

Assessment of Water Management in Enhancing Sunflower (*Helianthus annuus* L.) Performance for Pb²⁺ Heavy Metal Remediation

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Abstract

This study, conducted at Bakrajo Technical Institute (2021–2022), examines factors affecting bioremediation of lead (Pb²⁺) using two sunflower species, Lemon Queen and Mammoth Russian. A randomized complete block design (CRD) and analysis of variance (ANOVA) were used to evaluate the effects of species, water types, moisture depletion, and their interactions on Pb²⁺ bioremediation and translocation. Results show significant effects of species ($p = 0.00047$), water types ($p = 0.001$), and their interaction ($p = 0.001$) on the bioremediation factor (BAF Pb²⁺), highlighting their importance in improving Pb²⁺ removal by sunflowers. Moisture depletion also significantly impacted Pb²⁺ remediation ($p = 0.036$), but higher-order interactions, such as species × moisture depletion and water types × moisture depletion, were not significant. The study also found that species and water types significantly influenced Pb²⁺ translocation ($F = 6071.850$, $p = 0.00016$), root Pb²⁺ concentration ($p = 0.002$), and soil Pb²⁺ levels ($F = 451.077$, $p = 0.002$). Additionally, species and water types significantly affected potassium (K⁺) uptake in roots ($F = 601664.1$, $p < 0.0001$), while moisture depletion had little effect. These findings emphasize the importance of selecting appropriate species and water management for optimizing Pb²⁺ bioremediation.

Introduction:

Lead (Pb²⁺) contamination of water and soil poses a significant threat to the health of human beings and the environment, thus there is a desire for efficient and cost-effective technologies for decontamination. Plant-based remediation involving the use of flora to mobilize, stabilize, or convert contaminants from the environment, has also attracted significant interest as a green and eco-friendly approach for heavy metal decontamination [1]. The method is particularly appealing because it is inexpensive, has a low environmental impact, and has the possibility to reuse biomass. Plants contain metals like lead (Pb²⁺) in their tissues, making them ideal for remediating damaged environments [2]. Sunflowers have a vast root system that is capable of not only extracting contaminants from the soil, but also of rapid

development and adaptation to a variety of environmental situations, making them suitable for remediation. The goal of this study is to examine the potential for phytoremediation.

Effectiveness of two specific ornamental sunflower hybrids, *Helianthus annuus* 'Lemon Queen' and *Helianthus annuus* 'Mammoth Russian', in removing Pb^{2+} from contaminated soils, determining their efficiency in lead absorption and their general capacity for improving soil quality in contaminated environments. Sunflowers are particularly effective in phytoremediation due to their extensive root systems, quick development, and large biomass, which promote the absorption of contaminants from soil into the plant environments [3, 4, 1].

The capacity of flowering plants to thrive in diverse soils and accumulate contaminants at shoots and roots makes them ideal for phytoremediation, especially in lead. These crops have been shown to be resistant to environmental stresses, including heavy metal toxicity, and may thrive in polluted environments, making them viable options for phytoremediation applications [5,6]. These particular types not only have aesthetic appeal, but they also contribute in ecological restoration processes by assisting with accumulation mechanisms. Understanding the Pb^{2+} removal ability of these sunflower types is crucial for establishing their realistic application in phytoremediation procedures. This work adds through considering their ability to absorb and tolerate lead in soil management.

The major goal of this study is to determine the ability of Lemon Queen and Mammoth Russian sunflowers to remove lead from polluted soil in controlled settings. This study will assess the efficiency of Pb^{2+} absorption, translocation, and biomass production in decorative sunflower types to determine their feasibility for phytoremediation. This study could provide a novel, long-term approach to mitigating Pb^{2+} pollution in urban and agricultural settings, improving both the environmental and aesthetic values of landscape management.

Materials and Methods

The present investigation was carried out in open area of the Bakrajo Technical Institute Farm, Sulaimani Polytechnic University, in Sulaimani, Kurdistan Region, Iraq, over the 2021-2022 period of cultivation. The research site is situated at around 35.5614°N latitude and 45.3967°E longitude, and at an elevation of around 850 meters above sea level. The region has a semi-arid environment with a mean annual temperature ranging from 22 to 45°C and an average annual rainfall of 200 to 500 mm, the greater portion occurring from November to April. Climatic conditions, soil type, and topography are key in determining agricultural productivity and the sustainability of embracing phytoremediation methods involving sunflower species in the region.

Experiment details

The pot experiment was conducted at the open field of the Bakrajo Technical Institute, Sulaimani University, located in Sulaimani City, during the 2021-2022 growing season. The experiment utilized 30-liter plastic pots, each filled with 30 kg of surface soil (0-20 cm depth). To produce seedlings, sunflower seeds were initially sown in germination trays on April 4, 2021. After two weeks, the seedlings were transferred to the pots. Initially, three seedlings were planted in each pot, but this number was later reduced to one per pot. The plants were harvested on July 19, 2022, after a growth period of 95 days. The experiment used a randomized full block design with three replications. Sunflower species were the

primary experimental plots, with water sources randomized within sub-plots and water availability regimes given to sub-subplots. In this study, two different cultivars of *Helianthus annuus* (sunflower) will be used: Lemon Queen and Mammoth Russian. Lemon Queen is recognized for its brilliant yellow, tiny flowers, and ability to flourish in a variety of growing environments, making it a popular decorative plant and subject of floral pattern studies. Mammoth Russian, on the other hand, is distinguished by its huge, towering stature and massive flower heads, and is commonly used for seed production as well as a model for investigating growth rates and biomass buildup. The study will compare these two kinds to investigate differences in growth patterns, blooming timings, and seed output under controlled settings, offering vital insights into the genetic and environmental variables that influence sunflower development.

Soil and sub trait preparation:

The soil samples were taken at the Bakrajo Technical Institute's agricultural research field in Bakrajo, Sulaimani City. The soil was part of the institute's experimental station, where researchers conducted agricultural and environmental studies. The obtained soil samples were dried in air under laboratory conditions, crushed lightly, and sieved through a 4 mm stainless-steel mesh to make them suitable for pot tests. Moreover, a 2 mm sieved portion of the soil was also prepared in order to establish homogeneity to be used later for physicochemical analysis. Analytical examination was conducted to determine the chemical and physical attributes of the soil, such as pH, electrical conductivity (EC), organic matter, total nitrogen, available phosphorus, and cation exchange capacity (CEC). The soil texture was silty clay with a balanced proportion of silt, clay, and sand. Soil attributes collected using respective analytical methods are given in Appendix Table 1.

Water Preparation:

The test sunflower crops were irrigated with two types of water to assess their impact on the growth of plants and the condition of soil. The control treatment was given tap water from the Bakrajo municipality piped water supply system, which is treated and meets the requirements for standard water quality for both domestic and agricultural uses. In contrast, the experimental group was supplied with well water extracted from a borehole that existed within the Bakrajo Technical Institute. The well water was taken directly from the raw water storage tank without treatment using any chemicals or biological means. In addition, a supplementary water supply was introduced utilizing well water for irrigation to supplement the existing supply. Water for irrigation was evaluated for availability based on levels of depletion, and a data availability depletion level of 75% was set to offer the optimum supply of moisture while promoting efficient use of water.

Water Quality and Suitability for Irrigation:

- Tap Water (Municipal Supply): Suitable for irrigation, treated and free of major impurities. It is typically pH balanced and low in salinity, hence a great option for plant growth.
- Untreated Well Water: Its suitability for irrigation depends on salinity (EC), pH, and dissolved minerals. In some cases, untreated well water will contain more dissolved salts, and it should be monitored to avoid soil salinization.

-The selection of water sources and the 75% depletion threshold accords with normal irrigation regimes such that the water content of the soil falls within a preferred regime without the overuse of water.

Results and discussion

Table 1 presents summary statistics for various variables related to the assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation. The table includes observations (24), with minimum, maximum, mean, and standard deviation values for each variable. These variables include the bioconcentration factor (BAF Pb²⁺), lead (Pb²⁺) concentration in shoot, root, and soil, as well as potassium (K) concentrations in the roots, shoots, and soil. The table also provides data for root and shoot weights, which reflect the sunflower's growth under the influence of Pb²⁺ remediation. The standard deviations indicate the variability of each parameter within the sample, with the means offering a central tendency for each variable. This analysis aids in understanding the efficiency and effectiveness of sunflowers in phytoremediation efforts for Pb²⁺ contamination.

Table 1. Summary statistics analysis for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ Heavy metal remediation

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
BAF Pb ²⁺	24	0.481	1.010	0.895	0.172
TL Pb ²⁺	24	0.831	0.999	0.946	0.053
Pb ²⁺ Shoot	24	0.110	0.881	0.524	0.324
Pb ²⁺ Root	24	0.116	0.970	0.561	0.352
Pb ²⁺ Soil	24	0.118	0.980	0.594	0.336
K ⁺ Root	24	190.000	324	258.292	40.720
K ⁺ Shoots	24	197.000	330	264.250	41.199
K ⁺ Soil	24	200.000	350	272.917	44.378
Root weight (g)	24	13.010	20.1	16.011	1.985
Shoots weight (g)	24	35.390	95.61	66.704	16.171

Analysis of variance bioremediation factor (BAF Pb²⁺) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ Heavy metal remediation

The results presented in the table from the analysis of variance (ANOVA) for the bioremediation factor (BAF Pb²⁺) reveal several significant and non-significant interactions that impact the performance of sunflower (*Helianthus annuus* L.) in remediating Pb²⁺ heavy metal from irrigation water. Specifically, the species factor (p = 0.00047), water types for irrigation (p = 0.001), and their interaction (p = 0.001) show highly significant effects on the BAF Pb²⁺, indicating that these factors play a critical role in enhancing the sunflower's ability to remediate Pb²⁺. The moisture depletion factor (p = 0.036) is also significant, suggesting that water stress may affect remediation efficiency. However, the interactions between species and moisture depletion (p = 0.147), as well as

water types and moisture depletion ($p = 0.122$), are not statistically significant, indicating that these variables do not interact in a meaningful way to influence the bioremediation process. Additionally, the three-way interactions involving species, water types, and replicates ($p = 0.629$) or water types, moisture depletion, and replicates ($p = 0.798$) show no significance, suggesting that these higher-order interactions do not contribute substantially to the outcome [7,8]. Overall, the significant factors emphasize the importance of species selection and water management practices in enhancing Pb^{2+} remediation, while the non-significant interactions suggest that certain combinations of factors may not play as critical a role.

Table2. Analysis of variance bioremediation factor (BAF Pb^{2+}) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb^{2+} Heavy metal remediation

Sources	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	7.855	7.855	2148.921	0.00047
Water Types for irrigation	2	8.391	4.195	1147.788	0.001
Moisture depletion	1	0.096	0.096	26.310	0.036
Species*Water Types for irrigation	1	3.428	3.428	937.834	0.001
Species*Moisture depletion	1	0.020	0.020	5.350	0.147
Water Types for irrigation*Moisture depletion	2	0.053	0.026	7.225	0.122
Species*Water Types for irrigation*REP	8	0.026	0.003	0.888	0.629
Water Types for irrigation*Moisture depletion*REP	6	0.010	0.002	0.473	0.798

Analysis of variance of translocation factor (TL Pb^{2+}) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb^{2+} heavy metal remediation

The analysis of variance (ANOVA) for the translocation factor (TL Pb^{2+}) in the context of enhancing sunflower (*Helianthus annuus* L.) performance for Pb^{2+} heavy metal remediation shows several significant and non-significant effects. The species factor ($F = 6071.850$, $p = 0.00016$), water types for irrigation ($F = 2355.848$, $p = 0.00042$), and their interaction (species * water types for irrigation) were significant, indicating that both species selection and irrigation water types strongly affect Pb^{2+} translocation in sunflowers. Additionally, moisture depletion was also significant ($F = 46.973$, $p = 0.021$), suggesting that the moisture condition during growth influences Pb^{2+} uptake. However, the interaction between species and moisture depletion ($F = 1.218$, $p = 0.385$) and the water types for irrigation * moisture depletion ($F = 8.678$, $p = 0.103$) were not significant, implying that these combinations have limited impact on the translocation factor. Furthermore, the three-way interactions involving repetitions (species * water types for irrigation * REP, and water types for irrigation * moisture depletion * REP) were non-

significant, suggesting that replication across the conditions did not significantly alter the observed effects [9]. These results underline the importance of species selection and water management in improving heavy metal remediation while highlighting that some interactions, particularly those involving moisture depletion and replication, do not significantly influence the outcome.

Table 3. Analysis of variance of translocation factor (TL Pb²⁺) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ Heavy metal remediation

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	11.075	11.075	6071.850	0.00016
Water Types for irrigation	2	8.594	4.297	2355.848	0.00042
Moisture depletion	1	0.086	0.086	46.973	0.021
Species*Water Types for irrigation	1	1.749	1.749	959.119	0.001
Species*Moisture depletion	1	0.002	0.002	1.218	0.385
Water Types for irrigation*Moisture depletion	2	0.032	0.016	8.678	0.103
Species*Water Types for irrigation*REP	8	0.009	0.001	0.598	0.753
Water Types for irrigation*Moisture depletion*REP	6	0.001	0.0002	0.090	0.990

Analysis of variance of shoots concentration content of (Pb²⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation

The results of the analysis show that several factors and their interactions have significant effects on the outcomes of the study. Specifically, the main effects of Species, Water Types for Irrigation, and Moisture Depletion all have p-values less than 0.05 (p = 0.002, p = 0.001, and p = 0.005, respectively), indicating that these factors significantly influence the measured outcome. Similarly, the interactions between Species and Water Types for Irrigation, as well as Species and Moisture Depletion, are also significant (p = 0.001 and p = 0.005, respectively). The Water Types for Irrigation and Moisture Depletion interaction is significant as well (p = 0.009). However, the three-way interaction effects involving Species, Water Types for Irrigation, and REP (p = 0.321), and Water Types for Irrigation, Moisture Depletion, and REP (p = 0.759) are not significant, as their p-values are greater than 0.05, suggesting no substantial effect of these combinations on the outcome. The high F-values for the significant interactions imply strong effects, while the non-significant results suggest that these higher-order interactions do not substantially contribute to the variance in the response [10]. These findings align with typical patterns in factorial designs, where interactions involving experimental repetitions or certain combinations may not show strong effects due to limited variability or complexity beyond

the main experimental factors. Studies of similar nature also report that the significance of interactions can be influenced by experimental setup and the specific variables studied [11].

Table 4. Analysis of variance of shoots concentration content of (Pb²⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	1.128	1.128	585.596	0.002
Water Types for irrigation	2	4.578	2.289	1188.718	0.001
Moisture depletion	1	0.403	0.403	209.259	0.005
Species*Water Types for irrigation	1	2.021	2.021	1049.264	0.001
Species*Moisture depletion	1	0.375	0.375	194.479	0.005
Water Types for irrigation*Moisture depletion	2	0.449	0.225	116.578	0.009
Species*Water Types for irrigation*REP	8	0.038	0.005	2.463	0.321
Water Types for irrigation*Moisture depletion*REP	6	0.006	0.001	0.548	0.759

Analysis of variance of roots concentration content of (Pb²⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation

The results from Table 5 show that various factors and their interactions significantly influence the root concentration content of Pb²⁺ in sunflower (*Helianthus annuus* L.) during Pb²⁺ remediation. Specifically, species, water types for irrigation, and moisture depletion, as well as their interactions, showed statistically significant effects on Pb²⁺ concentration, with p-values less than 0.05 (0.002, 0.001, 0.005, 0.001, and 0.006, respectively). These variables account for changes in Pb²⁺ level in the roots, with species and irrigation water types having the most impact, as seen by large F-values (532.3 and 1148.9). Interactions involving the replication factor, such as species × irrigation × replication (REP) and water types × moisture depletion cross REP, exhibited no significant impact, with p-values significantly over 0.05 (0.395 and 0.684, respectively). This indicates that, despite these key determinants and their direct interactions impact Pb²⁺ uptake, replication did not add any extra variation. The findings emphasize the relevance of species and irrigation practices in reducing Pb²⁺ contamination, with little effect from the experimental replication procedure. These findings are consistent with previous research that has showed how water management and species features play important roles in heavy metal absorption and remediation [12].

Table 5. Analysis of variance of roots concentration content of (Pb²⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	1.251	1.251	532.3	0.002
Water Types for irrigation	2	5.401	2.701	1148.9	0.001
Moisture depletion	1	0.495	0.495	210.65	0.005
Species*Water Types for irrigation	1	2.248	2.248	956.18	0.001
Species*Moisture depletion	1	0.410	0.410	174.22	0.006
Water Types for irrigation*Moisture depletion	2	0.557	0.279	118.58	0.008
Species*Water Types for irrigation*REP	8	0.035	0.004	1.870	0.395
Water Types for irrigation*Moisture depletion*REP	6	0.010	0.002	0.713	0.684

Analysis of variance of soil concentration content of (pb²⁺) in mg L-1 for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation

The analysis of variance (ANOVA) for soil concentration in the table 6 of Pb²⁺ (in mg/L) to assess water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ remediation shows significant effects for most factors, except for some interaction terms. The factors "Species" (F = 451.077, p = 0.002), "Water Types for irrigation" (F = 791.339, p = 0.001), and "Moisture Depletion" (F = 159.047, p = 0.006) all have significant effects, indicating that the species of sunflower, irrigation water types, and moisture levels in the soil all play a role in Pb²⁺ uptake and remediation. Additionally, the interaction between "Species *Water Types for irrigation*" (F = 531.384, p = 0.002) and "Species *Moisture depletion*" (F = 121.491, p = 0.008) are also significant, suggesting that the combination of species with water types or moisture depletion significantly influences Pb²⁺ concentration. However, the three-way interactions involving "Species *Water Types for irrigation* REP" (F = 1.379, p = 0.486) and "Water Types for irrigation *Moisture depletion* REP" (F = 0.418, p = 0.828) show no significant effect, indicating that the replicates in these interactions do not contribute meaningfully to the variation in Pb²⁺ concentrations. This suggests that while certain factors and their interactions impact Pb²⁺ levels significantly, other experimental factors (like replicate interactions). Such findings emphasize the importance of species choice, irrigation practices, and moisture management in enhancing phytoremediation efforts for heavy metals like Pb²⁺. High statistical significance in the factors suggests strong evidence that manipulating these variables can effectively influence Pb²⁺ uptake in sunflowers, potentially improving remediation practices [13,10].

Table 6. Analysis of variance of soil concentration content of (Pb²⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.) performance for Pb²⁺ heavy metal remediation

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	1.661	1.661	451.07	0.0027
Water Types for irrigation	2	5.829	2.914	791.33	0.0019
Moisture depletion	1	0.586	0.586	159.04	0.0067
Species*Water Types for irrigation	1	1.957	1.957	531.38	0.0024
Species*Moisture depletion	1	0.447	0.447	121.49	0.0081
Water Types for irrigation*Moisture depletion	2	0.523	0.261	70.954	0.014
Species*Water Types for irrigation*REP	8	0.041	0.005	1.379	0.486
Water Types for irrigation*Moisture depletion*REP	6	0.009	0.002	0.418	0.828

Analysis of variance of roots plant concentration content of (K+) in mg L-1 for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

The analysis of variance (ANOVA) for potassium (K⁺) concentration in sunflower (*Helianthus annuus* L.) roots reveals several significant and non-significant interactions between variables. The species factor (F = 601664.1, p < 0.0001), water types for irrigation (F = 420998.4, p < 0.0001), and the interaction between species and water types for irrigation (F = 188603.4, p < 0.0001) all have highly significant effects on the K⁺ concentration, suggesting that different sunflower species and water management strategies (irrigation type) play crucial roles in determining K⁺ levels in roots. In contrast, the species moisture depletion interaction (F = 0.37, p = 0.603) and the water types for irrigation moisture depletion interaction (F = 0.37, p = 0.727) were not significant, indicating that the moisture depletion factor did not notably influence K⁺ content when considering species and water types independently. Fluctuations in the results could be linked to the complex interplay between species-specific responses and the environmental factors, with some interactions, like species water types for irrigation REP (F = 66.5, p = 0.015), showing moderate significance, suggesting that replication and external factors might further influence the potassium concentration [14]. Thus, water management strategies are crucial for enhancing nutrient uptake, while moisture depletion and specific species adaptations may not have the same pronounced effect on K⁺ concentration.

Table 7. Analysis of variance of roots plant concentration content of (K⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	601664.08	601664.08	601664.	< 0.0001
Water Types for irrigation	2	841996.69	420998.35	420998.	< 0.0001
Moisture depletion	1	6486.43	6486.43	6486.43	0.000
Species*Water Types for irrigation	1	188603.34	188603.34	188603.	< 0.0001
Species*Moisture depletion	1	0.38	0.38	0.37	0.603
Water Types for irrigation*Moisture depletion	2	0.75	0.38	0.37	0.727
Species*Water Types for irrigation*REP	8	532.00	66.50	66.50	0.015
Water Types for irrigation*Moisture depletion*REP	6	1.33	0.22	0.22	0.936

Analysis of variance of shoots plant concentration content of (K⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

The analysis of variance (ANOVA) presented in Table 8 highlights the significant and non-significant effects of different factors on the concentration of potassium (K⁺) in sunflower (*Helianthus annuus* L.) roots. The factors "Species," "Water Types for irrigation," and their interaction "Species Water Types for irrigation" are significant (p-values of 0.002, 0.005, and 0.008, respectively), indicating that variations in these factors contribute to the observed differences in K⁺ concentration. Specifically, differences between species and water types significantly impact K⁺ content, potentially due to species-specific uptake mechanisms or the differential availability of potassium in various irrigation regimes. However, factors such as "Moisture depletion," "Species Moisture depletion," and "Water Types for irrigation Moisture depletion" show non-significant effects (p-values of 0.116, 0.866, and 0.502, respectively), suggesting that moisture levels, either independently or in combination with other variables, do not notably influence K⁺ concentrations. The lack of significance in some interactions and the fluctuations in results, such as those related to the "Species Moisture depletion" and "Water Types for irrigation*Moisture depletion," may arise from environmental variability, or insufficient effect size of these factors under the experimental conditions [15,16]. These findings underscore the importance of species and irrigation strategies in managing nutrient content in plants, particularly potassium, but indicate that moisture depletion may not play a central role in influencing root K⁺ concentration in this study.

Table 8. Analysis of variance of roots plant concentration content of (K⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	850136.3	850136.3	513.1	0.002
Water Types for irrigation	2	626926.7	313463.3	189.2	0.005
Moisture depletion	1	11804.5	11804.5	7.1	0.116
Species*Water Types for irrigation	1	203797.0	203797.0	123.0	0.008
Species*Moisture depletion	1	60.2	60.2	0.0	0.866
Water Types for irrigation*Moisture depletion	2	3283.3	1641.7	1.0	0.502
Species*Water Types for irrigation*REP	8	8226.0	1028.3	0.6	0.742
Water Types for irrigation*Moisture depletion*REP	6	7364.5	1227.4	0.7	0.672

Analysis of variance of soil concentration content of (K⁺) in mg L⁻¹ for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

The analysis of variance (ANOVA) results presented in Table 9 for the soil concentration content of K⁺ (potassium) in mg L⁻¹ highlight significant effects of species, water types for irrigation, and their interaction, while other factors like moisture depletion and specific interactions were non-significant. The species factor had a highly significant effect on K⁺ concentration (p = 0.003), indicating that different species of sunflower (*Helianthus annuus* L.) influence potassium content in the soil. Similarly, water types for Irrigation also had a significant effect (p = 0.007), indicating that differing irrigation strategies influence potassium concentrations. However, moisture depletion (p = 0.118) had no significant effect on K⁺ levels, most likely due to the soil's buffering capacity or the narrow range of moisture fluctuations seen throughout the experiment. The relationship among species and water types for watering was significant (p = 0.014), while other interactions, such as species moisture depletion and water type moisture depletion, were not significant (p = 0.497 and p = 0.321, respectively). This suggests that moisture depletion had a lesser effect on K⁺ levels. The variability in results might be explained by the intricate interplay of species-specific responses to irrigation systems, with each species interacting differently with water types to influence nutrient absorption [17,18]. These data show that the biological properties of sunflower species and irrigation strategies have a greater impact on K⁺ concentration than moisture depletion.

Table 9. The analysis of variance of soil concentration (K⁺) in mg L⁻¹ for assessment in enhancing sunflower (*Helianthus annuus* L.).

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	902008.3	902008.3	366	0.003
Water Types for irrigation	2	705625.0	352812.5	143.2	0.007
Moisture depletion	1	17265.4	17265.4	7	0.118
Species*Water Types for irrigation	1	168934.6	168934.6	68.5	0.014
Species*Moisture depletion	1	1666.7	1666.7	0.7	0.497
Water Types for irrigation*Moisture depletion	2	10416.7	5208.3	2.1	0.321
Species*Water Types for irrigation*REP	8	10241.7	1280.2	0.5	0.792
Water Types for irrigation*Moisture depletion*REP	6	11812.5	1968.8	0.8	0.649

3.9 Analysis of variance of root weight in (g) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

The results of the analysis of variance (ANOVA) performed for root weight in sunflower (*Helianthus annuus* L.) demonstrated significant implications for different species, irrigation water types, and the interaction between species and irrigation water types, with p-values of 0.002, 0.007, and 0.019, respectively, showing that these factors had a significant impact on root weight. The species effect suggests that different sunflower species respond differently to water management strategies, and varying water types for irrigation also significantly impacted root development. In contrast, moisture depletion did not have a significant effect ($p = 0.170$), indicating that this factor alone did not significantly influence root weight. Similarly, interactions involving species and moisture depletion ($p = 0.376$), as well as water types for irrigation and moisture depletion ($p = 0.960$), showed no significant impact, suggesting these combinations did not produce notable changes in root weight. Furthermore, the interaction effects with REP (random effects) were non-significant, with p-values greater than 0.05, indicating limited variation in root weight owing to experimental duplicates. The variance in outcomes can be due to the complex interplay of environmental and treatment parameters, with species and irrigation water type having the greatest influence. These findings are consistent with previous research in agricultural water management, emphasizing the importance of water type and species selection for optimal root growth [19].

Table 10. The analysis of variance of root weight in (g) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	3505.2	3505.2	449.1	0.002
Water types of Irrigation	2	2244.6	1122.3	143.8	0.007
Moisture Depletions	1	34.5	34.5	4.4	0.170
Species*Water Types for irrigation	1	398.6	398.6	51.1	0.019
Species*Moisture depletion	1	9.9	9.9	1.3	0.376
Water Types for irrigation*Moisture depletion	2	0.7	0.3	0.0	0.960
Species*Water Types for irrigation*REP	8	24.3	3.0	0.4	0.863
Water Types for irrigation*Moisture depletion*REP	6	9.7	1.6	0.2	0.944

Analysis of variance of shoots weight in (g) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

The table 11's analysis of variance (ANOVA) results reveal that species, irrigation water types, moisture depletion, and their interactions all have a significant influence on sunflower shoot weight. The species factor ($p = 0.00043$) and water types for irrigation ($p = 0.002$) both exhibit strong significance, with F-values of 2318.9 and 445.7, respectively, indicating their substantial impact on shoot weight. Additionally, the interaction between species and water types for irrigation is significant ($p = 0.005$), with an F-value of 218.5, suggesting that the effect of water management differs across species. The moisture depletion factor also shows significance ($p = 0.034$), with an F-value of 28.1, highlighting its role in shoot weight variation. In contrast, the interactions involving species and moisture depletion ($p = 0.103$), as well as water types for irrigation and moisture depletion ($p = 0.163$), are not statistically significant, indicating that these combined factors have minimal influence on shoot weight. Further, the higher-order interactions involving replication (species \times water types for irrigation \times replication and water types for irrigation \times moisture depletion \times replication) show non-significant results ($p > 0.191$), suggesting that the experimental replicates did not significantly affect the observed trends. Fluctuations in results, such as the non-significant interactions, may arise from variability in environmental conditions, experimental setup, or underlying biological factors influencing sunflower growth. These findings emphasize the primary influence of species and water management strategies in determining sunflower shoot biomass [20].

Table 11. Analysis of variance of shoots weight in (g) for assessment of water management in enhancing sunflower (*Helianthus annuus* L.)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Species	1	74264.5	74264.5	2318.9	0.00043
Water Types for irrigation	2	28546.2	14273.1	445.7	0.002
Moisture depletion	1	898.7	898.7	28.1	0.034
Species*Water Types for irrigation	1	6998.1	6998.1	218.5	0.005
Species*Moisture depletion	1	263.5	263.5	8.2	0.103
Water Types for irrigation*Moisture depletion	2	328.7	164.3	5.1	0.163
Species*Water Types for irrigation*REP	8	1175.9	147.0	4.6	0.191
Water Types for irrigation*Moisture depletion*REP	6	261.8	43.6	1.4	0.481

Explain summary (LS means) - Species*Water Types for irrigation

The results in Table 12, which summarize the Least Squares (LS) means for species and water types (Well Water), demonstrate significant differences across various parameters, including BAF Pb, TL Pb, Pb Shoot, Pb Root, Pb Soil, K Root, K Shoots, K Soil, Root Weight, and Shoot Weight (p-values < 0.05). Specifically, *Mammoth Russian* exhibited higher values for several variables such as Pb Shoot, Pb Root, and K Root, while *Lemon Queen* had higher shoot weight and K Shoots. These results suggest that the species respond differently to irrigation with well water, influencing Pb uptake, nutrient content, and biomass production. The significant differences are likely due to inherent species differences in their physiological characteristics, such as root structure and nutrient absorption capacity, which could cause variability in how each species interacts with water and soil conditions. The fluctuation in results, particularly between root and shoot weights, may indicate differential growth patterns or adaptive strategies to optimize nutrient acquisition under stress conditions such as Pb exposure. The high level of statistical significance (p-values < 0.05) for each of the tested variables indicates that species and water relationships strongly influence the development of plants and Pb accumulation. This supports the hypothesis that irrigation with well water affects species differently across multiple biological markers [21]

Table 12. Summary (LS means) - Species*Water Types for irrigation

Sources	BAF Pb	TL Pb	Pb Shoot	Pb Root	Pb Soil	K Root	K Shoot	K Soil	Root Weight (g)	Shoot s Weight (g)
Lemon Queen * Well water	0.978 _a	0.96 ^a	0.48 ^b	0.51 _b	0.52 ^b	241.7 _b	282.5 ₀₀	0.978 ^a	0.96 ^a	0.48 ^b
Mammoth Russian* Well Water	0.97 _{9 a}	0.91 ^a	0.74 ^a	0.81 _{2 a}	0.83 ^a	310 ^a	229.3 _{4 a}	250.0 _a	14.58 ^a	48.67 ^b
Pr > F(Model)	0.004	0.002	0.005	0.005	0.007	< 0.000	0.021	0.029	0.027	0.006
Significant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Explain summary (LS means) - Species*Moisture depletion

The data in Table 13 presents the interaction between species (Lemon Queen and Mammoth Russian) and moisture depletion levels (0.3 and 0.65) for various parameters, such as BAF Pb²⁺, TL Pb²⁺, Pb²⁺ in shoot, root, and soil, K⁺ levels in root, shoot, and soil, and the weight of roots and shoots. The results show statistically significant effects ($p < 0.05$) for all parameters, indicating that both species and moisture depletion levels influence the measured variables. The variations in findings, such as greater Pb²⁺ concentrations and K⁺ in Lemon Queen shoots and roots at 0.65 moisture depletion compared to Mammoth Russian, might be related to species-specific responses to moisture stress and metal absorption. Furthermore, the huge variance in root and shoot weights among species, as well as moisture depletion levels, indicate that these parameters have a major impact on growth, most likely due to differences in nutrient and metal availability or absorption methods. These findings underline the importance of moisture levels in moderating plant responses, with significant variations observed in all tested parameters. Such responses could be linked to the plants' adaptive strategies for managing metal stress and nutrient acquisition under water-limited conditions [22,23].

Table 13. Explain summary (LS means) - Species*Moisture depletion

Sources	BAF Pb ²⁺	TL Pb ²⁺ +	Pb ²⁺ Shoot	Pb ²⁺ root	Pb ²⁺ Soil	K ⁺ ROO T	K ⁺ Shoo ts	K ⁺ Soil	Root weight (g)	Shoots weight (g)
Lemon Queen *0.3	0.86 b	1.0 4 b	0.52 b	0.60 b	0.68 b	273. 08 b	283. 03 b	273. 61 b	18.63 b	82.72 b
Lemon Queen *0.65	1.06 b	1.1 7 b	0.27 b	0.26 b	0.28 b	291. 08 b	300. 92 b	310. 28 b	20.05 b	81.59 b
Mammoth Russian*0.3	0.73 b	0.6 6 b	0.62 b	0.64 b	0.65 b	185. 58 b	181. 86 b	183. 61 b	10.16 b	37.10 b
Mammoth Russian*0.65	0.67 b	0.6 3 b	0.55 b	0.58 b	0.58 b	202. 58 b	170. 75 b	163. 61 b	8.88 b	35.51 b
Pr > F(Model)	0.00 4	0.0 02	0.005	0.00 5	0.00 7	< 0.00 01	0.02 1	0.02 9	0.027	0.006
Significant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Explain Summary (LS means) - Water Types for irrigation*Moisture depletion

The results from Table 14 show significant differences across the water types for irrigation in various parameters (Pb²⁺ concentrations in the shoot, root, and soil, K⁺ levels in the root, shoot, and soil, as well as root and shoot weight). All p-values for the parameters are below 0.05, indicating statistical significance. For instance, Well Water0.3 exhibited the highest concentrations of Pb²⁺ across all measured categories (1.31 for BAF Pb²⁺ and 0.83 for Pb²⁺ in shoots), whereas Tap Water0.65 showed consistently lower values (0.49 for BAF Pb²⁺). The root and shoot weights also fluctuated, with the Well Water*0.3 treatment leading to the highest root weight (22.51 g) and shoot weight (82.60 g), suggesting that water type significantly influences both plant health and metal uptake. These variations can be attributed to different nutrient availability and heavy metal accumulation under each irrigation treatment, with well water potentially providing more favorable conditions for growth compared to tap water, possibly due to differences in its mineral content or water quality. The significant fluctuation observed across treatments highlights the impact of both water type and moisture depletion on plant physiological responses, emphasizing the need for careful water management in agricultural practices [24].

Table 14. Summary (LS means) - Water Types for irrigation*Moisture depletion

Sources	BAF Pb ²⁺	TL Pb ²⁺	Pb ²⁺ Shoot	Pb ²⁺ root	Pb ²⁺ Soil	K ⁺ ROO T	K ⁺ Shoot s	K ⁺ Soil	Root weight (g)	Shoots weight (g)
Well Water*0. 3	1.31 a	1.25 a	0.83 a	1.00 a	1.08 a	423. 33 a	332.8 3 a	351. 67 a	22.51 a	82.60 a
Tap water*0. 65	0.88 a	0.95 a	0.51 a	0.55 a	0.58 a	249. 67 a	284.5 0 a	258. 33 a	16.15 a	66.73 a
Tap water*0. 3	0.74 a	0.96 a	0.37 a	0.38 a	0.44 a	231. 83 a	260.6 7 a	303. 33 a	16.51 a	71.81 a
Well water*0. 3	0.61 a	0.54 a	0.70 a	0.70 a	0.69 a	111. 00 a	185.8 3 a	143. 33 a	8.59 a	45.18 a
Well water*0. 65	0.49 a	0.51 a	0.07 a	0.06 a	0.07 a	127. 83 a	143.6 7 a	155. 00 a	8.74 a	31.96 a
Pr > F(Model)	0.00 4	0.00 2	0.005	0.00 5	0.00 7	< 0.00 01	0.021	0.02 9	0.027	0.006
Significan t	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Conclusion

The ANOVA study shows that sunflower's ability to remediate Pb²⁺ is significantly influenced by species selection, water type, and moisture depletion. The primary impacts of species and water types were discovered to be critical for bioremediation effectiveness, with moisture depletion having little impact. This shows that optimizing species selection and water management practices is critical to increasing phytoremediation performance. The examination of root and soil concentrations also highlighted the importance of species and water types in nutrient absorption and heavy metal remediation, with focused water management critical to sunflower performance in polluted areas.

Additionally, the study found that sunflower development, as evaluated by root and shoot weights, was considerably influenced by species and irrigation water types, with moisture depletion having a minor impact. Species-specific reactions to water treatments were identified, emphasizing the need of selecting the appropriate species and irrigation systems for optimal development. The results further highlight the importance of water type and moisture control in nutrient absorption and metal buildup. These findings are important for future study and practical applications in phytoremediation because they indicate that targeted irrigation systems can improve sunflower performance, particularly in places with varied water quality.

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Appendix Table 1: Soil Properties and Analytical Method

Soil Property	Unit	Value (Approx.)	Analytical Method
pH	-	7.6	pH meter (1:2.5 soil-to-water ratio)
Electrical Conductivity (EC)	dS/m	1.05	EC meter (1:2.5 soil-to-water ratio)
Organic Matter (OM)	%	1.02	Walkley-Black Method
Total Nitrogen (N)	%	0.12	Kjeldahl Method
Available Phosphorus (P)	mg/kg	7.5	Olsen Method
Available Potassium (K)	mg/kg	250	Flame Photometry
Cation Exchange Capacity (CEC)	cmol/kg	32.5	Ammonium Acetate Method
Soil Texture	-	Silty Clay	Hydrometer Method

تقييم إدارة المياه في تحسين أداء عباد الشمس (*Helianthus annuus L.*) لإزالة معدن الرصاص الثقيل Pb^{2+}

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الخلاصة:

أجريت هذه الدراسة في معهد بکراجو التقني (2021-2022)، لدراسة العوامل المؤثرة في إزالة الرصاص (Pb^{2+}) باستخدام نوعين من عباد الشمس، هما "اليمون كوين" و"ماموث روسي". تم استخدام تصميم كتلة عشوائية كاملة (CRD) وتحليل التباين (ANOVA) لتقييم تأثيرات الأنواع، وأنواع المياه، واستنفاد الرطوبة، وتفاعلاتها على إزالة الرصاص (Pb^{2+}) والتنقل الحيوي له. أظهرت النتائج تأثيرات كبيرة للأنواع ($p = 0.00047$)، وأنواع المياه ($p = 0.001$)، وتفاعلها ($p = 0.001$) على عامل إزالة الرصاص الحيوي ($BAF Pb^{2+}$)، مما يبرز أهمية هذه العوامل في تحسين إزالة الرصاص بواسطة نباتات عباد الشمس. كما أثر استنفاد الرطوبة بشكل كبير على إزالة الرصاص ($p = 0.036$)، إلا أن التفاعلات من الدرجة الأعلى، مثل الأنواع × استنفاد الرطوبة وأنواع المياه × استنفاد الرطوبة، لم تكن ذات دلالة إحصائية. كما أظهرت الدراسة أن الأنواع وأنواع المياه أثرت بشكل كبير في انتقال الرصاص ($F = 6071.850$)، ($p = 0.00016$)، وتركيز الرصاص في الجذور ($p = 0.002$)، ومستويات الرصاص في التربة ($F = 451.077$)، ($p = 0.002$). بالإضافة إلى ذلك، أثرت الأنواع وأنواع المياه بشكل كبير في امتصاص البوتاسيوم (K^+) في الجذور ($F = 601664.1$)، ($p < 0.0001$)، بينما كان لاستنفاد الرطوبة تأثير ضئيل. تؤكد هذه النتائج أهمية اختيار الأنواع المناسبة وإدارة المياه لتحقيق أقصى استفادة من إزالة الرصاص الحيوي

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المياه، إزالة التلوث، المعادن الثقيلة،

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