



(RESEARCH ARTICLE)



Synergistic modulation of Lead (II) bioavailability by polyethylene terephthalate microplastics and insights into assimilation kinetics in *Canna indica*

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Abstract

The proliferation of microplastics (MPs) in terrestrial ecosystems has introduced a novel variable into the biogeochemical cycling of heavy metals. This study elucidates the role of Polyethylene Terephthalate (PET) microplastics in modulating the bioavailability and assimilation kinetics of Lead(II) ions Pb²⁺ in *Canna indica*. Through a 35-day microcosm experiment, we investigated the interplay between PET dosage (0.5–2.5 g), initial Pb²⁺ concentration (5–45 mg/L), and soil pH (4.0–7.0). Our findings reveal a significant "vector effect," where PET amendment increased Pb uptake by up to 250% compared to MP-free controls. Assimilation was highest under acidic conditions (pH 4.0), reaching 4.529 mg g⁻¹, suggesting that pH-mediated desorption from PET surfaces governs metal mobility. The uptake behavior conformed to the Freundlich isotherm (R² > 0.98), indicating a multi-layer, heterogeneous sorption process, while pseudo-first-order kinetics highlighted a time-dependent saturation of plant tissues. These results underscore the potential for microplastics to exacerbate heavy metal bioaccumulation in phytoremediation-relevant species, necessitating a re-evaluation of soil safety standards in plastic-contaminated agricultural zones.

Keywords: Soil contamination; Vector Effect; Trojan Horse Mechanism; Rhizosphere Chemistry; PET Microplastics; Lead Bioavailability

1. Introduction

Plastic items are used worldwide, resulting in widespread dispersal and accumulation of plastic debris in all terrestrial and aquatic environments (Bläsing & Amelung, 2018). The degradation of plastic polymers produces smaller particles classified as microplastics, when smaller than 5 mm, or as nanoplastics, when smaller than 1 μm (Gigault *et al.*, 2018, Verla *et al.*, 2020). The increasing occurrence of plastic in terrestrial and aquatic environments, progressively reaching ever more remote areas, has made plastic pollution one of the most pressing environmental issues that our society has to deal with (Hu *et al.*, 2022). The negative effects of microplastic pollution have been extensively studied on humans and animals (Patil *et al.*, 2022). The most common ways microplastics can, directly or indirectly, alter plant growth include: reductions in shoot and root biomass, germination rates and photosynthetic activity; genotoxic and oxidative damage; and alterations of plant ionome and metabolic profile (Jiang *et al.*, 2019). Nevertheless, a wide range of effects (from positive to negative) has been reported depending on the plant species and the type of polymer used (Rillig *et al.*, 2019).

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Abiotic stresses including metal toxicity, salinity, temperature extremes, soil microplastic, and drought are enormous threats that are affecting agriculture and the natural environment (Hasanuzzaman *et al.*, 2020). Heavy metals are one of the abiotic factors and are demarcated as metals with a density above 5 g/cm³ e.g., chromium (Cr), lead (Pb), nickel (Ni), cobalt (Co), arsenic (As) and silver (Ag), etc. These heavy metals are taken as substantial environmental pollutants owing to their toxic interaction with soil properties, plants, animals, and humans (Karkush & Ali, 2020). Lead (Pb) ranked as the second most toxic metal on earth's crust is toxic to humans and other living things including plants (World Health Organization, 2010). Several industrial processes include Pb-use in their products like oil and paint, mines, agrochemicals, etc. Moreover, Pb as salts or oxides is also being added to the environment through atmospheric dust, and automobile exhaust (Kumar *et al.*, 2019). In nature, Pb remains below 50 mg kg⁻¹, but in some plants, Pb usually inhibits the growth mechanism when it is at a concentration of 30 mg/kg or more (Usman *et al.*, 2020), while some of the plant species can tolerate Pb stress up to 1,000 mg kg⁻¹ (Reeves *et al.*, 2018). Pb have a strong effect on different growth attributes of plants and inhibit seed germination, plant height, root-shoot length, fresh-dry weight of seedlings, tolerance index, leaf number and photosynthesis (Kanwal *et al.*, 2020).

There are over 2 million identified species of plants worldwide, constituting major components of ecosystems, but a very limited number of species have been investigated for their interactions with microplastics and heavy metals (Enyoh *et al.*, 2020). Among these understudied species is *Canna indica*. *Canna indica* (canna lily) is a perennial herbaceous plant, belonging to the family Cannaceae. The plant grows from a large, thick, underground rootstock that is edible. Its large leaves resemble those of the banana plant but are not so large. The flowers of wild canna lily are usually small, relatively inconspicuous, and brightly colored reds, oranges, or yellows (Mishra *et al.*, 2013).

A wide range of effects of microplastics has been reported, varying depending on the plant species and the type of microplastic involved (Rillig *et al.*, 2019). A growing body of evidence revealed how plants are affected by microplastics present in soil (Ge *et al.*, 2021). According to Colzi *et al.*, (2022), microplastics can directly or indirectly alter plant growth through various mechanisms, including reductions in shoot and root biomass, germination rates, and photosynthetic activity. They can also cause genotoxic and oxidative damage, as well as alterations in the plant ionome and metabolic profile. Notwithstanding the growing body of research on microplastics and heavy metal contamination in soils, there is a lack of empirical evidence on how microplastics affect the assimilation of lead (II) ions from soil by *Canna indica*. Existing studies have largely overlooked the combined influence of microplastic dosage, lead concentration, soil pH variations, and exposure duration on heavy metal uptake by plants. Therefore, this study examines the impact of microplastics on the assimilation of lead (II) ions from the soil by *Canna indica*, with particular emphasis on these critical factors.

2. Materials and Methods

2.1. Study Area and Environmental Conditions

The experimental work was conducted in a suburban area of Aba, Abia State, Nigeria. The region is characterized by a humid tropical climate, with a mean annual temperature of approximately 27°C and a mean annual precipitation of 2200 mm. These conditions represent a typical tropical ecosystem susceptible to heavy metal leaching and plastic accumulation.

2.2. Soil Collection and Characterization

Loamy soil was sourced from the study site and subjected to oven-drying at 105°C to achieve a constant weight, remove moisture, and devitalize any indigenous seeds or pathogens. The dried soil was homogenized and passed through a 2 mm sieve to ensure a uniform substrate for both the nursery and the experimental phases.

2.3. Plant Material and Cultivation

Seeds of *Canna indica* were mechanically scarified (cracked) to break dormancy and sown in polyethylene nursery bags containing the processed loamy soil. After successful germination and the emergence of true leaves, 21 seedlings of uniform vigor and height were selected. These were transplanted into individual experimental units (round bottles) wrapped in aluminum foil to exclude light (preventing algal growth) and minimize moisture loss through evaporation.

2.4. Preparation of Lead(II) Nitrate Stock Solution

Analytical reagent (AR) grade Lead(II) nitrate Pb(NO₃)₂ was used to prepare the contaminant source.

Technical Note: To achieve a true $1000 \text{ mg L}^{-1} \text{ Pb}^{2+}$ stock solution, approximately 1.61 g of $\text{Pb}(\text{NO}_3)_2$ must be dissolved in 1 liter of deionized water (accounting for the molar mass of the nitrate salt).

The stock solution was subsequently diluted to the required experimental concentrations ranging from 5 to 45 mg L^{-1} .

2.5. Microplastic (PET) Preparation and Soil Amendment

Polyethylene terephthalate (PET) was sourced from post-consumer plastic bottles. The materials were cleaned with distilled water, air-dried, and mechanically pulverized using a Silver Crest Industrial Blender (Model 5000 W, 2023). The resulting particles were sieved through a $1.7 \times 1.2 \text{ mm}$ mesh to isolate the microplastic (MP) fraction.

The experimental soil was amended with varying dosages of PET microplastics (0.5, 1.0, 1.5, 2.0, and 2.5 g). The MPs were thoroughly incorporated into the soil matrix via manual agitation to ensure a heterogeneous distribution of the plastic particles before seedling transplantation.

2.6. Experimental Design and Monitoring

The study employed a randomized design consisting of 21 experimental units. Twenty units were subjected to varying combinations of Pb concentration, PET dosage, and soil pH, while one unit served as the control.

Growth Parameters: Plant height was measured from the soil baseline to the apical tip using a graduated tape. The total leaf count per plant was recorded weekly.

Sampling: Over a 35-day exposure period, plant tissues were harvested at 7-day intervals to monitor lead uptake.

2.7. Chemical Analysis and Statistical Treatment

Following the exposure period, plant samples were harvested, dried, and digested. The concentration of Pb^{2+} was determined using an Atomic Absorption Spectrophotometer (Model AA-7000).

All data were subjected to statistical analysis using SPSS version 23.0. Mean values and standard deviations were calculated to evaluate the variance between treatments. Linear regression and isotherm modeling (Freundlich and Pseudo-first-order kinetics) were performed using Microsoft Excel to determine the relationship between PET dosage, pH, and lead assimilation efficiency.

3. Results

3.1. Effect of Lead(II) Nitrate Concentration on Assimilation

Table 1 Influence of physicochemical parameters and PET microplastic loading on the Pb^{2+} assimilation capacity (q_t) of *Canna indica*

Pb Concentration (mg/L)	Pb Uptake, q_t (mg g^{-1})
5	0.531
15	1.346
25	2.247
35	3.510
45	5.325
Soil pH	Pb Uptake, q_t (mg g^{-1})
4.0	4.529
5.0	3.582
6.0	2.821
7.0	0.728

Time (days)	Pb Uptake, q_t (mg g^{-1})
7	0.578
14	1.183
21	1.974
28	3.162
35	4.345
PET(g)	Pb Uptake, at q_t (mg g^{-1})
0.5	1.183
1.0	2.191
1.5	3.284
2.0	3.569
2.5	4.137

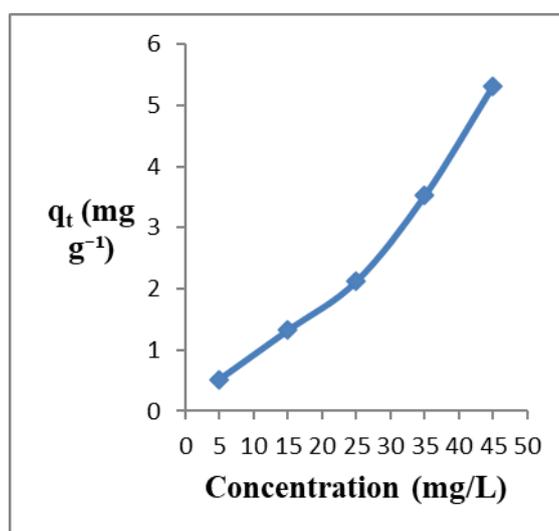


Figure 1 Plot of q_t (mg g^{-1}) vs. Concentration (mg/L)

The data revealed a consistent increase in lead(II) ions uptake by *Canna indica* as the Pb concentration in the growth medium increased. The Pb uptake (q_t) rose from 0.531 mg g^{-1} at 5 mg/L to 5.325 mg g^{-1} at 45 mg/L , indicating that the assimilation of Pb by *Canna indica* is strongly influenced by the availability of Pb in the medium. This trend aligns with the findings of Corley et al. (2017), who reported increasing shoot Pb uptake in Chinese cabbage with rising soil Pb levels. Similarly, Bravo et al., (2017) observed concentration-dependent increases in metal uptake across several edible plants grown in contaminated soils.

3.2. Effect of Soil pH on Lead Assimilation

Soil pH exhibited a strong inverse relationship with lead(II) ions uptake. The highest Pb uptake (q_t) (4.529 mg g^{-1}) occurred at pH 4.0, while the lowest Pb uptake (0.728 mg g^{-1}) occurred at pH 7.0. The natural soil pH (5.82) resulted in moderate uptake ($q_t = 1.621 \text{ ppm}$). This indicates that acidic soils substantially increase Pb solubility and availability, thereby enhancing plant assimilation. As pH approaches neutral values, Pb becomes increasingly adsorbed onto soil particles, reducing its availability for root uptake. These observations are in agreement with Adamczyk-Szabela et al. (2022), who reported that plant uptake of Pb and other heavy metals increases significantly under acidic soil conditions. Similarly, Bravo et al. (2017) found that metal solubility is higher at low pH, which correlates strongly with increased tissue metal concentrations.

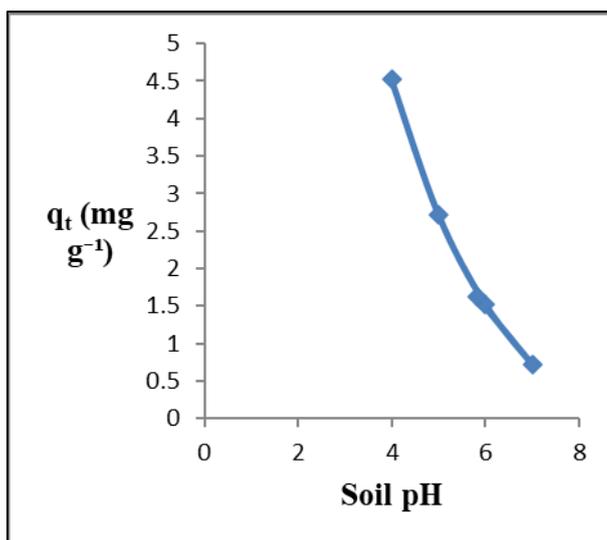


Figure 2 Plot of q_t (mg g⁻¹) vs. Soil pH

3.3. Effect of Time on Lead Assimilation by *Canna indica*

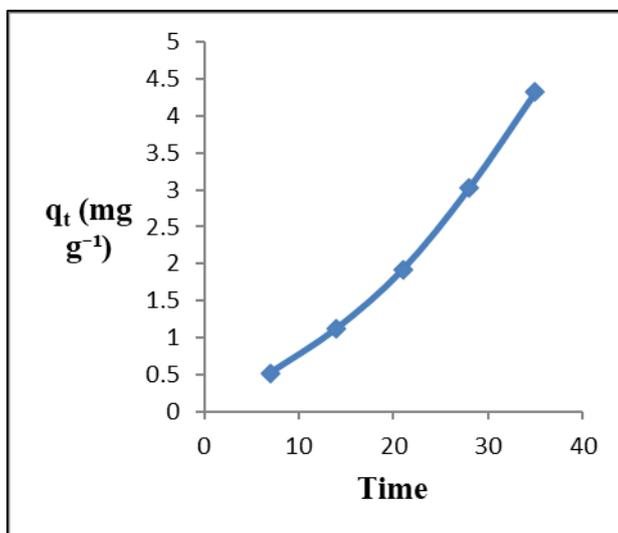


Figure 3 Plot of q_t (mg g⁻¹) vs. Time (t)

The data revealed a progressive lead(II) ions accumulation over the 35-day exposure period. Pb uptake (q_t) increased from 0.578 mg g⁻¹ at 7 days to 4.345 mg g⁻¹ at 35 days, with a noticeable acceleration beyond 21 days. This temporal trend reflects the gradual binding of lead(II) ions to root surfaces, followed by translocation into above-ground tissues over time. It also indicates that *Canna indica* sustains metal uptake as long as the metal remains available in the soil environment. These findings are in line with Corley *et al.*, (2017), who reported that metal concentrations in plant tissues tend to increase with growth duration due to cumulative root uptake and sequestration. Similarly, Adamczyk-Szabela *et al.*, (2022) observed that for many heavy metals, uptake continues gradually over time as roots remain exposed to contaminated soils.

3.4. Effect of PET Microplastic Dosage on Lead Assimilation

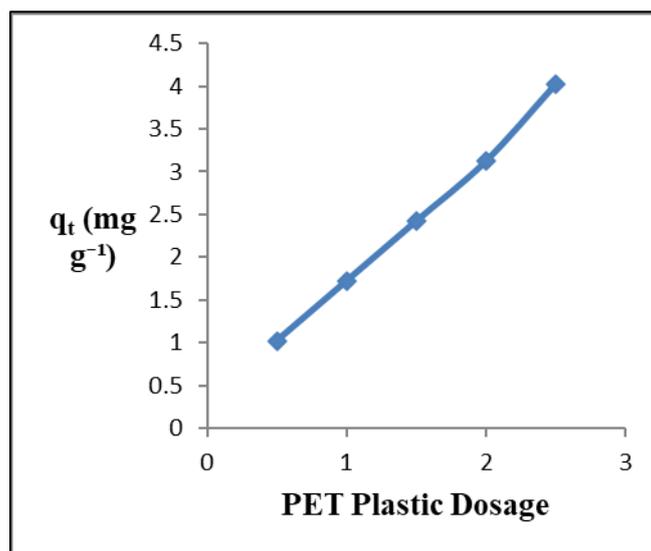


Figure 4 Plot of q_t (mg g^{-1}) vs. PET plastic dosage

The data revealed that the presence of PET microplastics significantly enhanced the assimilation of lead(II) ions by *Canna indica* compared with the plant-only controls. While the Pb uptake for plant-only samples remained constant at 1.183 mg g^{-1} across all treatments, the PET-amended treatments showed a steady increase in Pb uptake from 1.183 mg g^{-1} at 0.5 g PET to 4.137 mg g^{-1} at 2.5 g PET . This increase indicates that higher PET dosages correspondingly increased the bioavailability of lead(II) ions to the plant. The strong PET-induced enhancement of Pb uptake is consistent with the findings of Roy *et al.*, (2024), who reported increased cadmium accumulation in lettuce when microplastics were present in the soil. Similarly, Kumar *et al.*, (2022) observed that microplastics elevate heavy-metal bioavailability through surface sorption, modifications of soil structure, and altered microbial activity.

3.5. Isotherm Modeling

Isotherm modeling was applied to describe the equilibrium relationship between the concentration of lead(II) ions and the amount assimilated by *Canna indica* under different treatment conditions. Isotherm modeling helps determine how lead(II) ions interacts with plant tissues and soil surfaces, indicating the intensity, capacity, and mechanism of plant assimilation.

Table 2 Data on Isotherm Modeling

$\text{Log}_{10}(C_0)$	$\text{Log}_{10}(q_e)$
0.6990	-3.2826
1.1761	-2.8792
1.3979	-2.6730
1.5441	-2.4524
1.6532	-2.2739
$\text{Log}_{10}(\text{pH})$	$\text{Log}_{10}(q_e)$
0.6021	-2.3440
0.6021	-2.4536
0.7781	-2.5980
0.8451	-3.1412
0.7649	-2.7894

Log ₁₀ (Time)	log ₁₀ (q _e)
0.8451	-3.2826
1.1461	-2.9504
1.3222	-2.7161
1.4472	-2.5050
1.5441	-2.3647
Log ₁₀ (PET)	Log ₁₀ (q _e)
-0.3010	-2.9905
0.0000	-2.6946
0.1761	-2.5205
0.3010	-2.4536

3.5.1. Freundlich Isotherm

The Freundlich isotherm was selected as the primary model because it is empirical, describes adsorption on heterogeneous surfaces, and does not assume a finite number of identical adsorption sites (Murphy *et al.*, 2023).

The linearized form of the Freundlich equation is:

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \tag{1}$$

Where:

- q_e = amount of lead(II) ions assimilated at equilibrium (mg g⁻¹)
- C_e = equilibrium concentration of lead(II) ions in solution (mg L⁻¹)
- K_F = Freundlich constant, indicating adsorption/uptake capacity
- 1/n = adsorption intensity (heterogeneity factor)

3.5.2. Concentration-Based Freundlich Isotherm

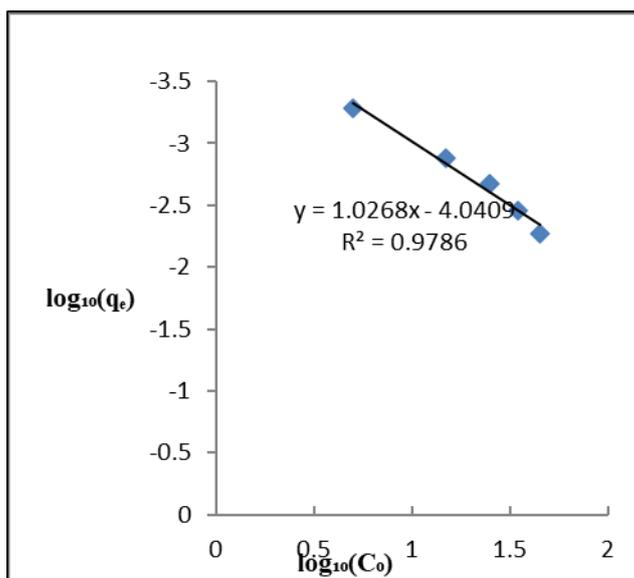


Figure 5 Freundlich isotherm plot of log₁₀(q_e) vs. log₁₀(C₀) for lead(II) ions concentration

The strong linear trend confirms that Pb assimilation increases with initial concentration in a non-linear manner, validating the Freundlich model. This reflects variable binding energies and multiple uptake pathways in plant tissues.

3.5.3. Soil pH Based Freundlich Isotherm

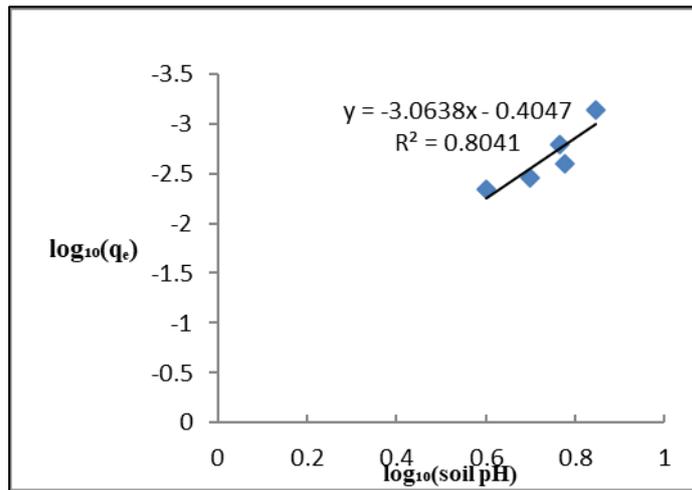


Figure 6 Freundlich isotherm plot of log₁₀(q_e) vs. log₁₀(soil pH)

The Freundlich pH isotherm shows a clear inverse relationship between soil pH and Pb uptake by *Canna indica*. As soil pH increased, log(q_e) values became more negative, indicating a reduction in Pb assimilation. At lower pH (log pH ≈ 0.6021, corresponding to pH 4–5), higher log(q_e) values (–2.3440 and –2.4536) were recorded, reflecting enhanced Pb bioavailability and stronger interaction with plant uptake sites. As pH increased toward neutral conditions (log pH = 0.8451, pH 7), log(q_e) decreased sharply to –3.1412, indicating minimal Pb assimilation. The natural soil pH (5.82; log pH = 0.7649) exhibited intermediate uptake behavior, confirming partial Pb availability under near-neutral conditions.

3.5.4. Time-Based Freundlich Isotherm

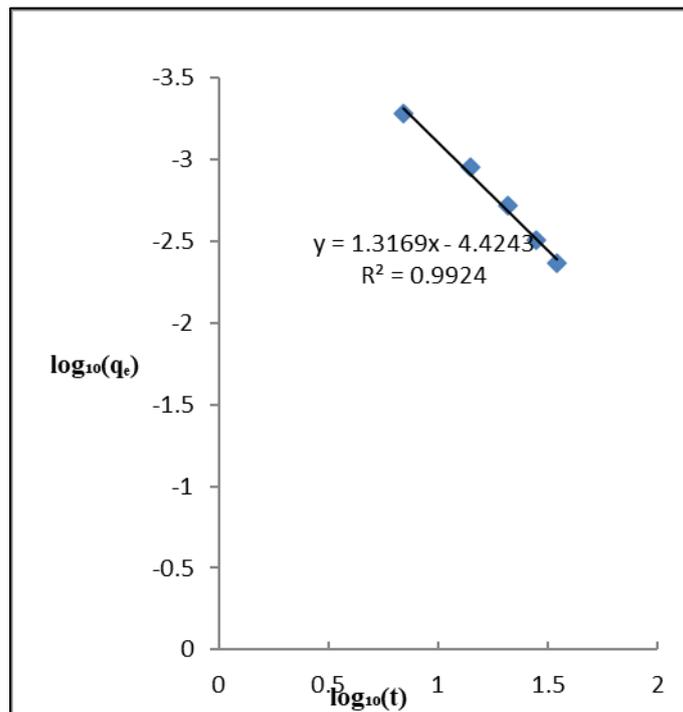


Figure 7 Freundlich isotherm plot of log₁₀(q_e) vs. log₁₀(t)

The linear relationship between log₁₀(time) and log₁₀(q_e) indicates that Pb assimilation increases with prolonged exposure following a power-law relationship. This confirms heterogeneous uptake behavior over time, consistent with Freundlich isotherm.

3.5.5. PET Dosage Freundlich Isotherm

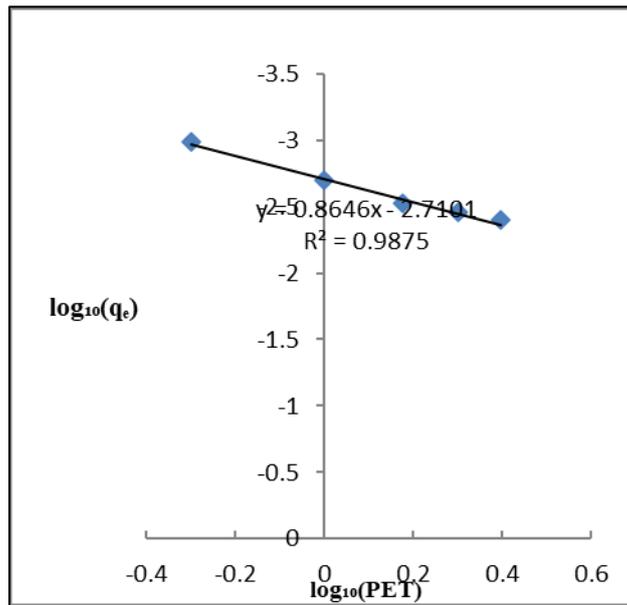


Figure 8 Freundlich isotherm plot of $\log_{10}(q_e)$ vs. $\log_{10}(\text{PET})$

The Freundlich plot for PET dosage demonstrates that increasing microplastic levels influence Pb assimilation through heterogeneous interactions. The linearity confirms that Pb uptake in the presence of PET microplastics follows non-uniform sorption behavior.

3.5.6. Kinetic Modeling

Kinetic modeling was conducted exclusively for the time-dependent lead(II) ions uptake data, because kinetic models require q_t values measured at multiple time points. The purpose was to understand the rate and mechanism of lead(II) ions assimilation by *Canna indica*. In this work, only pseudo-first-order (PFO) kinetic model was used to simulate experimental data.

Table 3 Data on Pseudo-First-Order and Pseudo-second -Order kinetic modelling

Pseudo-First-Order Data	
Time (days)	$q_t(\text{mg.g}^{-1})$
7	0.000521
14	0.001121
21	0.001921
28	0.003121
35	0.000000
Pseudo-second -Order Data	
Time (days)	$q_t(\text{mg.g}^{-1})$
7	0.000521
14	0.001121
21	0.001921
28	0.003121

Pseudo-First-Order Kinetic Model

The pseudo-first-order (Lagergren) model describes the uptake rate assuming that the driving force is proportional to the difference between equilibrium uptake (q_e) and uptake at time t (q_t). The linearized equation is:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \tag{2}$$

Where:

q_t = amount of lead(II) ions taken up at time t (mg g^{-1})

q_e = equilibrium uptake (mg g^{-1})

k_1 = pseudo-first-order rate constant (day^{-1})

Pseudo-First-Order Kinetics

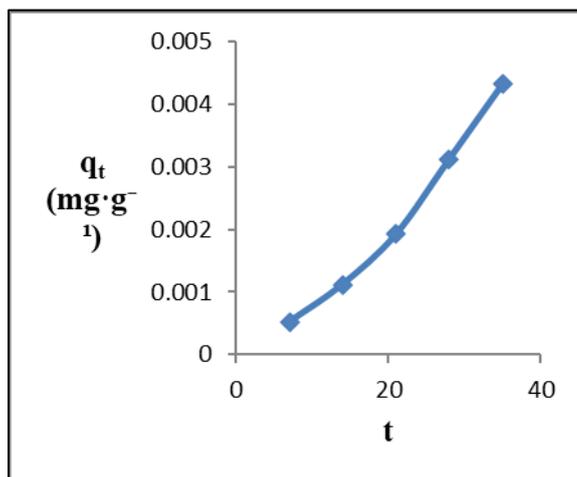


Figure 9 Pseudo-First-Order kinetic plot of q_t vs. time

The increasing q_t values up to 28 days indicate progressive Pb uptake, after which equilibrium is reached. The zero value at 35 days represents equilibrium where $q_e - q_t$ equals zero, justifying exclusion from logarithmic linearization.

Pseudo-Second-Order Kinetics

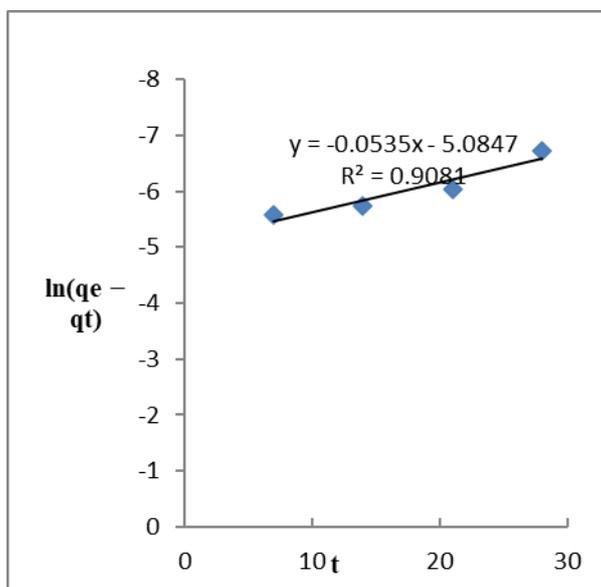


Figure 10 Pseudo-second-Order kinetic plot of $\ln(q_e - q_t)$ vs. time

The data show a steady increase in q_t from 0.000521 mg g⁻¹ at 7 days to 0.004321 mg g⁻¹ at 35 days, indicating progressive Pb accumulation with time. These values were used to construct the pseudo-second-order plot to assess whether chemisorption controlled kinetics govern Pb uptake. Although the model produced a linear relationship, the derived kinetic parameters were not physically meaningful for this system; therefore, the pseudo-second-order model was considered less suitable than the pseudo-first-order model for describing Pb assimilation by *Canna indica*.

4. Conclusion

The findings of this study showed that lead uptake increased with higher lead(II) ions concentrations, longer exposure times, and more acidic soil conditions, indicating that metal availability and soil chemistry are key factors influencing bioaccumulation. Acidic soils enhanced lead uptake compared to neutral soils, demonstrating the importance of pH in controlling metal solubility and mobility in soil and plant systems. The presence of polyethylene terephthalate microplastics significantly increased lead bioavailability and plant assimilation compared to microplastic free controls. Higher polyethylene terephthalate dosages corresponded to greater lead(II) ions uptake, suggesting that microplastics facilitate metal transport and retention in the soil through surface sorption and modifications of soil physicochemical properties. Freundlich isotherm analysis confirmed heterogeneous uptake behavior, while pseudo first order kinetic modeling indicated that lead assimilation by *Canna indica* is time dependent and proceeds progressively toward equilibrium. The enhanced transfer of toxic metals into plant tissues raises concerns about food safety and the potential propagation of contaminants through terrestrial food webs. This study also identifies *Canna indica* as a responsive species for assessing microplastic and heavy metal interactions in soils. Further research is recommended to investigate the long term effects of microplastics and the influence of different polymer types in order to better inform monitoring, risk assessment, and remediation strategies for microplastic and heavy metal pollution in terrestrial ecosystems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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