



Spatial and Biological Assessment of Heavy Metal Pollution in *Atriplex halimus* Around the Sabkhas of the Libyan Coast

Bled Abdalah Fadel Abdala^{1*}, Mohammed Abraheem Mohammed Arqeeq²
^{1,2} Department of Plant Sciences, Kufra University, Kufra, Libya

التقييم المكاني والحيوي للتلوث بالمعادن الثقيلة في نبات القطف (*Atriplex halimus*) حول سبخات
الساحل الليبي

بلعيد عبدالله فضيل عبدالله^{1*}، محمد ابراهيم محمد ارقيق²
^{2,1} قسم علم النباتات، جامعة الكفرة، الكفرة، ليبيا

*Corresponding author: bled.abdalah@uob.edu.ly

Received: June 17, 2026

Accepted: August 25, 2026

Published: September 20, 2026

Abstract:

This study investigates the spatial distribution and bioaccumulation of heavy metals, specifically Lead (Pb), in the halophytic plant *Atriplex halimus* and its associated soil across selected sabkha ecosystems along the Libyan coastline. Sabkhas are unique transitional environments increasingly threatened by anthropogenic activities, including industrial discharge and urban runoff. The primary objective was to quantify Lead concentrations in both soil and plant tissues (leaves and stems) to assess the phytoremediation potential and ecological health of these regions. Samples were collected from strategic geographical coordinates using GPS from three distinct coastal sabkhas. Chemical analysis was conducted using Atomic Absorption Spectroscopy (AAS) to determine metal concentrations. The results indicated significant spatial variability in Lead levels, with higher concentrations observed in sites adjacent to industrial zones and highways. In *Atriplex halimus*, Lead accumulation was higher in the roots and leaves compared to the stems, suggesting a high bioconcentration factor (BCF). Statistical analysis revealed a strong positive correlation between soil metal content and plant uptake, confirming that *Atriplex halimus* serves as an effective bio-indicator for environmental Lead pollution. The study concludes that the Libyan coastal sabkhas are experiencing moderate to high levels of heavy metal stress, necessitating urgent conservation strategies. The findings provide a foundational database for environmental monitoring and suggest that *Atriplex halimus* can be utilized in phytostabilization programs to mitigate the spread of metallic contaminants in arid coastal environments.

Keywords: *Atriplex halimus*, Heavy Metals, Lead (Pb), Sabkhas, Libya, Bioaccumulation, Phytoremediation.

المخلص

تتناول هذه الدراسة التوزيع المكاني والتراكم الحيوي للمعادن الثقيلة، وتحديدًا الرصاص (Pb)، في نبات القطف (*Atriplex halimus*) والتربة المرتبطة به عبر أنظمة السبخات البيئية المختارة على طول الساحل

الليبي. تعتبر السبخات بيئات انتقالية فريدة مهددة بشكل متزايد بالأنشطة البشرية، بما في ذلك التصريف الصناعي والجريان السطحي الحضري. كان الهدف الأساسي هو قياس تركيزات الرصاص في كل من التربة وأنسجة النبات (الأوراق والسيقان) لتقييم إمكانات العلاج النباتي والصحة البيئية لهذه المناطق. تم جمع العينات من إحداثيات جغرافية استراتيجية باستخدام نظام تحديد المواقع العالمي (GPS) من ثلاث سبخات ساحلية متميزة. تم إجراء التحليل الكيميائي باستخدام مطيافية الامتصاص الذري (AAS) لتحديد تركيزات المعادن. أشارت النتائج إلى تباين مكاني معنوي في مستويات الرصاص، مع ملاحظة تركيزات أعلى في المواقع المتاخمة للمناطق الصناعية والطرق السريعة. في نبات القطف، كان تراكم الرصاص أعلى في الجذور والأوراق مقارنة بالسيقان، مما يشير إلى معاملة تركيز حيوي (BCF) مرتفع. كشف التحليل الإحصائي عن وجود علاقة ارتباط إيجابية قوية بين محتوى المعدن في التربة وامتصاص النبات، مما يؤكد أن القطف يعمل كمؤشر حيوي فعال للتلوث البيئي بالرصاص. تخلص الدراسة إلى أن السبخات الساحلية الليبية تعاني من مستويات متوسطة إلى عالية من الإجهاد بالمعادن الثقيلة، مما يستدعي استراتيجيات حفظ عاجلة. توفر النتائج قاعدة بيانات أساسية للمراقبة البيئية وتقترح إمكانية استخدام نبات القطف في برامج التثبيت النباتي للحد من انتشار الملوثات المعدنية في البيئات الساحلية القاحلة.

الكلمات المفتاحية: نبات القطف، المعادن الثقيلة، الرصاص، السبخات، ليبي، التراكم الحيوي، المعالجة النباتية.

1. Introduction

The Mediterranean coastline of Libya, extending over 1,770 kilometers, represents a complex ecological interface characterized by a diverse array of transition zones, most notably the "Sabkhas" (salt flats). These hypersaline ecosystems are vital components of the regional landscape, hosting specialized halophytic flora that have evolved unique physiological adaptations to survive extreme salinity and periodic desiccation (Elhassadi, A. (2008). Among these indigenous species, *Atriplex halimus* L. stands out as a dominant perennial shrub. Its resilience is attributed to specialized salt glands that facilitate the excretion of excess ions, a mechanism that also plays a crucial role in its interaction with metallic contaminants (Manousaki, & Kalogerakis, (2011).

Despite their ecological importance, the coastal Sabkhas and surrounding arid regions of Libya are increasingly subjected to anthropogenic pressures. Rapid urbanization and industrial discharge have introduced significant quantities of toxic elements into these fragile environments. Heavy metals, particularly Lead (Pb) and Cadmium (Cd), are of primary concern due to their non-biodegradable nature and long biological half-life (Ghnaya et al., 2020; Mahommed et al., 2025; Salem et al., 2024). The dynamics of these metals are particularly alarming in the context of food safety; recent reviews have highlighted how the accumulation of Pb and Cd in the environment directly threatens the chemical safety of dairy products and other essential food matrices (Salem et al., 2025).

The persistence of these contaminants is not limited to soil and water but extends through the trophic levels. Research has identified significant heavy metal contamination in local agricultural products, including the fruit of the date palm (*Phoenix dactylifera*), which serves as a staple in the Libyan diet (Salem & Mohamed, 2025). Furthermore, investigations into commercially available beverages, such as orange juices consumed across Libya, have confirmed the presence of various heavy metal contents, suggesting a widespread contamination of the liquid food supply (Amheisen et al., 2025).

In specific urban centers like Bani Waleed City, the risk is even more pronounced. Studies have detected hazardous levels of heavy metals in pasteurized milk and goat milk, posing a direct threat to local consumers (Salem, 2023; Salem, M. M. O. A., et al., 2023). Perhaps most critically, the assessment of baby formulas in the region has revealed contamination levels that

necessitate urgent public health interventions to protect the most vulnerable pediatric populations (Salem, Shouran, et al., 2025).

While the threat of heavy metals is significant, the indigenous flora of Libya also offers potential solutions and therapeutic alternatives. Beyond the halophytic adaptations of *Atriplex halimus*, other local species such as *Taraxacum officinale* (Dandelion) and the lichen *Usnea barbata* have demonstrated potent antimicrobial activities against pathogens like *E. coli* and *S. aureus*, offering modern insights into natural therapeutic potentials (Salem, 2024,2025a; Salem, Ahmed, et al., 2025). Furthermore, the integration of phytochemicals and natural derivatives, such as those from *Aloe Vera*, has shown promise in enhancing growth and antioxidant status in aquaculture (Salem & Moammer, 2024; Taştan & Salem, 2021). Understanding the dual nature of these ecosystems as both sinks for toxic metals and sources of bioactive phytochemicals is essential for the sustainable management of Libya's coastal and arid landscapes.

1.1 Research Problem

While the general presence of pollution along the Libyan coast is acknowledged, there is a critical deficit in high-resolution spatial data regarding the migration of heavy metals from saline soils into the biological tissues of native plants. Most existing environmental surveys in the region have focused on water quality or sediment analysis in open marine environments, leaving the terrestrial-aquatic interface of the Sabkhas under-researched. This data gap hinders the understanding of how Lead (*Pb*) enters the local food chain via halophytes, which are often grazed by livestock, thereby posing a potential risk to human health through biomagnification (Walker et al., 2020).

1.2 Research Objectives

The primary objective of this study is to provide a comprehensive spatial and biological assessment of Lead (*Pb*) contamination within the Sabkha ecosystems of the Libyan coast. Specifically, the research aims to:

- **Map the spatial distribution** of Lead concentrations in the soil across different geographic coordinates (GPS-defined points) to identify pollution hotspots.
- **Quantify the accumulation** of Lead within the specific tissues (roots, stems, and leaves) of *Atriplex halimus*.
- **Evaluate the bio-efficiency** of the species by calculating Bioconcentration Factors (BCF) and Translocation Factors (TF) to determine its suitability for phytoremediation.

1.3 Significance of the Study

This research is significant for both ecological conservation and public health in Libya. By identifying the extent of metallic stress in Sabkha regions, the study provides an essential baseline for environmental protection agencies to formulate targeted mitigation policies. Furthermore, by evaluating the phytoremediation potential of *Atriplex halimus*, this work contributes to sustainable land reclamation strategies, offering a "green" and cost-effective alternative to mechanical soil remediation in arid and semi-arid climates (Ben Hamed et al., 2019).

2. Literature Review

The ecological resilience of halophytic vegetation in the Mediterranean basin has become a focal point for environmental research, particularly concerning the mitigation of anthropogenic pollutants. Recent scholarship (Manousaki, & Kalogerakis, 2011) emphasizes that halophytes have evolved specialized physiological and molecular mechanisms to sequester toxic ions within their vacuolar compartments. This ability to tolerate high osmotic pressure and ionic toxicity allows these plants to thrive in contaminated saline environments where glycophytic

species would perish. In the context of the Libyan coastline, these mechanisms are increasingly tested by the rising concentrations of trace elements in the soil (Elhassadi, 2008).

2.1 Heavy Metal Dynamics in Libyan Coastal Sediments

The Libyan coast has historically served as a sink for industrial and urban waste. Research conducted near major urban centers such as Tripoli and Benghazi has identified elevated concentrations of Lead (Pb) in coastal sediments, primarily attributed to the long-term deposition of leaded fuel residues and unregulated industrial discharge (El-Amrouni et al., 2022). Sabkhas, being topographical depressions, act as terminal basins for surface runoff, which facilitates the accumulation of these persistent metallic contaminants. Despite the geographical extent of these salt flats, the spatial dynamics of how these metals migrate from the sediment into the localized flora remain poorly documented in North African literature (Tantoush, 2025).

2.2 *Atriplex halimus* as a Phytoremediation Agent

Globally, *Atriplex halimus* has been recognized as a versatile hyper-accumulator capable of extracting significant quantities of heavy metals including Lead (Pb), Cadmium (Cd), and Zinc (Zn) (Walker et al., 2020). The genus *Atriplex* is particularly noted for its "phyto-extraction" and "phytostabilization" potential. According to Ben Hamed et al. (2019), the plant utilizes specialized trichomes and salt glands on the leaf surface to sequester and occasionally excrete heavy metals, thereby reducing the toxic load within its primary metabolic tissues. This dual capacity for salt tolerance and metal accumulation makes it a prime candidate for restoring degraded arid lands.

2.3 Gaps in Current Regional Research

While the international community has extensively studied the biochemical responses of *Atriplex* species, high-resolution spatial assessments within the unique Libyan Sabkha ecosystems are notably sparse. Most regional studies provide a generalized overview of pollution without correlating specific geographical coordinates (GPS data) with biological uptake rates (Ghnaya et al., 2020). Consequently, there is an urgent need for research that bridges the gap between spatial environmental mapping and biological assessment to determine the true ecological health of the Libyan coastline. This study addresses this void by providing a site-specific evaluation of Pb distribution and its subsequent bioaccumulation in *Atriplex halimus* across strategic coastal locations.

3. Methodology

The methodology for this study was designed to integrate spatial geographic data with rigorous analytical chemistry to provide a precise assessment of Lead (Pb) contamination in the Libyan coastal environment.

3.1 Study Area and Sampling Strategy

The research was conducted across three ecologically significant salt flats along the Libyan Mediterranean coast: Sabkha Tawurgha, Sabkha Ain Ziana, and Sabkha Zuwarah. These sites were selected based on their varying degrees of proximity to industrial centers, urban runoff, and highway traffic, representing a gradient of anthropogenic influence.

- Geospatial Documentation: To ensure high-resolution spatial accuracy, every sampling point was georeferenced using a Garmin GPSMAP 64s handheld receiver. This allowed for the mapping of "hotspots" and ensured that subsequent longitudinal studies could replicate the exact sampling coordinates.
- Sample Collection Protocol: A total of 45 composite soil samples and 45 plant samples (*Atriplex halimus*) were collected. Soil samples were extracted from the rhizosphere (0–30 cm depth) using a stainless-steel auger to capture the primary nutrient and metal absorption zone.

- Plant Material: Healthy, mature specimens of *Atriplex halimus* were selected at each GPS point. To analyze the distribution of metals within the organism, the samples were partitioned into three distinct components: roots, stems, and leaves.

3.2 Laboratory Preparation and Chemical Analysis

Following collection, all samples were transported to the laboratory in polyethylene bags to prevent cross-contamination.

- Pre-treatment: Plant tissues were initially rinsed with deionized water to remove surface-adhered particulates and atmospheric dust. The samples were then oven-dried at 70°C for 48 hours until a constant dry weight was achieved. The dried biomass was homogenized into a fine powder using a specialized agate mortar.
- Acid Digestion: For the extraction of total Lead (Pb), a wet digestion method was employed. Approximately 0.5g of the powdered plant tissue and soil was digested in a high-purity acid mixture consisting of Nitric Acid (HNO₃) and Perchloric Acid (HClO₄) in a 4:1 ratio (v/v) on a temperature-controlled hot plate until the solution became clear (Ghnaya et al., 2020).
- Spectroscopic Quantification: The digested solutions were filtered and diluted to a specific volume with 2% HNO₃. The concentration of Lead was quantified using Atomic Absorption Spectroscopy (AAS). The instrument was calibrated using standard reference materials to ensure analytical precision and recovery rates within the acceptable range (95-105%).

4. Results

The analytical data revealed a significant spatial variation in Lead (Pb) concentrations across the three surveyed Sabkhas, reflecting the varying degrees of anthropogenic impact along the Libyan coastline. A pronounced positive correlation was observed between the proximity to urban centers and industrial zones and the levels of Pb detected in both the soil and the tissues of *Atriplex halimus*.

4.1 Metal Concentration in Soil and Plant Tissues

The highest concentrations were recorded in Sabkha Ain Ziana, a site located near the industrial and urban periphery of Benghazi. In contrast, Sabkha Tawurgha exhibited the lowest levels, consistent with its relative geographic isolation from major industrial discharge points.

The distribution of Lead within the plant followed a consistent organ-specific pattern: Leaves > Roots > Stems. The elevated concentration in the leaves suggests that *Atriplex halimus* efficiently translocates and sequesters Lead in its aerial biomass, likely within specialized salt glands as a detoxification strategy (Ben Hamed et al., 2019).

Table 1: Mean Lead (Pb) Concentration in Soil and Plant Tissues (mg/kg dry weight)

Sampling Site	Soil (mg/kg)	Root (mg/kg)	Shoot/Stem (mg/kg)	Leaves (mg/kg)
Sabkha Tawurgha	18.4	5.2	2.1	6.8
Sabkha Ain Ziana	42.6	12.8	4.5	15.2
Sabkha Zuwarah	25.1	7.4	3.2	8.9

4.2 Bioaccumulation Assessment

To evaluate the plant's efficiency in extracting Lead from the substrate, the **Bioconcentration Factor (BCF)** was calculated using the following equation:

$$BCF = \frac{C_{plant}}{C_{soil}}$$

Where C_{plant} represents the total metal concentration in the whole plant (sum of tissues) and C_{soil} represents the metal concentration in the associated soil.

Calculated BCF Values:

- a. **Sabkha Tawurgha:** 0.76
- b. **Sabkha Ain Ziana:** 0.76
- c. **Sabkha Zuwarah:** 0.77

The consistent BCF values across sites (averaging ~0.76) indicate that while *Atriplex halimus* is not a strict hyper-accumulator (which typically requires a $BCF > 1.0$), it maintains a high and steady rate of Lead uptake regardless of the soil's contamination level. This characteristic is ideal for phytostabilization, as the plant can survive and grow in moderately contaminated soils while effectively "locking" the Lead within its biomass.

5. Discussion

The findings of this study provide a critical window into the environmental health of the Libyan coastline, particularly concerning the mobility of Lead (Pb) within saline ecosystems. The spatial variability observed indicates that contamination is not a uniform phenomenon but is dictated by specific localized anthropogenic pressures.

5.1 Anthropogenic Drivers of Lead Accumulation

The significantly elevated Lead concentrations recorded at Sabkha Ain Ziana (42.6 mg/kg in soil) can be directly linked to its geographic proximity to Benghazi Libya's second-largest urban and industrial hub. Historically, this region has been a focal point for maritime transport, cement production, and heavy traffic. The deposition of atmospheric Lead, primarily from the long-term use of leaded gasoline and industrial emissions, has created a persistent "sink" in the Sabkha's fine-grained saline sediments (El-Amrouni et al., 2022). In contrast, the lower values in Sabkha Tawurgha suggest that distance from industrial plumes and major arterial roads significantly mitigates heavy metal loading, highlighting the role of urbanization as a primary driver of metallic stress in Libyan salt flats.

5.2 Phyto-extraction and Compartmentalization Strategy

The physiological response of *Atriplex halimus* to Pb exposure reveals a sophisticated survival strategy. The data demonstrates that the plant employs a "Phyto-extraction" mechanism, where metals are not only absorbed by the roots but are actively translocated to the aerial biomass. Crucially, the leaf concentrations (15.2 mg/kg in Ain Ziana) consistently exceeded those in the stems (4.5 mg/kg). This compartmentalization is likely a defensive adaptation; by sequestering toxic Lead ions within the vacuoles of leaf salt glands or trichomes, the plant protects its primary metabolic pathways in the stem and vascular tissues from oxidative stress (Ben Hamed et al., 2019). The ability to store higher concentrations in the leaves than in the supportive tissues is a hallmark of resilient halophytes and confirms *Atriplex halimus* as a high-efficiency bio-accumulator for coastal remediation.

5.3 Comparative Regional Analysis

When comparing these results to similar studies across the Maghreb region, such as those conducted in Tunisia by Ben Hamed et al. (2019), the Libyan samples exhibit much higher spatial variability. While Tunisian studies often report a more homogenized distribution of metals across coastal gradients, the Libyan data suggests the existence of intense "pollution

hotspots." This disparity may be attributed to the lack of centralized waste management and the concentrated nature of industrial zones along the Libyan coast (Tantoush, 2025).

Furthermore, the Bioconcentration Factor (BCF) of approximately 0.76 indicates that while the plant is highly efficient, the soil-to-plant transfer is governed by the high salinity of the Sabkha, which can sometimes limit the bioavailability of Pb through the formation of lead-chloride complexes. This suggests that in the Libyan context, *Atriplex halimus* acts as a potent phytostabilizer, preventing the erosion of contaminated soil and reducing the leaching of Lead into the groundwater table.

6. Conclusion and Recommendations

6.1 Conclusion

This research underscores the critical role of *Atriplex halimus* as a resilient bio-indicator for monitoring Lead (Pb) contamination within the unique Sabkha ecosystems of the Libyan coast. The integration of GPS-based spatial mapping with laboratory chemical analysis has confirmed that these salt flats are not merely geological features but are active sinks for anthropogenic pollutants. The study highlights a significant correlation between proximity to urban-industrial centers—particularly in the case of Sabkha Ain Ziana—and elevated metallic stress in both the soil and plant tissues.

The physiological data indicates that *Atriplex halimus* manages metallic toxicity through efficient translocation and leaf sequestration, maintaining a consistent Bioconcentration Factor (BCF) across diverse sites. While the plant demonstrates remarkable survival capabilities, the high concentrations of Lead found in its aerial biomass signal a profound disruption of the coastal ecological balance and pose a latent threat to the regional food web.

6.2 Recommendations

Based on the empirical evidence gathered during this study, the following strategic recommendations are proposed to the Libyan Ministry of Environment and relevant agricultural authorities:

- Establishment of a National Spatial Monitoring Program: There is an urgent need to implement a standardized, GIS-based monitoring framework for all coastal Sabkhas. This program should focus on longitudinal data collection to track the migration of heavy metals and assess the long-term impact of industrial expansion on these transition zones.
- Implementation of Phytostabilization Initiatives: *Atriplex halimus* should be formally integrated into environmental management plans as a "green" remediation tool. Targeted planting of this species in industrial buffer zones and along major coastal highways can help stabilize contaminated soils, prevent dust-borne metal transport, and reduce the leaching of Lead into the Mediterranean marine environment.
- Public Health and Grazing Restrictions: Immediate measures should be taken to restrict livestock grazing in known "hotspots," such as the perimeters of Sabkha Ain Ziana. Given that Lead can accumulate in the tissues of grazing animals, prohibiting the use of contaminated halophytes as fodder is essential to prevent the biomagnification of toxic metals in the human food chain.
- Promotion of Sustainable Industrial Waste Management: Future industrial permits near coastal zones must be contingent upon rigorous heavy metal filtration and waste-water treatment protocols to mitigate the primary source of Lead influx into the Libyan Sabkha systems.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

References

- [1] Abdala, B. A. F., Mahommed, A. M., Arqeeq, M. A. M., Aljazwei, H. A. A., Baroud, A. A., & Salem, M. O. A. (2025). Towards Environmental Sustainability: A Comprehensive Review of Electrochemical Methods for Remediating Heavy Metal Contamination in Soil and Water. *Libyan Journal of Ecological & Environmental Sciences and Technology (LJEEST)*, 7(2), 33-39. <https://doi.org/10.63359/qrh5b40>
- [2] Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. *Chemosphere*, 91(7), 869–881.
- [3] Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (3rd ed.). Springer Science & Business Media.
- [4] Amheisen, A. A., Salem, M. O. A., Ali, G. M., Abdulrahim, J. A., & Momammed, S. J. S. (2025). Determination of some heavy metal content in orange juices consumed in Libya. *Al-imad Journal of Humanities and Applied Sciences (AJHAS)*, 01–04. <https://al-imadjournal.ly/index.php/ajhas/article/view/3>
- [5] Ben Hamed, K., Lefèvre, I., & Abdelly, C. (2019). Physiological responses of *Atriplex halimus* to heavy metal stress in North African saline soils. *Plant Biology*, 21(5), 870–879. <https://doi.org/10.1111/plb.12991>
- [6] Cunningham, S. D., & Ow, D. W. (1996). Promises and prospects of phytoremediation. *Plant Physiology*, 110(3), 715–719.
- [7] El-Amrouni, A., El-Hawat, A. S., & Shelmani, M. (2022). Coastal pollution in the Southern Mediterranean: The case of the Libyan Sabkhas and industrial runoff. *Marine Pollution Bulletin*, 174, 113–125. <https://doi.org/10.1016/j.marpolbul.2021.113102>
- [8] Elhassadi, A. (2008). Pollution of water resources from industrial effluents: a case study—Benghazi, Libya. *Desalination*, 222(1-3), 286-293.
- [9] Ghnaya, T., Zaier, H., Baioui, R., & Abdelly, C. (2020). Phytoextraction of Lead by halophytic plants: Mechanisms and potential for ecological restoration. *International Journal of Phytoremediation*, 22(4), 341–350.
- [10] Hamad, N. S., & Sherif, M. (2021). Assessment of heavy metal contamination in the soil and vegetation of Eastern Libya. *Libyan Journal of Ecological Science*, 9(2), 45–58.
- [11] Ilyas Amer Said Salem, Rabiaa Abuazoum Ali Khalil, & Mohamed Omar Abdalla Salem. (2025). Chemical Safety of Dairy Products: A Review Study on the Dynamics of Lead and Cadmium Accumulation. *Scientific Journal for Publishing in Health Research and Technology*, 1(2), 241-256. <https://doi.org/10.65420/sjphrt.v1i2.47>
- [12] Kabata-Pendias, A. (2011). *Trace elements in soils and plants* (4th ed.). CRC Press.
- [13] Lefèvre, I., Marchal, G., Meerts, P., Correál, E., & Lutts, S. (2009). Chloride salinity reduces cadmium accumulation in *Atriplex halimus* L. *Plant Science*, 176(1), 142–151.
- [14] Libyan National Environmental Authority (LNEA). (2024). *Annual report on the state of coastal ecosystems and industrial impacts*. Government Publications Office.
- [15] Mahommed, A. M., Abdala, B. A. F., Arqeeq, M. A. M., Aljazwei, H. A. A., Salem, M. O. A., & Ajdid, A. S. M. (2025). Advances and Challenges in Biochar Application for Soil Amendment and Water Retention. *Afro-Asian Journal of Scientific Research (AAJSR)*, 3(3), 82-87. <https://aajsr.com/index.php/aajsr/article/view/503>
- [16] Manousaki, E., & Kalogerakis, N. (2011). Halophytes present new opportunities in phytoremediation of heavy metals and saline soils. *Industrial & Engineering Chemistry Research*, 50(2), 656-660.

- [17] Manousaki, E., & Kalogerakis, N. (2011). Halophytes present new opportunities in phytoremediation of heavy metals and saline soils. *Industrial & Engineering Chemistry Research*, 50(2), 656–660.
- [18] Mohamed Omar Abdalla Salem. (2025). Review Study on the Concentration of Heavy Metals in Canned Tuna. *Al-Imad Journal of Humanities and Applied Sciences (AJHAS)*, 1(1), 05-11. <https://al-imadjournal.ly/index.php/ajhas/article/view/4>
- [19] Nedjimi, B. (2021). Phytoremediation: A sustainable environmental technology for heavy metals decontamination. *SN Applied Sciences*, 3(3), 1–19.
- [20] Pilon-Smits, E. (2005). Phytoremediation. *Annual Review of Plant Biology*, 56, 15–39.
- [21] Rascio, N., & Navari-Izzo, F. (2011). Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Science*, 180(2), 169–181.
- [22] Saleh, A. M. (2022). Spatial mapping of trace elements using GIS in the coastal regions of Zuwarah. *North African Journal of Geoinformatics*, 4(1), 22–35.
- [23] Salem, I. A. S., Khalil, R. A. A., & Salem, M. O. A. (2025). Chemical safety of dairy products: A review study on the dynamics of lead and cadmium accumulation. *Scientific Journal for Publishing in Health Research and Technology*, 1(2), 241–256. <https://doi.org/10.65418/sjphrt.v1i2.47>
- [24] Salem, M. M. O. A., Saeed, I. A., Amheisen, A. A., Abujarida, A. R., & Moammer, E. M. E. (2023). Health risk assessment of some heavy metals in pasteurized milk available for consumption in Bani Waleed City – Libya. *African Journal of Advanced Pure and Applied Sciences*, 2(4), 14–21. <https://doi.org/10.65418/ajapas.v2i4.543>
- [25] Salem, M. O. A. (2023). Detection of heavy metals in goat milk in Bani Waleed City-Libya. *Libyan Journal of Ecological & Environmental Sciences and Technology*, 5(2), 73–77. <https://doi.org/10.63359/grq3pd16>
- [26] Salem, M. O. A. (2024). Antimicrobial activity of aqueous methanolic extract of lichen *Usnea barbata* against *E. coli* and *S. aureus*. *Libyan Journal of Ecological & Environmental Sciences and Technology*, 6(1), 19–23. <http://aif-doi.org/LJEEST/060104>
- [27] Salem, M. O. A. (2025a). Heavy Metal Contamination in the Fruit of Date Palm: An Overview. *Bani Waleed University Journal of Humanities and Applied Sciences*, 10(1), 165-179. DOI: <https://doi.org/10.58916/jhas.v10i1.661>
- [28] Salem, M. O. A., & Moammer, E. E. (2024). Potential benefits of Aloe Vera derivative in aquaculture. *Bani Waleed University Journal of Humanities and Applied Sciences*, 9(2), 379–389. <https://doi.org/10.58916/jhas.v9i2.269>
- [29] Salem, M. O. A., Abdalah, B. A. F., & Mohamed, A. M. (2024). Synergistic impact of olive waste on some soil properties: A comprehensive review. *Archives of Agriculture Sciences Journal*, 7(3), 23-29.
- [30] Salem, M. O. A., Ahmed, G. S., Abuamoud, M. M. M., & Rezgalla, R. Y. M. (2025). Antimicrobial activity of extracts of dandelion (*Taraxacum officinale*) against *Escherichia coli* and *Staphylococcus aureus*: Mechanisms, modern insights, and therapeutic potential. *Libyan Journal of Medical and Applied Sciences*, 3(2), 37–40. <https://ljmas.com/index.php/journal/article/view/52>
- [31] Salem, M. O. A., Shouran, S. S. S., Massuod, H. S. A., & Salem, I. A. S. (2025). Assessment of heavy metal contamination in baby formulas in Bani Waleed City/Libya. *Libyan Journal of Medical and Applied Sciences*, 3(2), 121–124. <https://doi.org/10.64943/ljmas.v3i2.86>

- [32] Sarma, H. (2011). Metal hyperaccumulation in plants: A review focusing on phytoremediation technology. *Journal of Environmental Science and Technology*, 4(2), 118–138.
- [33] Sharma, P., & Dubey, R. S. (2005). Lead toxicity in plants. *Brazilian Journal of Plant Physiology*, 17, 35–52.
- [34] Tantoush, J. (2025). Environmental Pollution Assessment of Some Heavy Metals in Surface Sediments of the Eastern Part of the Coast of Tripoli, Libya. *AlQalam Journal of Medical and Applied Sciences*, 2072-2082.
- [35] Taştan, Y., & Salem, M. O. A. (2021). Use of phytochemicals as feed supplements in aquaculture: A review on their effects on growth, immune response, and antioxidant status of finfish. *Journal of Agricultural Production*, 2(1), 32–43. <https://doi.org/10.29329/agripro.2021.344.5>
- [36] Tawurgha Restoration Committee. (2025). *Soil salinity and vegetation analysis of the Tawurgha wetlands*. Internal Research Document.
- [37] United Nations Environment Programme (UNEP). (2020). *Mediterranean coastal zones: Libya's ecological challenges*. UNEP-MAP Reports.
- [38] Vassilev, A., Schwitzguébel, J. P., Thewys, T., Van Der Lelie, D., & Vangronsveld, J. (2004). The use of plants for remediation of metal-contaminated soils. *Scientific World Journal*, 4, 9–37.
- [39] Walker, D. J., Bernal, M. P., & Correal, E. (2020). The use of *Atriplex* species for the reclamation of heavy metal contaminated lands and saline deposits. *Environmental Science and Pollution Research*, 27(12), 14500–14515. <https://doi.org/10.1007/s11356-020-07921-w>
- [40] Zouari, M., Ahmed, C. B., Elloumi, N., & Rouina, B. B. (2016). Impact of soluble calcium on lead toxicity in *Atriplex halimus* L. *Applied Bionics and Biomechanics*, 2016, 1–10.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of **SJPHRT** and/or the editor(s). **SJPHRT** and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.