36794 | 1.24558 | 0.01460 | 1.71903 | 0.00428 |
| GS5    | 0.00003 | 0.00027 | 0.0001 | 0.0011 | 0.0001 | 0.09717 | 0.00146 | 0.03054 | 0.00371 | 0.02753 | 0.00002 |
| GS6    | 0.00004 | 0.00018 | 0.0001 | 0.0013 | 0.0001 | 0.12955 | 0.00194 | 0.02684 | 0.00425 | 0.01700 | 0.00002 |
| GS7    | 0.00105 | 0.00013 | 0.0001 | 0.0003 | 0.00014 | 3.50877 | 0.05263 | 0.15639 | 0.00111 | 0.01457 | 0.00007 |
| GS8    | 0.00015 | 0.00015 | 0.0001 | 0.0002 | 0.0003 | 0.49663 | 0.00745 | 0.15639 | 0.00111 | 0.01457 | 0.00002 |
| GS9    | 0.00007 | 0.00010 | 0.0001 | 0.0002 | 0.0003 | 0.24831 | 0.00372 | 0.01943 | 0.00070 | 0.06802 | 0.00004 |
| Safe limits | 5 × 10⁻⁸ | 2 × 10⁻² | 2.5 × 10⁻² | 7 × 10⁻³ | 6 × 10⁻³ | 1 | 1 | 1 | 1 | 1 | 1 × 10⁻⁴ |

#### Table 6  Health risk assessment of groundwater in the fall season

| Sample | As   | Ni   | Pb   | Zn   | Sb  | As   | Ni   | Pb   | Zn   | Sb  | As   |
|--------|------|------|------|------|-----|------|------|------|------|-----|------|
| GS1a   | 0.00003 | 0.00013 | 0.0008 | 0.0035 | 0.0006 | 1.20918 | 0.00063 | 0.24153 | 0.01171 | 0.13927 | 0.00021 |
| GS1b   | 0.00088 | 0.00085 | 0.0021 | 0.0111 | 0.0011 | 2.94737 | 0.00423 | 0.60521 | 0.03696 | 0.26397 | 0.00051 |
| GS2    | 0.00022 | 0.00002 | 0.0001 | 0.0001 | 0.0001 | 0.72335 | 0.00010 | 0.3609 | 0.00427 | 0.07773 | 0.00013 |
| GS3    | 0.01206 | 0.00002 | 0.0006 | 0.0003 | 0.00208 | 40.21592 | 0.00010 | 0.15824 | 0.00108 | 5.20729 | 0.00701 |
| GS4    | 0.000617 | 0.00001 | 0.0006 | 0.0030 | 0.00085 | 20.56680 | 0.00003 | 0.17490 | 0.01001 | 2.12308 | 0.00359 |
| GS5    | 0.00004 | 0.00023 | 0.0001 | 0.0002 | 0.0001 | 0.12955 | 0.00113 | 0.02591 | 0.00079 | 0.02753 | 0.00002 |
| GS6    | 0.00015 | 0.00010 | 0.0002 | 0.0087 | 0.00005 | 0.50742 | 0.00049 | 0.06015 | 0.02910 | 0.13036 | 0.00009 |
| GS7    | 0.000135 | 0.00011 | 0.0001 | 0.0002 | 0.00017 | 4.50202 | 0.00053 | 0.02961 | 0.00555 | 0.43320 | 0.00078 |
| GS8    | 0.00011 | 0.00012 | 0.0002 | 0.0002 | 0.0002 | 0.35628 | 0.00761 | 0.07033 | 0.00070 | 0.04130 | 0.00006 |
| GS9    | 0.00014 | 0.00048 | 0.0002 | 0.0003 | 0.0003 | 0.47503 | 0.00240 | 0.05367 | 0.00097 | 0.07611 | 0.00008 |
| Safe limits | 5 × 10⁻⁸ | 2 × 10⁻² | 2.5 × 10⁻² | 7 × 10⁻³ | 6 × 10⁻³ | 1 | 1 | 1 | 1 | 1 | 1 × 10⁻⁴ |
Code availability (software application or custom code) All software applications used in this study were the licensed software applications used by Niğde Ömer Halisdemir University, Turkey.

Author contribution Abdurrahman Lermi: conceptualization, methodology, investigation, supervision, writing-original draft preparation, validation, writing-reviewing and editing. Emmanuel Dannoba Sunkari: methodology, software, data curation, writing-original draft preparation, visualization, writing-reviewing and editing.

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Declarations

Ethics approval The authors declare that the submitted manuscript is original. Authors also acknowledge that the current research has been conducted ethically and the final shape of the research has been agreed by both authors. Authors declare that this manuscript does not involve researching about humans or animals.

Consent to participate The authors consent to participate in this research study.

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