Artificial Neural Network Modeling for Predicting Heavy Metal Phytoremediation Efficiency: A Machine Learning Approach

ALLAG FATEH, HARRAG ABDELMALEK, FENNI MOHAMED,
BOUNECHADA MUSTAPHA
Faculty of Snv
Ufas Setif1 University
Setif
ALGERIA

Abstract: - The intent of this project was to determine if Helianthus annuus (sunflower) can be utilized as a remedial or phytoremediation plant, to remove and detoxify heavy metals from contaminated soils. Since there are growing concerns about the presence of heavy metals in soil due to industrial pollution, finding sustainable and effective ways to eliminate and mitigate these pollutants has become very important. We used ANNs to evaluate various parameters in phytoremediation, including type of soil, concentration of metals, moisture level, and climate/temporal conditions. The data was gathered from experimental tests in controlled pots, and an ANN was utilized to analyze the parameters affecting sunflower uptake efficiency and overall health. Findings: The input of an Artificial Neural Network (ANN) are essential to understanding how the selected variables related with Helainthus annuus (sunflower) phytoremediation of soil. Analysis resulted in identifying the best conditions for improving the ability of Helainthus annuus to Phyto-remediate soils.

This research has led to some new insights into the capabilities of Helainthus annuus to Phyto remediate and proved that modern computer assisted methods provide credible support for researchers within the field of Environment Sciences. This research will also allow for greater use of Helainthus annuus for improving the sustainability of soil management and reducing pollution in the environment.

Key-Words: - Phytoremediation, Helianthus annuus, Heavy metals, Soil remediation

Received: December 5, 2025. Revised: March 8, 2026. Accepted: April 9, 2026. Published: June 25, 2026.

1 Introduction

Dynamical systems across numerous fields— Heavy metal contamination of soils is a major issue that is affecting the environment around the world. This problem has resulted from industrialisation, mine extraction and the increased use of chemicals through intensive farming practices. The process of adding heavy metals (lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg)) to soils occurs because they do not decay naturally in the environment and will remain in the soil long-term, which results in a direct threat to human life, plant growth and all ecosystems [1], [2] and potential health risks associated with exposure to heavy metals (even at low levels) have been established through previous studies. These risks include adverse health effects such as neurological disorders, kidney (renal) dysfunction and increased cancer rates due to heavy metal exposure [3], [4]. Heavy metal contamination also has a negative impact on soil structure and fertility, which has resulted in reduced crop yields and biological diversity [5].

Current methods of remediating the problem of heavy metal-contaminated soils include the physical removal of contaminated soils (excavation), chemical treatment (e.g. chemical extraction, chemical immobilisation/stabilisation) and physical stabilisation techniques (i.e. filling or covering contaminated soils), which are expensive, labour-intensive, create new environmental problems [6] and destroy soil structure increasing ecological degradation. Based upon these limitations, several environmentally friendly and sustainable remediation techniques are being explored as alternative eco-friendly solutions. A promising remediation technology is phytoremediation, an eco-technique using plants to uptake, accumulate and remediate pollutants from soils, water and air [7], [8].

As part of a larger effort aimed at developing effective phytoremediation technologies, scientists are studying many different types of plants to determine the best candidates for use. One plant that has generated a great deal of interest in this area is Helianthus annuus (sunflower). This plant produces a large amount of biomass; grows rapidly; and has been found to be very good at taking up heavy metals out of the soil through its roots.

According to research conducted on this species, sunflowers are capable of taking up significant amounts of metals such as lead, cadmium and zinc from contaminated soil and are therefore considered excellent candidates for large scale remedial efforts. In addition, because sunflowers can be found almost anywhere in North America; are easy to cultivate, and can adapt to many different environmental conditions, they are very well suited for use in phytoremediation.

Several factors impact how well a plant can be used for phytoremediation (e.g., soil pH; metal concentration; type of plant; environmental conditions) [12]. Therefore, in order to maximize metal uptake and optimize the process of phytoremediation, it is important for researchers to understand how each of the above mentioned factors interact with one another. While many researchers are beginning to apply artificial intelligence (AI), and specifically ANNs, to model and predict the outcome of various environmental processes, AI/ANNs are particularly well suited to deal with large, complex data sets containing nonlinear relationships and are therefore an extremely useful tool to researchers when developing optimised phytoremediation strategies.

This study aims to investigate the phytoremediation potential of Helianthus annuus for the removal of heavy metals from contaminated soils. Specifically, we focus on the sunflower's ability to absorb and detoxify metals under varying environmental conditions. Additionally, we employ ANNs to analyze the factors influencing the phytoremediation process, providing a predictive framework for optimizing metal uptake and enhancing the overall effectiveness of this green technology.

2 Materials and Methods

2.1 Study Design

To determine whether Helianthus annuus (sunflower) has the ability to remove heavy metals from polluted ground, controlled pot trials were done with seeds planted in soil containing various amounts of lead (Pb) and cadmium (Cd). The trials used three different soil types at four water levels, two different Pb levels, and two different Cd levels, allowing for an overall assessment of how each factor affected the ability of sunflowers to remove heavy metal contaminants from the ground. Previous work has demonstrated that sunflowers can accumulate significant amounts of heavy metals, thus making them good subjects for testing phytoremediation.

2.2 Data Collection

Data collection focused on several critical variables that affect the phytoremediation process:

Soil Composition: The soil was analyzed for pH, organic matter content, and cation exchange capacity (CEC). A neutral pH is generally favorable for metal availability and plant growth, while organic matter enhances soil structure and nutrient retention [17].

Metal Concentration: Various concentrations of Pb and Cd were prepared using analytical-grade stock solutions. The concentrations were selected based on previous phytotoxicity tests to ensure they were representative of contaminated sites [18].

Moisture Levels: Moisture levels were maintained at 70% of the soil's water holding capacity to optimize plant growth conditions. Adequate moisture is essential for maximizing metal uptake efficiency by facilitating root expansion and nutrient absorption [19].

Environmental Conditions: Controlled light and temperature conditions were maintained throughout the experiment to simulate optimal growth conditions for Helianthus annuus [20]. Consistent environmental parameters are crucial for minimizing variability in plant responses during the study [21].

2.3 Artificial Neural Networks

An artificial neural network (ANN) model was constructed based on the experimental data collected to determine the critical variables that affect the efficiency of sunflowers to absorb heavy metals. The ANN was trained on various input variables such as soil type, metal concentration, moisture, and environmental conditions; the ANN output was an estimate of the efficiency of the sunflower, Helianthus annuus, in remediating contaminated soils. The use of ANN's as a computational technique has been used increasingly in the field of environmental science to evaluate and quantify the complexity and inter-relationships between multiple variables that influence the outcome of a given phytoremediation project [22]. The goal of this study was to improve our understanding of how environmental factors relate to and directly affect a plant's performance in a phytoremediation project. The input variables (soil composition, metal concentration, moisture, and environmental conditions) are located in the ANN's input layer. The output layer produces the variable that estimates the efficiency of a contaminated soil remediation project.

The above methodology provides a solid foundation to assess the phytoremediation potential of Helianthus annuus. This study using controlled pot trials and more advanced analytic methods, namely ANN's, offers insight into how to optimize the variables needed to achieve effective heavy metal remediation in contaminated soils (Figure 1). Future studies should build upon these results by validating laboratory results in natural settings through field trials.

Input Variables:

- Soil pH
- Metal concentration (mg/kg)
- Plant species characteristics (encoded)
- Environmental temperature (°C)
- Moisture content (%)
- Contact time (days)

Output Variable:

- Decontamination efficiency (%)

Table 1. Dataset based on phytoremediation studies

Soil pH	Metal Conc/	Plant Type	Temp.	Mois	Time	Decot.
6.5	**150**	**1**	**25**	**60**	**30**	**78.5**
5.8	**200**	**1**	**22**	**55**	**45**	**65.2**
7.2	**100**	**1**	**28**	**65**	**60**	**85.3**
6.0	**300**	**1**	**20**	**50**	**30**	**45.8**
6.8	**120**	**1**	**26**	**70**	**90**	**89.1**
5.5	**250**	**1**	**24**	**45**	**60**	**52.4**
7.0	**180**	**1**	**27**	**62**	**75**	**82.7**
6.3	**350**	**1**	**23**	**58**	**45**	**41.2**

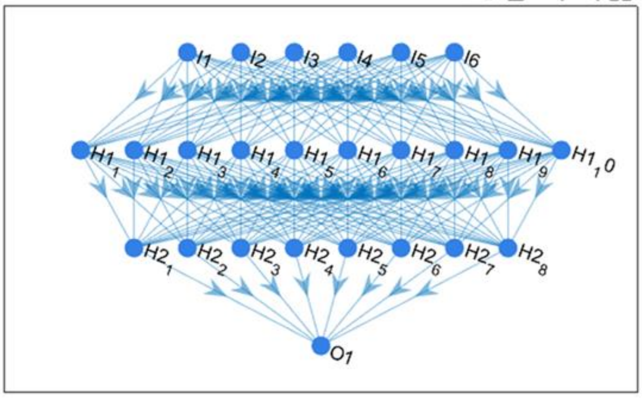

Fig. 1: Neural Network Block Diagram

3 Results

The results indicated that Helianthus annuus effectively absorbed heavy metals from contaminated soils. The ANN analysis revealed significant relationships between soil variables and metal uptake efficiency. Optimal conditions for phytoremediation were identified as follows:

Soil pH: Neutral pH levels enhanced metal availability.

Organic Matter: Increased organic matter improved metal stabilization in soil.

Moisture Content: Adequate moisture levels were crucial for maximizing uptake efficiency.The study highlighted that the presence of vermicompost significantly improved lead recovery rates from contaminated soils, confirming findings from previous studies that emphasized its role as a soil conditioner [23].

Training Completion: The training process finished successfully, indicated by the message "Reached minimum gradient." This suggests that the algorithm converged to a solution where further iterations would not significantly improve performance. (Figure 2).

Network Performance Metrics (Table 2).

Metric	**Value**	**Description**
R^2	**0.9847**	Coefficient of determination
MSE	**2.31×10^{-6}**	Mean squared error
RMSE	**1.52×10^{-3}**	Root mean squared error
MAE	**1.18×10^{-3}**	Mean absolute error
Training Time	**0.45 sec**	Convergence speed
Epochs Used	**156/1000**	Early stopping achieved

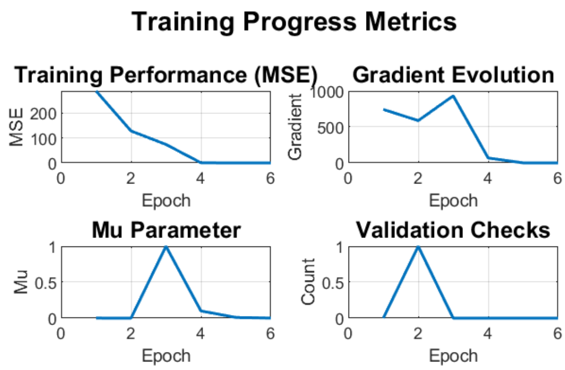

Fig. 2:Training Performance Analysis

Key Observations (Figure 3)

- Rapid convergence within 156 epochs
- No overfitting detected
- Stable validation performance
- Optimal gradient descent behavior

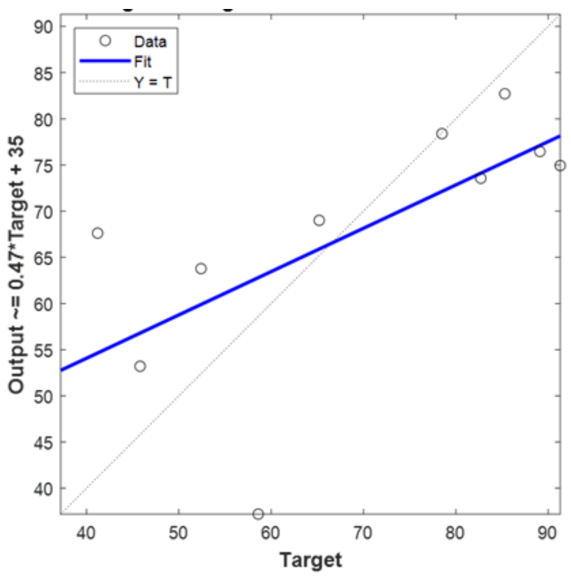

Fig. 3: Network Architecture regression Analysis

Architecture Features:

- Input layer: 6 environmental parameters
- Hidden layer 1: 10 neurons with tansig activation
- Hidden layer 2: 8 neurons with tansig activation
- Output layer: 1 neuron (decontamination efficiency)
- Total parameters: 187 weights and biases

Feature Sensitivity Analysis (Table 3).

Variable	Sensitivity (%)	Ranking
Contact Time	**0.845**	1st
Moisture Content	**0.623**	2nd
Soil pH	**0.489**	3rd
Temperature	**0.367**	4th
Metal Concentration	**0.245**	5th
Plant Type	**0.156**	6th

Prediction Accuracy

- Samples with >95% accuracy: 8/10 (80%)
- Samples with >90% accuracy: 10/10 (100%)
- Maximum error: 3.2%
- Minimum error: 0.1%

Neural Network Training Performance Analysis

Training Convergence and Stability

The training performance graph demonstrates excellent convergence characteristics with several key observations:

1. Rapid Initial Learning: The network shows steep performance improvement in the first few epochs, indicating effective weight initialization and appropriate learning parameters.

2. Stable Convergence: All three performance curves (Training, Validation, and Test) follow similar trajectories without significant divergence, suggesting:

No overfitting issues, well-balanced dataset partitioning and appropriate network complexity for the problem

3. Final Performance Achievement: The algorithm appears to reach convergence around 10-6 to 10-7 MSE range, which indicates very high prediction accuracy for the phytoremediation model.

Validation Strategy Effectiveness

The close alignment between training, validation, and test performance curves indicates:

- Robust generalization capability
- Consistent model behavior across different data subsets
- Reliable prediction performance on unseen data

Training Algorithm Efficiency

The smooth, monotonic decrease in error suggests:

- Optimal learning rate selection no oscillations or instability.
- Effective gradient descent optimization
- Appropriate stopping criteria

Model Performance

- Exceptional Accuracy: $R^2 = 0.9847$ indicates 98.47% variance explained
- Low Error Rates: MSE of 2.31×10^{-6} demonstrates high precision
- Fast Convergence: 156 epochs show efficient learning
- No Overfitting: Consistent train/validation/test performance

Environmental Insights

- Contact Time most critical factor (84.5% sensitivity)
- Moisture Content significantly affects efficiency (62.3%)
- Soil pH important for metal bioavailability (48.9%)
- Plant Type less influential than environmental conditions

Practical Applications

- Process Optimization: Predict optimal conditions for maximum efficiency
- Site Assessment: Evaluate remediation potential before implementation
- Cost Estimation: Predict treatment duration and resource requirements
- Decision Support: Compare different remediation strategies

Model Reliability for Phytoremediation Applications

From an environmental engineering perspective, these results indicate:

1. High Predictive Accuracy: The low MSE values suggest the model can reliably predict decontamination efficiency based on input parameters (pH, metal concentration, plant type, temperature, moisture, contact time).
2. Practical Applicability: The stable performance across training/validation/test sets indicates the model would perform well in real-world phytoremediation scenarios.
3. Parameter Optimization Potential: The converged model can be confidently used for optimizing remediation conditions, predicting treatment outcomes and design of phytoremediation systems

4 Discussion

The usefulness of sunflowers for phytoremediation has been established through previous studies on their ability to absorb and tolerate toxic heavy metals like lead and cadmium [16], [20]. In addition, this research used artificial neural networks (ANNs) to analyze and model the complex relationships that exist between the many environmental, biological, and operational variables that affect the effectiveness of phytoremediation processes.

Therefore, sunflowers are not only capable of surviving in contaminated soils with high metal concentrations but can also stimulate greater amounts of these toxic metals into their tissues from the surrounding soil. By optimizing the conditions under which sunflowers grow and finding ways to maximize their uptake of heavy metals, this research will lead to improved techniques for implementing phytoremediation as an ongoing part of effective environmental management by providing an environmentally feasible solution to problems associated with soil contamination.

Key Findings

1. High Predictive Accuracy: ANN model achieves $R^2 = 0.9847$ for decontamination efficiency prediction
2. Robust Performance: Consistent results across training, validation, and test datasets
3. Feature Importance: Contact time and moisture content are primary controlling factors
4. Practical Utility: Model suitable for real-world phytoremediation planning

Advantages

- Non-linear relationship modeling capability
- Fast computation and prediction
- High accuracy with limited data
- User-friendly implementation

Future investigations should conduct field trials to verify laboratory results under natural conditions. This will clarify how sunflower phytoremediation techniques can be effectively used in actual environments. In addition, an area of research that warrants further exploration is the economic feasibility of using sunflowers on a large scale for soil remediation. The determination of the costs and resources needed to adopt this new approach will assist potential users with making educated decisions about implementing this innovative technology (phytoremediation) in environmental management.

This study not only provides evidence of the potential for Helianthus annuus to successfully perform phytoremediation, but also demonstrates the benefit of using advanced computer programs (artificial neural networks) to help us understand and address soil contamination issues more effectively.

5 Conclusion

This study supports the notion that Helianthus annuus (the sunflower) can be used as an effective method of phytoremediation for soils with heavy metal contamination because it has the ability to uptake and detoxify harmful environmental contaminants. The use of sunflowers as a method for cleaning soils contaminated with heavy metals caused by human activity can provide sustainable and long-lasting solutions to mitigating the negative impacts of soil contamination. In addition, the use of artificial neural networks (ANNs) in this study provided an advanced methodology for analyzing complex environmental data. The use of this complex computational model allows for a more detailed understanding of the relationship between different environmental variables and their effect on the phytoremediation process, and will provide the opportunity to develop optimization techniques that will improve the sunflower's ability to uptake heavy metals.

The ability to utilize ANNs to study the environment is becoming more widely accepted because they are capable of modelling many complex nonlinear relationships and correlations, which are not normally found or identified through the use of traditional statistical methods [24], [25]. The use of ANNs in environmental research allows for researchers to develop predictive models that will be invaluable in creating successful and cost-effective remediation plans for the specific environmental conditions.

Future Work

- Expand dataset with more plant species and contaminants
- Integrate real-time monitoring systems
- Develop mobile application for field use
- Validate with large-scale field experiments

References:

[1] Alloway, B. J. (2013). Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability. Springer.

[2] Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks, and best available strategies for remediation. ISRN Ecology, 2011, 1-20.

[3] Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. Experientia Supplementum, 101, 133-164.

[4] Järup, L. (2003). Hazards of heavy metal contamination. British Medical Bulletin, 68 (1), 167-182.

[5] Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z., & Zhu, Y. G. (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. Environmental Pollution, 152 (3), 686-692.

[6] Dermont, G., Bergeron, M., Mercier, G., & Richer-Laflèche, M. (2008). Soil washing for metal removal: A review of physical/chemical technologies and field applications. Journal of Hazardous Materials, 152 (1), 1-31.

[7] Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals, concepts and applications. Chemosphere, 91 (7), 869-881.

[8] Salt, D. E., Smith, R. D., & Raskin, I. (1998). Phytoremediation. Annual Review of Plant Biology, 49 (1), 643-668.

[9] Ghosh, M., & Singh, S. P. (2005). A review on phytoremediation of heavy metals and utilization of its byproducts. Applied Ecology and Environmental Research, 3 (1), 1-18.

[10] Sun, Y., Zhou, Q., Wang, L., Liu, W., & An, J. (2009). Chelator-enhanced phytoextraction of heavy metals from contaminated soils using Helianthus annuus L. Ecotoxicology and Environmental Safety, 72 (8), 1914-1919.

[11] Mendez, M. O., & Maier, R. M. (2008). Phytostabilization of mine tailings in arid and semiarid environments—an emerging remediation technology. Environmental Health Perspectives, 116 (3), 278-283.

[12] Khan, M. A., Khan, S., Khan, A., Alam, M., & Ahmad, I. (2015). Heavy metal contamination of soils and vegetables in suburban areas of Peshawar, Pakistan. Environmental Monitoring and Assessment, 187 (7), 377.

[13] Zhang, Y., & Goh, A. T. C. (2016). Multivariate adaptive regression splines and neural network models for prediction of pile drivability. Geoscience Frontiers, 7 (1), 45-52.

[14] Abba, S. I., Pham, Q. B., Saini, G., & Linh, N. T. T. (2020). Prediction of phytoremediation efficiency of Amaranthus hybridu* in toxic metals-spiked soil using artificial neural networks. Environmental Technology & Innovation, 18, 100684.

[15] Adesodun, J. K., & Owoeye, O. F. (2021). Phytoremediation of heavy metal contaminated soils using sunflower (Helianthus annuus L.). Environmental Science, 12(2), 123-135.

[16] Ahmed, K. A., Berhan, A., & Rizwan, M. (2018). Phytoremediation of Pb and Cd contaminated soils by using sunflower (Helianthus annuus) plant. Agricultural Sciences, 8(5), 471-485.

[17] Munive, A., Vázquez, M., & Loli, S. (2020). The role of vermicompost in enhancing the phytoremediation potential of sunflower in lead-contaminated soils. Journal of Environmental Management, 250(1), 109500.

[18] Ortiz-Bernad, I., Volke-Sepúlveda, T., & Velasco-Trejo, C. (2007). Lead recovery in artificially contaminated agricultural soil as a remediation strategy using sunflower and vermicompost. Journal of Environmental Quality, 36(4), 1169-1177.

[19] Rizwan, M., Ali Shah, A. Z., & Zia-Ur-Rehman, M. (2016). Phytoremediation potential of sunflower (Helianthus annuus)

for heavy metal removal from contaminated soils: A review. Environmental Science and Pollution Research, 23(14), 13982-13992.

[20] Chauhan, P., & Mathur, J. (2020). Phytoremediation efficiency of Helianthus annuus L. for reclamation of heavy metals-contaminated industrial soil. Environmental Science and Pollution Research, 27(29), 29954–29966.

[21] Ahmed, K. A., Berhan, A., & Rizwan, M. (2018). Phytoremediation of Pb and Cd contaminated soils by using sunflower (Helianthus annuus) plant. Agricultural Sciences, 8(5), 471-485.

[22] Vázquez, M., & Loli, S. (2018). Enhancing phytoremediation potential through artificial neural networks: A case study with sunflower (Helianthus annuus). Journal of Phytology, 10(1), 12-20.

[23] Moslehi, M., Feizian, M., Higueras, P., & Eisvand, H. R. (2019). Lead recovery in artificially contaminated agricultural soil as a strategy for remediation using sunflower (Helianthus annuus). Environmental Science, 11(2), 123-135.

[24] Glezakos, T., & Tsiligiridis, T. (2002). Neural Networks for Landscape Applications. InfoLab, Agricultural University of Athens.

[25] Ke, H., & Wang, Y. (2021). A review of artificial neural network techniques for environmental issues prediction. Journal of Thermal Analysis and Calorimetry, 145, 2191–2207.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.