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Article

Assessment of heavy metal contaminations in irrigation water, soils, and onions in the Isser and Zemmouri Regions, Algeria

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Abstract: This study investigates heavy metal contamination in irrigation water, soil, and onion (*Allium cepa L.*) samples from the Isser and Zemmouri regions of Boumerdes, Algeria, to assess potential health risks from consuming these vegetables. The analysis focused on both essential and toxic heavy metals, including iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni). Atomic Absorption Spectroscopy (AAS) was employed for accurate quantification, and results were compared with FAO/WHO 2001 standards. Elevated copper (0.72 mg/L) and zinc (0.19 mg/L) levels were detected in Isser's irrigation water, while Zemmouri's water contained near-threshold concentrations of nickel (0.18 mg/L), chromium (0.09 mg/L), and copper (0.14 mg/L). Soil contamination was observed at both sites, with Isser showing high Cu (68.41 mg/kg), Zn (62.12 mg/kg), and Pb (71.63 mg/kg) levels, while Zemmouri exceeded limits for Pb (64.32 mg/kg) and Ni (11.21 mg/kg). In onion bulbs, Isser showed elevated chromium (3.1 mg/kg) and lead (0.31 mg/kg), while Zemmouri exhibited high zinc (11.34 mg/kg) and iron (43.76 mg/kg) levels in leaves. These findings indicate significant health risks associated with onion consumption from these regions, highlighting the need for improved monitoring and management of water quality and agricultural practices.

Keywords: heavy metals; soil contamination; vegetables; AAS; health risk

1. Introduction

Vegetables are essential components of diets worldwide, providing key nutrients, antioxidants, and metabolites. They also help buffer acidic byproducts from digestion. However, vegetables absorb both essential and toxic elements from the soil, with varying levels of accumulation. Metals can contaminate soil and integrate into its solution, ultimately entering the plant, including its consumable parts, even at low soil concentrations [1,2]. Different vegetables accumulate these metals to varying degrees.

Heavy metals, even at low concentrations, pose significant risks to human health due to the body's limited excretion mechanisms [3]. These metals are hazardous and can contribute to conditions like cancer, liver disease, heart problems, and cognitive impairments, as well as damage to the liver, kidneys, and other organs [4].

Onion (*Allium cepa L.*) is one of the most important and widely consumed vegetable crops globally [5]. According to the Food and Agriculture Organization (FAO), the world's onion production was approximately 100 million tons in 2019. Asia accounts for the largest share of global onion production at 64%, followed by the Americas and Europe at 12.7% each, Africa at 11%, and Oceania at 0.4% [6].

Irrigation water is a major pathway for heavy metal contamination in agricultural systems. Contaminants in water can stem from various anthropogenic sources, such as industrial waste discharge, mining activities, sewage sludge, and the use of contaminated water for irrigation [7,8]. Heavy metals such as lead, cadmium, and chromium can accumulate in irrigation water, posing a significant risk when used to irrigate crops. The contaminated water, in turn, affects the soil and subsequently the plants, leading to the uptake of these metals into the food chain. This route of contamination is particularly concerning in regions where water sources are polluted by industrial and vehicular activities, as the metals can persist in water bodies and affect agricultural practices over the long term.

Soil contamination with heavy metals often results from human activities, including the use of agrochemicals, industrial emissions, mining, and the application of sewage sludge [9–15]. When these metals accumulate in soil, they become bioavailable to plants, potentially leading to their uptake and accumulation in crop tissues. Soils near industrial zones, mining areas, or where polluted irrigation water is used are particularly vulnerable to high metal concentrations. Over time, this can lead to significant contamination, not only of the soil but also of the crops grown in it, posing serious risks to food safety. Monitoring and controlling soil contamination is essential to prevent the transfer of harmful metals to crops, which can affect both crop yields and human health. Vegetables, including onions, are susceptible to heavy metal contamination through both natural and anthropogenic processes. Natural sources, such as volcanic eruptions and the release of metals from soil and rocks, contribute to the presence of these contaminants in the environment [16–21].

Onions (*Allium cepa L.*) are particularly susceptible to heavy metal accumulation due to their ability to absorb metals from both soil and water. Contaminants such as lead, cadmium, chromium, and arsenic can accumulate in onion tissues, with higher concentrations often found in the bulb and leaves. These metals, even at low levels, can be toxic to humans, with prolonged exposure leading to health issues such as developmental problems, kidney damage, and cancer [22–28]. Onions grown in contaminated soils or irrigated with polluted water are particularly at risk, and the accumulation of these metals in edible parts of the plant makes them a potential health hazard. The widespread contamination of agricultural products, including onions, highlights the need for better management of irrigation practices and soil health to minimize heavy metal uptake in food crops.

Algeria faces unique environmental and agricultural challenges, particularly in its arid and semi-arid regions. Soil degradation, water scarcity, and pollution are significant concerns that affect agricultural productivity. In the Isser and Zemmouri regions, the use of river water for irrigation is widespread, despite concerns over contamination from industrial and household waste. The Isser and Zemmouri regions were selected for this study due to their reliance on irrigation from river water, which can carry pollutants such as heavy metals from various sources, including industrial discharge and runoff. Furthermore, these regions are known for their agricultural activity, with vegetables such as onions being vital to local diets and economies. However, the extensive use of river water and its potential to introduce contaminants into the soil and crops makes these areas a focal point for assessing the risks associated with heavy metal accumulation.

Boumerdes, a city with an extensive irrigation system, primarily uses river water for irrigation. Due to limited access to these canals, some farmers turn to wastewater, which may contain pollutants from household liquids, industrial discharge, and rainwater [29]. River waters provide essential nutrients as well as metals like iron (Fe), lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), chromium (Cr), and nickel (Ni). While irrigation water contributes to contamination, soil also absorbs heavy metals through runoff from road traffic and industrial waste [30].

This study, building on previous work in the region [31], aims to assess the levels of heavy metals (Fe, Pb, Cd, Zn, Cu, Cr, and Ni) and their accumulation in commonly grown vegetables, particularly onions (*Allium cepa L.*: Bulb and leaf), an essential vegetable in Algerian cuisine. This research was prompted by the common use of river water for irrigation in the region and the need to understand the extent of contamination in these agricultural zones.

2. Materials and methods

2.1. Study area

The study area is located in Boumerdes, Algeria, in North Africa (see **Figure 1**). In two regions namely Isser (Located Latitude: 36°72′34″.84 N, Longitude: 3°66′91″.30 E) and Zemmouri (Located Latitude: 36°80′32″.97 N, Longitude: 3°60′72″.43 E), covering an estimated area of 1456.68 km^2 and inhabited by approximately 831,000 people. It is surrounded by the Algerian regions of Blida, Tizi Ouzou, and Bouira. The two sampling sites, Issers and Zemmouri, are situated in this region. The region experiences an average annual temperature of about 18 ℃ along the coast and 25 ℃ in the inland provinces, making it a crucial area for agricultural production. Annual precipitation ranges from 500 mm to 1300 mm. However, the intensive agricultural activity requires substantial water resources for irrigation to meet the demands of this production [31].

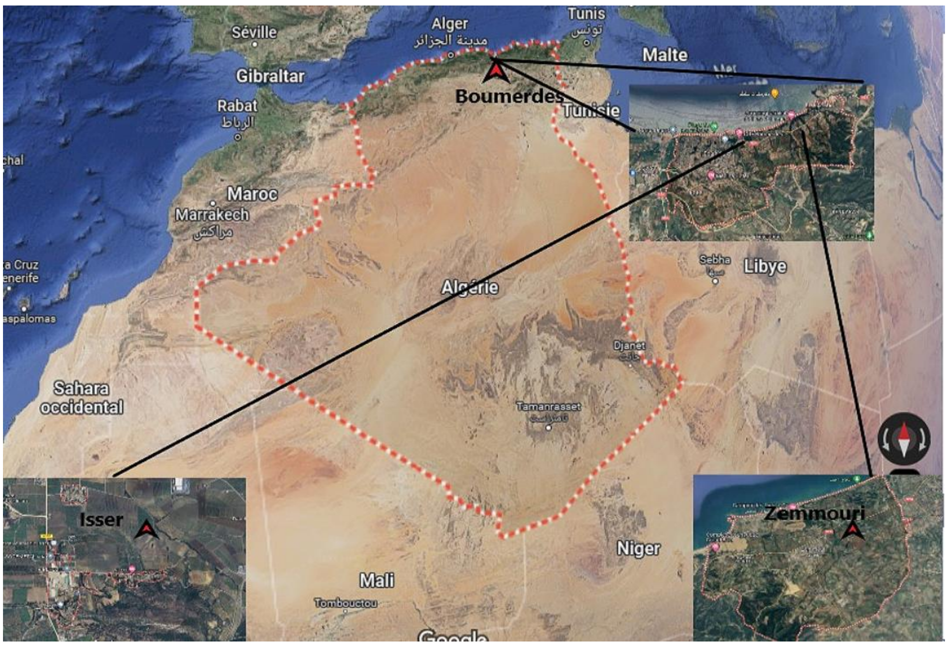

Figure 1. Localisation of studied sites area in region of Boumerdes, Algeria.

2.2. Soil sampling

Samples of soil were collected from agricultural fields by excavating a cubic monolith measuring 10 × 10 × 10 cm^3 using a stainless-steel auger. Any non-soil materials, such as wood fragments, stones, organic debris, and rocks, were eliminated from the samples. Afterward, all the collected samples were mixed and subjected to 12 h drying process at a temperature of 100 ℃. Subsequently, they were ground to a pass through a 2 mm sieve and stored in polyethylene bags until further analysis. Throughout the sampling and storage processes, precautions were taken to prevent any contact with metal tools to prevent cross-contamination [29,30,32–34].

2.3. Water sampling

We collected water used in the irrigation of cultivated onion samples into thoroughly cleaned bottles, which had been previously washed with a soap free of metals and then rinsed with deionized water. These samples were stored in a refrigerator at 4 ℃ to minimize any biodegradation or volatilization before they were analyzed [35–37].

2.4. Vegetables sampling

In the year 2020, a total of 30 samples of freshly harvested vegetable onions (*Allium cepa L.*) were acquired from various farm locations in the Isser and Zemmouri regions in Boumerdes, Algeria. These samples of onion were divided into two groups: The leafy vegetable part and the bulb part (**Figure 2**). For each vegetable type at each site, samples were collected in triplicate and transported to the laboratory in clean polyethylene bags. The samples underwent a cleaning process with distilled water to remove any extraneous materials, followed by drying. After drying, they were ground into a powder form in preparation for further analysis [38].

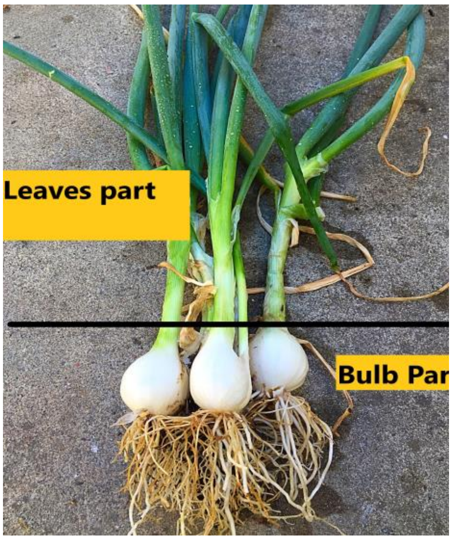

Figure 2. Leaves and bulbs parts of studied onions (*Allium cepa L.*).

3. Analytical method

100 g of each sample part was subjected to a temperature of 105 ℃ for 4 h in an oven [31].

It's crucial to emphasize that all procedures and analytical methods employed in this study underwent thorough evaluation and testing to ensure the production of reliable results suitable for their intended purpose. In other words, these methods underwent validation. Validation was accomplished through the analysis of certified reference materials or by comparing the methods with established standard procedures. This validation process covered the full range of concentrations at which the analyte could potentially be present in the analyzed samples [31,32]. The main text should contain information regarding the accuracy and precision of these methods. Additionally, it is important to include further details about sensitivity, potential interferences, and the effects of the sample matrix.

3.1. Sampling and preparation of water

Two 100 mL water samples were gathered at the source of irrigation water points at various sites using thoroughly cleaned polyethylene bottles. Upon arrival at the laboratories, these collected samples underwent filtration through a 0.45 μm cellulose acetate membrane filter. To prevent precipitation, concentrated nitric acid was subsequently introduced to lower the pH to below 2. After this adjustment, the samples were stored in a refrigerator at 4 ℃ prior to analysis [31,32].

3.2. Digestion of soils

The soil sample was digested following the method outlined in FAO/SIDA [32]. One gram of dried and finely powdered soil sample was placed in a Pyrex beaker, and 15 mL of aqua regia was introduced. This mixture was allowed to stand overnight and was then heated on a hot plate until no further production of brown fumes was observed. Subsequently, 5 mL of concentrated $HClO_4$ were added, and the mixture was gently heated once more until the solution had nearly evaporated to dryness. The resulting extracts were then filtered, and a final volume of 50 mL was prepared using distilled water [32,34].

3.3. Digestion of vegetables

To digest the vegetable samples, two grams of each sample were placed in a Pyrex beaker. Subsequently, 10 mL of concentrated HNO3 were added, and the mixture was left to stand overnight without applying heat. Following this, it was heated on a hot plate. Once the sample had nearly evaporated to dryness, it was allowed to cool, and 5 mL of HClO4 were introduced. The heating process was resumed until digestion was deemed complete. The resulting solution was then filtered through Whatman filter paper No. 42 into a volumetric flask and topped with distilled water to 50 mL using distilled water [33].

3.4. Instrumental calibration

In this study, the calibration of calibration curves played a crucial role in determining the concentration of heavy metals in the analyzed samples. To achieve a higher level of reliability in the results, a stock standard solution with a concentration of 100 mg/L was prepared for each element (Fe, Zn, Cd, Cr, Ni, Cu, Pb), and calibration curves were plotted using this solution. The 100 mg/L stock solution for calibration was chosen to ensure flexibility in preparing standards for the expected range of heavy metal concentrations. It optimizes the sensitivity and linearity of the analytical method, allowing for reliable detection and accurate quantification of metals in environmental and agricultural samples. Calibration curves are an essential component of instrumental analysis, providing a foundation for accurate quantification. They involve plotting known concentrations of a substance (in this case, heavy metals) against the instrument's response, such as absorbance or intensity. These curves establish a linear relationship between concentration and response, enabling the precise determination of unknown concentrations in samples based on their instrument responses. Calibration is a critical step in validating the analytical method, ensuring that it delivers accurate and reliable results for its intended purpose.

3.5. Analysis of samples

The flame atomic absorption spectrometer Thermo-Fischer ICE 3000 FAA (USA), fully automated and PC-controlled using SOLAAR software versions and equipped with fast sequential operation for multi-element flame determinations, was used for metal (Cd, Cr, Cu, Fe, Ni, Pb, and Zn) analysis. Validation parameters of the applied method are shown in **Table 1**. The detection limit (LOD) (mg kg^{-1}) and wavelength (nm) of heavy metals were: 0.040 and 213.9 for Zn; 0.010 and 357.9 for Cr; 0.006 and 217.0 for Pb; 0.005 and 228.8 for Cd; 0.020 and 248.3 for Fe; 0.030 and 324.8 for Cu; and 0.010 and 232.0 for Ni respectively.

Table 1. Validation parameters of the used method.

Element	λ [nm]	Concentration range [mg/L]	Correlation coefficient (r)	Limit of detection [mg/L]	Limit of quantification [mg/L]	Limit of detection [mg/kg]	Limit of quantification [mg/kg]
Cd	228.8	0–2.0	0.9995	0.005	0.015	0.005	0.015
Cr	357.9	0–2.0	0.9991	0.010	0.030	0.010	0.030
Cu	324.8	0–2.0	0.9990	0.030	0.090	0.030	0.090
Fe	248.3	0–2.0	0.9992	0.020	0.060	0.020	0.060
Ni	232.0	0–2.0	0.9987	0.010	0.030	0.010	0.030
Pb	217.0	0–2.0	0.9998	0.006	0.018	0.006	0.018
Zn	213.9	0–20.0	0.9975	0.040	0.120	0.040	0.120

4. Results and discussion

The summarized results in **Figure 3** indicate varying concentrations of heavy metals in the irrigated waters of Issers, with the following order: Pb > Cu > Zn > Fe > Ni. Chromium and cadmium concentrations fell below the detection limit. Notably, copper (Cu) concentration (0.72 mg/L) exceeded the standard, while the concentrations of zinc (Zn) and lead (Pb) were near the limits established by the FAO/WHO in 2001 [33].

A comparison of the obtained results with existing literature data (**Figure 3**) reveals that the irrigation waters in the Boumerdes region used for crop irrigation contain lower levels of copper, zinc, and lead than those in other regions [20,23,25]. In contrast, the lead content in these waters is similar to that found in Ghana [32] but several times lower than in waters from other regions [23,25]. Zinc concentrations in the Boumerdes waters are comparable to those in Ghana [25], except for Ethiopia [32], where cadmium levels are several times lower [33]. Additionally, the tested waters have significantly lower chromium content (approximately 0.09 mg/L) compared to other Algerian waters [31], but their iron content is higher, ranging from 0.04 to 1.10 mg Fe per liter.

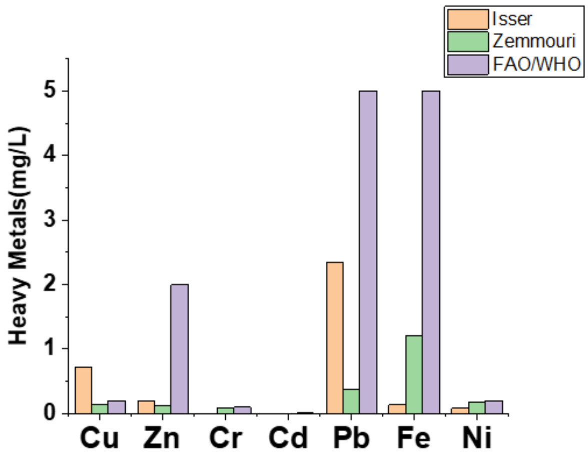

Figure 3. Concentration of heavy metals (mg/L) in irrigation waters of Zemmouri and Issers Regions.

These results suggest a potential risk of contamination in the water sources, which may be attributed to pollutants, such as industrial effluents and wastewater, entering the water system. Industrial and agricultural runoff, including waste from local factories and heavy traffic, may contribute to elevated levels of these metals in the water [19].

In contrast, the Zemmouri site demonstrated a concentration trend of heavy metals as follows: Fe > Pb > Ni > Cu > Zn > Cr > Cd. These values were within the limits set by FAO/WHO [33]. However, chromium and nickel levels approached the upper limits, indicating that continued use of this water for irrigation may pose risks of contamination by these metals. Such contamination could stem from industrial discharges and vehicle emissions in nearby areas, as these metals are commonly associated with industrial processes, including steel manufacturing and automotive exhaust [23,24,31].

Regarding the onion bulb samples, Issers showed a concentration trend of Fe > Zn > Cu > Cr > Pb > Ni > Cd, while Zemmouri exhibited a slightly different trend: Fe > Zn > Cr > Cu > Pb > Cd > Ni (**Table 1**). Lead (Pb) and nickel (Ni) concentrations were below detection in all onion leaf samples from both sites. In the onion bulbs at Issers and Zemmouri, Pb concentrations were approximately 0.31 mg/kg and 0.19 mg/kg, respectively, exceeding the standard for Issers, based on the relevant norms [35]. These findings are concerning as Pb is often linked to contamination from vehicular emissions and industrial activities. Additionally, the concentration of Ni in Issers and Zemmouri, although below the detection limit in the leaf samples, suggests a possible localized source of contamination, likely stemming from nearby industrial activities such as smelting or the use of contaminated fertilizers.

For other analyzed elements, the results showed concentrations below

WHO/FAO limits, but some elements were still near the tolerance threshold. This proximity to the limits may indicate ongoing contamination risks, particularly from airborne industrial pollution or soil runoff containing heavy metals. Previous studies have highlighted that agricultural areas located near roads or industrial zones tend to have higher metal concentrations in crops due to vehicular emissions and industrial effluents [34].

In the onion leaf samples, the Isser site showed heavy metal concentrations ranked as follows: Fe > Zn > Cu > Cr. For Zemmouri, the order was Fe > Zn > Cu. At the Isser site, average concentrations in the onion leaves were 54.13 mg/kg for Fe, 49.40 mg/kg for Zn, and 10.23 mg/kg for Cu (**Table 2**). Notably, the concentration of iron at Zemmouri exceeded the WHO/FAO tolerance limit of 43.76 mg/kg. While other elements remained below the limits, the near-exceedance for Zn and Cu suggests that prolonged exposure to polluted water or contaminated soil could elevate these levels over time, potentially leading to bioaccumulation in crops. Such levels are often associated with pollution from industrial activities, agricultural runoff, and the use of contaminated irrigation sources.

Table 2. Concentration of heavy metals in different parts of onion samples in mg/kg (mean ± standard deviation).

Heavy metals (mg/kg)	Sampling Sites				FAO/WHO 2001 (mg/kg) [33]	Algerian standards [31]
	Site of Issers		Site of Zemmouri			
	Onion Bulb	Onion Leaf	Onion Bulb	Onion Leaf		
Cu	4.3 ± 0.1	10.23 ± 0.3	1.02 ± 0.2	19.24 ± 0.3	73.3	40
Zn	15.63 ± 0.3	49.40 ± 0.2	11.34 ± 0.3	76.97 ± 0.2	99.4	100
Cr	3.1 ± 0.1	< LOD	1.22 ± 0.1	0.07 ± 0.1	2.3	1
Cd	0.04 ± 0.01	< LOD	0.11 ± 0.01	0.02 ± 0.01	0.2	0.05
Pb	0.31 ± 0.01	< LOD	0.19 ± 0.01	< LOD	0.3	0.1
Fe	17.12 ± 0.2	54.13 ± 0.4	29.31 ± 0.3	43.76 ± 0.7	425.5	425
Ni	0.08 ± 0.02	< LOD	0.02 ± 0.01	< LOD	0.1	10

< LOD: Bellow limit of detection (LOD).

The higher zinc concentrations in onion leaves, despite soil concentrations falling within safe limits, are likely due to a combination of factors, including the soil pH, plant physiology, and possible environmental stressors. While the soil's pH may facilitate zinc availability, the plant's mechanisms for nutrient uptake and detoxification also play a significant role. Moreover, irrigation water quality and fertilization practices may exacerbate zinc accumulation. Continued monitoring and management of these factors are crucial to ensure that zinc concentrations do not reach levels that could pose a risk to human health.

When comparing the results with existing literature (**Table 3**), it is evident that the soils of Boumerdes contain lower levels of cadmium, chromium, iron, and nickel but higher levels of zinc than soils from other regions [33,38–43]. In contrast, copper concentrations in Boumerdes soils were similar to those found in Iran [20], Ghana [25], and Ethiopia [26], but were significantly lower than in soils from other regions. Zinc concentrations in Boumerdes soils were comparable to those in most regions, with the exception of Ethiopia [17,26]. Furthermore, the soils tested in Boumerdes had notably lower iron content (around 23 mg/kg) compared to other soils, which typically contain 1.27 to 1034 mg Fe per kg of soil in regions like Ethiopia [17].

Table 3. Comparison of the mean concentration (mg/kg) of the heavy metals in onion in the current study with previously reported values.

Element	Current study (Algeria)	[17] (Ethiopia)	[18] (Macedonia)	[19] (Pakistan)	[20] (Iran)	[21] (Ghana)	[25] (Ghana)	[26] (Ethiopia)	[27] (Nigiria)	[28] (Nigeria)
Zn	13.48	44.23	30.25	1.426	6.30	-	34.94	12.42	0.98	1.62
Cu	2.66	9.23	6.21	0.297	2.81	-	3.82	3.93	-	0.30
Ni	0.05	0.18	0.90	-	1.73	62.11	0.38	-	N.D	N.D
Pb	0.250	7.68	5.62	0.567	12.96	5.67	1.51	0.33	1.31	N.D
Mn	-	659.59	16.24	1.420	-	58.57	-	8.20	0.25	0.96
Fe	23.25	1034.27	167.00	3.573	-	-	265.94	20.87	1.27	28.02
Cr	2.16	-	-	0.06	0.31	9.23	1.49	4.87	N.D	N.D
Cd	0.09	-	-	0.04	0.13	9.63	0.60	0.05	0.06	-

N.D: Not Detected, -: Not investigated.

Overall, the results emphasize the need for close monitoring of both water and soil quality in agricultural regions, especially in areas affected by industrial pollution and vehicular emissions. These findings align with previous studies, which have reported increasing concerns about the accumulation of heavy metals in crops grown near industrial zones and major transportation routes [19–24]. To mitigate these risks, enhanced waste management practices and stricter regulations on industrial discharges are essential, along with public awareness campaigns regarding the use of contaminated irrigation sources.

4.1. Comparative assessment of heavy metal concentrations in bulbs and leaves

Overall, heavy metal concentrations were higher in the leaves than in the bulbs, a trend consistent with previous studies [39]. The elevated levels in leaves may be due to their greater exposure to contaminants, including heavy metals entering through stomata or being transported via xylem vessels from contaminated soil and water. In the bulbs, Fe had the highest concentration, followed by Zn, Cu, and Cr. Pb were present in trace amounts, while Ni and cadmium (Cd) were the least concentrated. Excessive Fe can disrupt metabolic processes and lead to gastrointestinal and cardiac issues [40], while excess Zn may cause anemia, obesity, and harm to the immune, reproductive, and circulatory systems [41,42]. Overall, leaves had higher concentrations of Fe, Cu, Cr, and Zn than bulbs, with Fe being the most dominant element. This is consistent with its role in chlorophyll synthesis [43]. In contrast, Cd and Ni were present in the least amounts in the leaves.

4.2. Relationships of heavy metals in onion

Table 4. Pearson correlation coefficient matrixes of heavy metals concentration (mg/kg) in the bulbs and leaves of onion.

Leaf	**Cu**	**Zn**	**Cr**	**Cd**	**Pb**	**Fe**	**Ni**
Cu	1.000						
Zn	0.718*	1.000					
Cr	0.771*	0.482	1.000				
Cd	−0.078	0.617	−0.289	1.000			
Pb	0.929**	0.523	0.923**	−0.325	1.000		
Fe	0.876**	0.745*	0.693	0.024	0.763*	1.000	
Ni	0.591	0.302	0.978*	−0.375	0.817**	0.537	1.000
Bulb	**Cu**	**Zn**	**Cr**	**Cd**	**Pb**	**Fe**	**Ni**
Cu	1.000	0.966**	0.658	−0.408	0.973*	0.943**	0.694
Zn		1.000	0.819**	−0.280	0.970**	0.985**	0.791*
Cr			1.000	−0.126	0.732*	0.783*	0.834**
Cd				1.000	−0.444	−0.141	−0.386
Pb					1.000	0.946**	0.836**
Fe						1.0000	0.765*
Ni							1.000

* Correlation is significant at the $p < 0.05$ level (2-tailed). ** Correlation is significant at $p < 0.01$ level (2-tailed).

The relationships and potential sources of heavy metal contamination in the bulbs and leaves of onion varieties were analyzed using Pearson's correlation coefficient matrix (**Table 4**). In the bulb samples, strong positive correlations were observed between iron (Fe) and zinc (Zn) ($r = 0.985$), followed by copper (Cu) and lead (Pb) ($r = 0.973$), lead (Pb) and zinc ($r = 0.970$), and copper and zinc ($r = 0.966$), all of which were statistically significant at $p < 0.01$. Iron (Fe) also showed significant positive correlations with Zn ($r = 0.791$), Cr (0.783) and Nickel ($r = 0.765$) at $p < 0.05$. In the leaf samples, Cr displayed strong positive correlations with Ni ($r = 0.978$), Cu with Pb (0.910), and Fe (0.876) at $p < 0.01$ and with Zn ($r = 0.718$) at $p < 0.05$. These strong correlations between Cu, Zn, Fe, Cr, and Pb in bulbs and Cu, Cr, Fe and Zn in leaves suggest a common origin of contamination. In contrast, negative correlations were found between cadmium (Cd) and most metals in bulbs and between cadmium (Cd) and Cu, Cr, Pb and Ni in leaves, indicating a distinct distribution and separate sources of contamination [44,45]. The synchronicity of Cu, Zn, Fe, and Cr in both bulbs and leaves points to common agronomic sources, such as the extensive use of agrochemicals (e.g., superphosphate fertilizers, pesticides) and contaminated irrigation water, affecting not only the onion fields but also surrounding agricultural areas [19]. Strong correlations between metallic elements (Cr-Ni, Cu-Pb, Cr-Pb, Cu-Fe) can result from various environmental, geochemical, or anthropogenic factors:

1) Geochemical Origins: These metals can naturally occur together in certain source rocks or sediments. For instance, Cr and Ni are often found in ultramafic

formations or soils derived from them, while Cu and Fe are common in sulfide ores like chalcopyrite and pyrite.

2) Anthropogenic Sources: Human activities often contribute to these correlations. Cu-Pb and Cr-Pb are linked to industrial discharges, such as metallurgical effluents, old lead paints, or leaded fuels. Cu-Fe correlations may arise from metal corrosion, while Cr-Ni often stems from surface treatment industries like electroplating.
3) Agricultural and Urban Sources: Fertilizers and pesticides may contain Cu, Cr, and Pb, and wastewater or industrial effluents used for irrigation can introduce these metals into crops.

The observed correlations between heavy metals in onion bulbs and leaves (**Table 5**) suggest complex interactions in their uptake and accumulation. Metals such as zinc (Zn), chromium (Cr), cadmium (Cd), lead (Pb), and nickel (Ni) often exhibit negative correlations with each other, particularly with copper (Cu) and iron (Fe). This could indicate competition or inhibition in their absorption or accumulation within the plant, as different metals might interfere with each other's uptake through shared transport pathways or biochemical mechanisms. Specifically, copper and zinc display a very strong positive correlation, likely due to their common routes of absorption in plants. In contrast, iron shows both positive and negative correlations with other metals, including strong negative relationships with lead, cadmium, and nickel. This pattern suggests that iron may play distinct roles in plant physiology, possibly influencing or being influenced by other metals through antagonistic interactions. These complex correlations highlight the intricate balance of heavy metal dynamics within the plant system, reflecting potential regulatory mechanisms that govern metal homeostasis in onions.

Table 5. Pearson correlation coefficient matrix of heavy metals in onion bulb and leaves.

Leaf/bulb	Cu	Zn	Cr	Cd	Pb	Fe	Ni
Cu	1.000						
Zn	0.991**	1.000					
Cr	−0.641	−0.707	1.000				
Cd	−0.705	−0.754	0.351	1.000			
Pb	−0.772	−0.835	0.973**	0.550	1.000		
Fe	0.627	0.791*	−0.943	−0.579	−0.965*	1.000	
Ni	−0.556	−0.618	0.989**	0.211	0.929**	−0.896	1.000

* Correlation is significant at the $p < 0.05$ level (2-tailed). ** Correlation is significant at $p < 0.01$ level (2-tailed).

4.3. Heavy metals content in agricultural soils

For all the metals analyzed in the agricultural soil, the concentrations are below the limits recommended by the WHO (**Figure 4**).

A comparison of the obtained results with the existing literature (**Figure 4**) indicates that the soils across all regions of Boumerdes contain lower levels of cadmium, chromium, and nickel [17–19,25], but higher levels of lead compared to soils from other regions of Iran [20]. The copper content in Boumerdes soils was found to be similar to that in Ethiopia [17], Iran [20], and Ghana [25], but it was several times higher than in soils from other regions. Zinc concentrations in Boumerdes soils were comparable to those found in other regions. Additionally, the tested soils exhibited significantly lower iron content (approximately 82 mg/kg) compared to other soils, where iron concentrations typically range from 53,847.41 to 16,475 mg Fe per kg in Iran [20] and Ghana [25].

4.3.1. Chromium

Chromium (III) is an essential element required for the normal metabolism of sugars and fats and plays a role in diabetes management by acting as a cofactor for insulin. Cr (III) and its compounds are not considered hazardous. However, the toxicity and carcinogenicity of chromium (VI) (Cr VI) have been well established [36]. In this study, the concentrations of chromium in onion bulbs from Issers and Zemmouri were 3.1 mg/kg and 1.22 mg/kg, respectively. These values exceed the maximum permissible limit of 2.3 mg/kg set by FAO/WHO for Issers [37], indicating a potential health risk, especially since Cr VI is known to be carcinogenic. The presence of chromium at elevated levels in the soil may be linked to industrial pollution, as Cr (VI) is commonly associated with industrial activities such as leather tanning, metal plating, and chemical manufacturing, which are prevalent in urban and industrial zones. Moreover, the concentration of Cr in onion leaves was extremely low, which is consistent with the behavior of Cr, as it is primarily taken up by the roots, with only a small portion reaching the shoots [37].

4.3.2. Zinc

Zinc is a vital trace element for human health, playing crucial roles in growth, development, and metabolism. However, excessive zinc intake can contribute to coronary diseases and other metabolic disorders [36]. The results (**Figure 4**) show elevated average zinc concentrations in onion bulbs, measuring 15.63 mg/kg and 11.34 mg/kg at the two sampling sites. In onion leaves, the concentrations were higher, reaching 49.40 mg/kg and 76.97 mg/kg. Although these values currently fall within established safety limits, the upward trend in zinc accumulation is concerning. Long-term exposure to elevated zinc levels may result from contaminated irrigation water, possibly due to agricultural runoff and industrial effluents, as studies have shown a correlation between zinc pollution and intensive agricultural practices that use fertilizers contaminated with heavy metals [38].

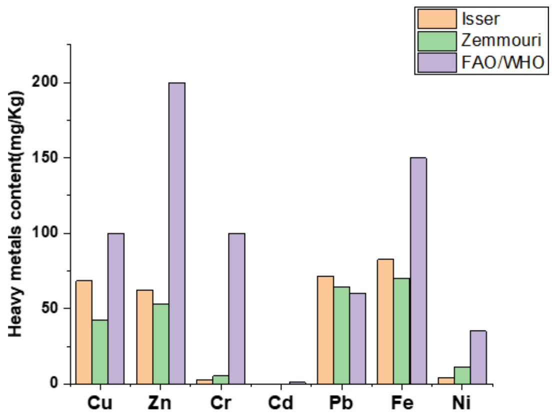

Figure 4. Concentration of heavy metals (mg/kg) in soil samples from sampling sites.

4.3.3. Copper

Copper is an essential micronutrient involved in various biological processes. However, excess copper can become toxic [38]. This study found copper concentrations in onion bulbs to be 4.3 mg/kg and 1.02 mg/kg at the two sites, while the concentrations in onion leaves were higher. This trend is due to the involvement of transporter proteins that facilitate the movement of metals from the roots to the leaves [36]. Although copper is essential in trace amounts, excessive levels, as seen in some areas, can pose a health risk. This elevated copper content could be attributed to industrial discharges, agricultural runoff, and waste from copper-processing industries that may contaminate soil and water sources used for irrigation [46].

4.3.4. Lead

Lead contamination in onion bulbs was found to be 0.31 mg/kg at Issers and 0.19 mg/kg at Zemmouri, exceeding the WHO/FAO limit of 0.3 mg/kg. This suggests a potential health risk to consumers, particularly at the Issers site. Lead toxicity is well-known to cause a range of disorders, including neurological, renal, and developmental issues [38]. The most likely source of lead contamination in the study area is vehicular emissions, as lead is a byproduct of fuel combustion. Additionally, lead can accumulate in the soil from historical use of leaded gasoline and industrial effluents. It is critical to address lead contamination to protect public health, especially in urban and industrial areas where road traffic and industrial activities are significant contributors to pollution.

4.3.5. Cadmium

Cadmium is a highly toxic metal with no essential biological role in humans. Even at low concentrations, it can cause severe health effects, including kidney damage and bone demineralization [46]. In this study, cadmium concentrations were below the FAO/WHO standards, with the highest value recorded at 0.11 mg/kg in onion bulbs from Zemmouri. While the values were within safe limits, the presence of cadmium at detectable levels underscores the need for continued monitoring, especially in areas where industrial activities, such as battery manufacturing and metal processing, could lead to cadmium contamination in soil and water.

4.3.6. Iron

Iron is an essential element for human health, playing a key role in hemoglobin formation, oxygen transport, and electron transfer in the body [30]. The concentrations of iron in onion leaves at both sites exceeded the WHO/FAO limit of 43.76 mg/kg, with values of 54.13 mg/kg at Issers and 43.76 mg/kg at Zemmouri. The levels in onion bulbs did not exceed the limit. Iron is commonly translocated from the roots to the leaves, similar to zinc and copper. Elevated iron levels in soil may result from the use of iron-rich fertilizers, industrial discharges, and contamination from nearby mining activities [47]. While iron is crucial for human health, excessive intake can lead to adverse effects, and thus it is important to regulate its levels in food crops.

4.3.7. Nickel

Nickel is a non-essential element for humans and does not participate in any biological processes. Its presence in the human body can lead to various health problems, including respiratory and skin disorders. In this study, nickel concentrations were below the standard in both onion bulbs and leaves [37]. Nickel contamination in soil may be due to industrial emissions, especially from nickel mining, smelting, and alloy production, as well as from automobile emissions. Although nickel concentrations were low, continuous monitoring is necessary to prevent potential health issues linked to prolonged exposure to high nickel levels.

4.4. Bioaccumulation factor (BCF)

Certain heavy metals have the ability to move from the soil to the edible parts of food crops. This ability can be quantified by the bioaccumulation factor (BCF) [48]:

$$\mathrm{BCF} = \frac{Concentration\ of\ metal\ in\ plant\ part\ (bulb\ part)}{Conentration\ of\ metal\ in\ soil}.$$

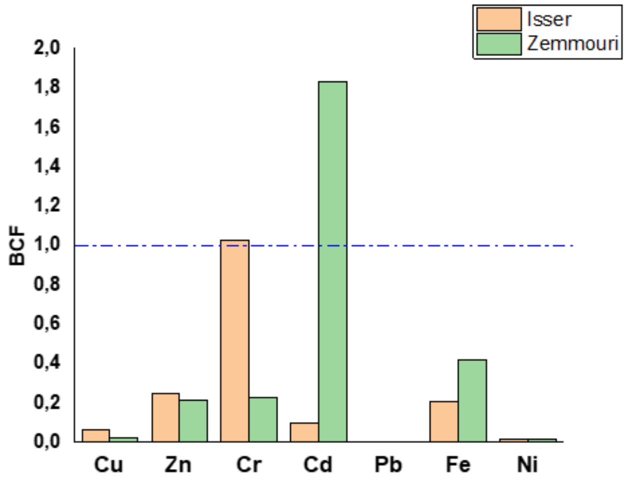

Figure 5. Bioconcentration factor (BCF) of metals between soil and onion (bulb) samples.

The present results (**Figure 5**) indicate that the values are less than 1, which means that the concentrations of heavy metals are higher in the soil compared to the onion samples, resulting in low absorption of heavy metals by onions.

Through these BCF results (**Figure 5**.), it is observed that the maximum transfer factor value was recorded for the element Cd. These values confirm that cadmium is poorly retained by the soil compared to the other analyzed elements, making it more mobile from the soil to vegetable crops. This information is important for understanding the potential risks of heavy metal contamination in agricultural products and their impact on human health.

4.5. Daily intake of heavy metals (DIM)

The Daily Intake of Heavy Metals (DIM) is related to the concentration of heavy metals in the crops intended for consumption and the quantity of the respective food crop consumed. It is calculated using the following equation [47]:

$$\mathrm{DIM} = \frac{\mathrm{Cmetal \times Cfactor \times Wfood}}{\mathrm{Bw}}.$$

where:

- C_{metal} represents the concentration of the metal in the vegetable crop.

- C_{factor} is the conversion factor (weight of fresh vegetables to dry weight).
- W_{food} is the daily consumption of vegetables (with justification for the value chosen, based on a questionnaire on Algerian dietary habits conducted with the
- B_w is the average body weight.

A correction factor of 0.085 has been incorporated into the equation to convert the weight of fresh vegetables to dry weight [47]. The daily consumption of onions has been considered as 0.01 kg/person/day, and the average body weight of an adult is estimated to be 63.6 kg. The results of the daily intake of heavy metals are reported in **Figure 6**. This calculation helps assess the potential health risks associated with the consumption of vegetables containing heavy metals.

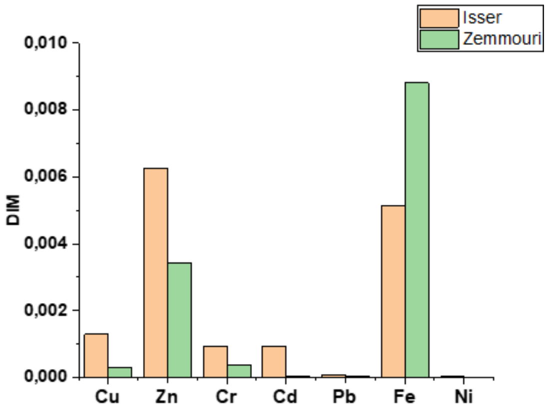

Figure 6. Daily metal intake (DIM) caused by the consumption of analyzed samples.

4.6. Health risk index (HRI)

The Health Risk Index (HRI) [49] is calculated by dividing the value of the daily intake of heavy metals for each element by the Reference Dose (RfD) [50]. This index represents the degree of harm for individuals consuming crops containing heavy metal elements. If this value is greater than 1, individuals who consume these types of vegetables may be exposed to a health hazard.

$$\text{HRI} = \frac{\text{DIM}}{\text{RfD}}.$$

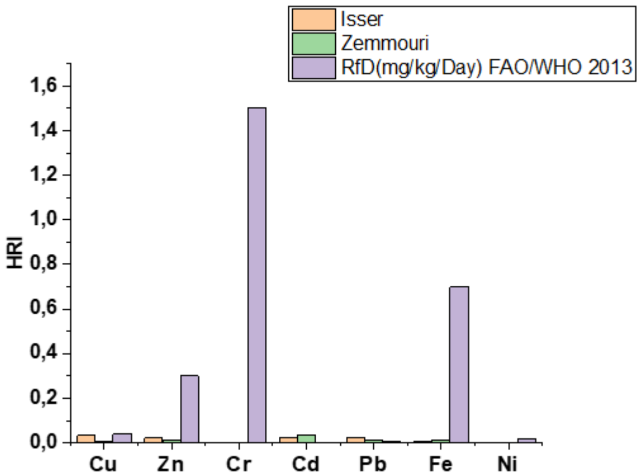

Figure 7. Health risk index (HRI) caused by the consumption of analyzed samples.

The calculation of the daily intake of metal (DIM) was done to assess the degree of exposure of vegetable consumers to various heavy metals (**Figure 7**). In this study, the evaluation involves the daily quantity that an adult consumes. It is observed that onions are an essential and highly consumed food item, which increases the level of risk compared to other crops with lower intake. However, the recorded values suggest that the consumption of this food is almost risk-free, based on the Provisional Tolerable Daily Intake (PTDIs) for Cu, Zn, Cd, Pb, and Fe, which are 3 mg, 60 mg, 60 µg, 214 µg, and 66 mg, respectively [51,52].

It's important to note that there are other pathways of exposure to heavy metals, such as skin contact, inhalation of particles brought by vegetables, and soil residue adhering to the crops, which were not considered in this study. Furthermore, a calculated HRI greater than 1 does not necessarily mean that a potential health hazard will occur, but it simply indicates a higher likelihood of presenting a health risk. Overall, the results suggest that the consumption of these vegetables does not pose a significant health risk based on the evaluated parameters.

5. Conclusion

This study highlights the presence of heavy metals in commonly consumed onions (*Allium cepa L.*) grown in the Isser and Zemmouri regions, with notable variations in metal accumulation between different parts of the plant. Elevated concentrations of copper, zinc, and iron in onion leaves, along with concerning levels of lead in onion bulbs, particularly in Isser, raise significant health concerns for consumers. These findings underscore the potential risk of chronic exposure to harmful metals, especially with the high levels of lead in the bulbs. The study stresses the urgent need for careful management of irrigation water quality and soil health to prevent the uptake of harmful metals, which could have long-term adverse effects on public health.

Although cadmium levels were within safe limits, the rising trend of zinc concentrations warrants continuous monitoring, as prolonged exposure to high zinc levels could have detrimental health impacts over time. To mitigate these risks, we recommend stricter surveillance of irrigation sources, especially those exposed to industrial and vehicular contamination, as well as the promotion of alternative irrigation methods such as rainwater harvesting or treated wastewater systems. Further investigation into the sources of chromium contamination is also crucial to ensure safe agricultural practices and to address potential risks from this metal.

The implications of these findings extend beyond immediate food safety concerns, highlighting the need for long-term strategies to reduce heavy metal contamination in agricultural practices. Policymakers and agricultural practitioners must prioritize sustainable, environmentally friendly practices, including the use of organic farming techniques and soil amendments that can reduce metal accumulation. Regular testing of irrigation water, soil, and crops is essential to safeguard public health and protect the environment from the harmful effects of metal pollution. By adopting these measures, we can ensure that onions and other agricultural products remain safe for consumption, promoting both food security and long-term agricultural sustainability.

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