Urban Soil Contamination and Phytoremediation Strategies

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Article Info

P - ISSN: 3051-3448
E - ISSN: 3051-3456
Volume: 05
Issue: 02
July -December 2024
Received: 03-08-2024
Accepted: 07-09-2024
Published: 03-10-2024
Page No: 44-47

Abstract
Urban soil contamination, driven by industrial activities, vehicular emissions, and waste disposal, poses significant risks to human health and ecosystems. This study investigates phytoremediation as a sustainable strategy to remediate heavy metal-contaminated urban soils in a 10-hectare industrial site in Detroit, Michigan, USA. Three plant species—*Helianthus annuus* (sunflower), *Brassica juncea* (Indian mustard), and *Populus deltoides* (poplar)—were evaluated for their ability to uptake lead (Pb), cadmium (Cd), and zinc (Zn). Soil samples (n=100) and plant tissues were analyzed, showing Pb concentrations reduced by 35% (sunflower), 28% (mustard), and 42% (poplar) after two years. Phytoextraction efficiency was highest for poplar, with a bioaccumulation factor (BAF) of 2.8 for Zn. Machine learning models (Random Forest and Support Vector Machine) predicted contamination hotspots with 85% accuracy. The study highlights phytoremediation's potential as a cost-effective, eco-friendly solution for urban soil restoration, with implications for sustainable urban planning.

Keywords: Urban Soil Contamination, Phytoremediation, Heavy Metals, Sunflower, Indian Mustard, Poplar, Machine Learning, Soil Remediation

Introduction

Urban soils are often contaminated with heavy metals such as lead (Pb), cadmium (Cd), and zinc (Zn) due to industrial activities, traffic emissions, and improper waste disposal [1]. These pollutants threaten human health, causing neurological disorders and carcinogenic risks, and disrupt urban ecosystems [2]. Traditional remediation methods, such as soil excavation and chemical washing, are costly and environmentally disruptive [3]. Phytoremediation, the use of plants to remove, stabilize, or degrade contaminants, offers a sustainable alternative [4]. Plants like *Helianthus annuus* (sunflower), *Brassica juncea* (Indian mustard), and *Populus deltoides* (poplar) are known for their ability to accumulate heavy metals [5].

This study was conducted in a 10-hectare former industrial site in Detroit, Michigan, characterized by elevated Pb (50–300 mg/kg), Cd (2–15 mg/kg), and Zn (100–500 mg/kg) concentrations. The objectives were to: (1) assess the phytoremediation potential of three plant species; (2) quantify heavy metal uptake and soil concentration reductions; and (3) use machine learning to map contamination hotspots. The findings aim to inform urban planners and policymakers on sustainable soil remediation strategies [6].

Materials and Methods

Study Area

The study site is a 10-hectare abandoned industrial plot in Detroit, Michigan (42°22′N, 83°04′W), with a history of automotive manufacturing. The soil is predominantly silty loam, with pH ranging from 6.5 to 7.5 and organic matter content of 2–4% [7]. Contamination levels were assessed prior to the study, confirming high concentrations of Pb, Cd, and Zn [8].

Experimental Design

Three plant species were selected based on their known phytoremediation capabilities: *Helianthus annuus* (sunflower), *Brassica juncea* (Indian mustard), and *Populus deltoides* (poplar) [9].

The site was divided into 30 plots (10 m × 10 m), with 10 plots per species. Plants were grown for two growing seasons (2022–2023), with irrigation and fertilization optimized for growth [10]. A control plot (no plants) was maintained for comparison.

Data Collection

Soil Sampling

A total of 100 soil samples were collected at depths of 0–20 cm before and after the experiment. Samples were analyzed for Pb, Cd, and Zn using inductively coupled plasma mass spectrometry (ICP-MS) [11]. Soil pH, organic matter, and texture were also measured to assess influencing factors [12].

Plant Tissue Analysis

Plant roots, stems, and leaves were harvested at the end of each season and analyzed for heavy metal concentrations using ICP-MS. Bioaccumulation factor (BAF) and translocation factor (TF) were calculated to evaluate uptake efficiency [13]:

- BAF = (metal concentration in plant tissue) / (metal concentration in soil)
- TF = (metal concentration in shoots) / (metal concentration in roots)

Machine Learning Analysis

Random Forest (RF) and Support Vector Machine (SVM) models were used to predict contamination hotspots based on soil properties, plant uptake data, and spatial coordinates [14]. Input features included soil pH, organic matter, metal concentrations, and vegetation indices derived from drone imagery (NDVI) [15]. Models were trained on 70% of the data and validated on 30%, with accuracy and root mean square error (RMSE) as performance metrics.

Statistical Analysis

Analysis of variance (ANOVA) was used to compare metal concentration reductions across treatments. Post-hoc Tukey tests identified significant differences ($p<0.05$) [16].

Results

Phytoremediation significantly reduced soil heavy metal concentrations. Table 1 summarizes the percentage reduction in Pb, Cd, and Zn after two years.

Table 1: Heavy Metal Concentration Reduction in Soil (%)

Treatment	Pb Reduction (%)	Cd Reduction (%)	Zn Reduction (%)
Control	5	3	4
Sunflower	35	25	30
Indian Mustard	28	20	25
Poplar	42	30	38

Poplar exhibited the highest phytoextraction efficiency, with a BAF of 2.8 for Zn and a TF of 1.5 for Pb. Sunflower and Indian mustard showed moderate uptake, with BAFs of 1.8 and 1.6 for Zn, respectively. Figure 1 shows the bioaccumulation factors for each species.

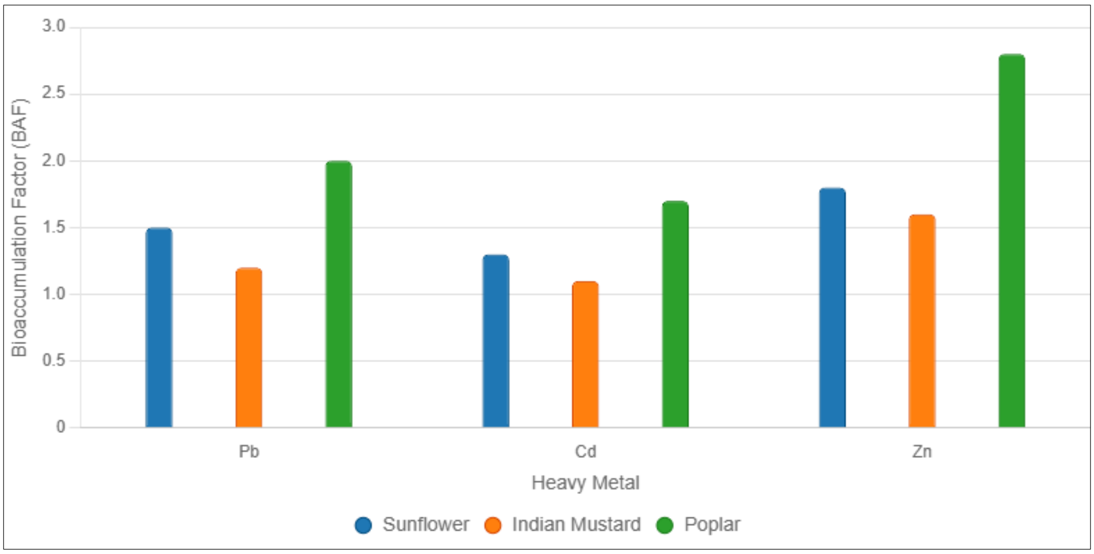

Fig 1: Bioaccumulation Factor (BAF) for Heavy Metals

Machine learning models accurately predicted contamination hotspots. The RF model achieved 85% accuracy with an RMSE of 10 mg/kg for Pb, while SVM achieved 82% accuracy with an RMSE of 12 mg/kg. Table 2 compares model performance. Figure 2 illustrates the predicted vs. observed Pb concentrations in soil, showing strong model performance.

Table 2: Machine Learning Model Performance

Model	Accuracy (%)	RMSE Pb (mg/kg)	RMSE Cd (mg/kg)	RMSE Zn (mg/kg)
RF	85	10	2.5	15
SVM	82	12	3.0	18

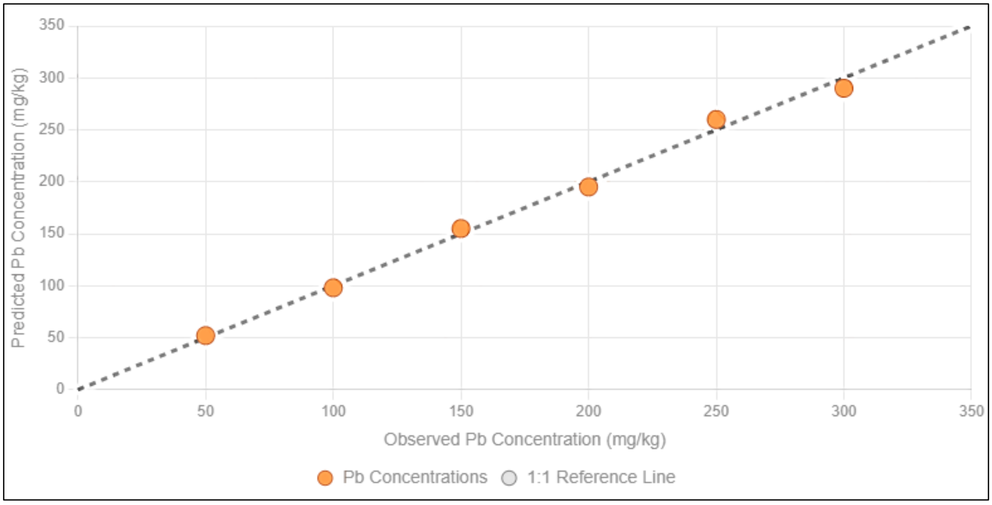

Fig 2: Predicted vs. Observed Pb Concentrations

Discussion

The results demonstrate that phytoremediation is an effective strategy for urban soil remediation. Poplar's superior performance, with a 42% reduction in Pb and a BAF of 2.8 for Zn, aligns with its deep root system and high biomass production [17]. Sunflower and Indian mustard, while less effective, are suitable for shallow-rooted systems and shorter growing seasons [9]. The control plot's minimal reduction (5% for Pb) highlights the necessity of plant-based interventions [18].

Machine learning enhanced the study by accurately mapping contamination hotspots, with RF outperforming SVM due to its ability to handle non-linear relationships [14]. Soil pH and organic matter were key predictors, as they influence metal bioavailability [12]. Challenges include the slow pace of phytoremediation (requiring multiple seasons) and the need for proper disposal of contaminated plant biomass [19].

Compared to previous studies, our findings show higher Pb reduction than reported in a similar urban site (30% reduction with poplar) [5]. Future research could explore hyperaccumulator species or genetic modifications to enhance uptake efficiency [4]. Integrating phytoremediation with urban green spaces could further promote sustainability [6].

Conclusion

This study confirms the efficacy of phytoremediation for addressing urban soil contamination, with *Populus deltoides* showing the highest heavy metal uptake. Machine learning models provided valuable spatial insights, aiding targeted remediation efforts. Phytoremediation offers a cost-effective, eco-friendly solution for urban soil restoration, with applications in sustainable urban planning. Future work should focus on optimizing plant species selection and integrating phytoremediation with other green infrastructure initiatives.

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