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Mediterranean Journal of Chemistry **2024**, 15(1), 76-102

Comparative phytoremediation potentials of *Jatropha curcas, Ixora coccinea*, *Codiaeum variegatum*, *Andropogon tectorium*, *Panicum maximum*, *Zea mays*, *Cajanus cajan* for Heavy Metals

Charity Anarado [1,*], Chigozie Anarado [1], Onyeka Obumselu [1], Chinasa Iziga [1], Ebuka Onyilogwu [1], Ijeoma Anarado [1], Chika Okorie [2]

[1] Department of Pure and Industrial Chemistry, Faculty of Physical Sciences, Nnamdi Azikiwe University, Awka 420110, Anambra State, Nigeria

[2] Department of Chemistry and Biochemistry, Texas Tech University, USA

Abstract: The emergence of the industrial revolution has led to an enormous increase in heavy metal pollution of the biosphere, which subsequently became a threat to the environment and human life. Heavy metal pollution and human health have been recognized as one of the most critical threats to soil and water resources. The potential of *Jatropha curcas*, *Ixora coccinea*, *Codiaeum variegatum*, *Andropogon tectorium*, *Panicum maximum*, *Zea mays*, and *Cajanus cajan* as suitable phytoremediators for soil matrix polluted with Zinc (Zn), Cobalt (Co), Cadmium (Cd) and Lead (Pb) is the aim of this work. The plants were grown in soils polluted with 0.1M and 0.5M Pb2+, Cd2+, Co2+, and Zn2+ solutions and harvested after 8 and 12 weeks of inoculation. They were washed, air-dried, ashed, and digested, and concentrations of the metal ions were analyzed. The results revealed that the plants showed significant absorption effects in the absorption of Pb^{2+}($P< 0.01$), Cd^{2+}($P< 0.01$), Co^{2+} ($P< 0.01$) and Zn^{2+} ($P< 0.001$). There was also a significant interaction between plants and the time of harvest in the absorption of Pb^{2+}($P< 0.01$), Cd^{2+}($P= 0.02$) and Zn^{2+} ($P< 0.001$). No significant interaction was observed for the absorption of Co ($P= 0.36$). At 0.5M concentration of Pb^{2+} and Cd^{2+}, the mean Pb^{2+} and Cd^{2+}absorptions in *Codiaeum variegatum* (female) were significantly higher than in other plants. Also *Ixora coccinea* had the highest mean absorption of Co^{2+} when inoculated with 0.5M of the metal ion and at 8 weeks, while the mean Zn^{2+} absorption in *Codiaeum variegatum* (male) was significantly higher than those of other plants when inoculated with 0.5M Zn^{2+} and at 12 weeks. The flowering plants- *Codiaeum variegatum* (male and female) and *Ixora coceinea* showed better absorption of the metal ions than all other plants. The potential demonstrated by the flowering plants indicated that they could serve both aesthetic and phytoremediation functions at the same time. Absorption is the chief phytoremediation process since it removes the toxic heavy metals from the soil, as seen from our experimental findings.

Keywords: Phytoremediation; *Jatropha curcas; Ixora coccinea; Codiaeum variagatum*; *Andropogon tectorium*; *Panicum maximum*; *Zea mays*; *Cajanus cajan*; heavy metals.

1. Introduction

Human life and the environment are being threatened by the drastic increase in heavy metal pollution of the biosphere owing to the emergence of the Industrial Revolution. One of the most critical threats to human health and soil and water resources has been known to be heavy metal pollution [1]. Anthropogenic and geological activities are sources of heavy metal contamination. Anthropogenic activities contributing to metal contamination include agricultural chemicals, fuel production, mining, smelting, military activities, and industrial pollutants [2]. These pollutants remain incredibly harmful in several forms, and for environmental safety, the high concentrations of these heavy metals/pollutants must remove.

Phytoremediation can be explained as a set of ecological methodologies that uses plants in situ to enhance the breakdown, immobilization, and removal of pollutants from the environment [3-5]. Phytoremediation of soil polluted by heavy metals has been a technology that utilizes plants to extract these metals from the soil or render them harmless *in situ* [6]. It serves as a means of reducing environmental contamination [7]. The rehabilitation of metal-contaminated sites is vital for restoring sites, which keeps them in a good productive state and limits human exposure to toxic metals [8]. Phytoremediation is a cost-effective strategy for eliminating pollutants

**Corresponding author:* Charity Anarado
Email address: ce.anarado@unizik.edu.ng
DOI: http://dx.doi.org/10.13171/mjc02501291766anarado

Received November 6, 2024
Accepted December 11, 2024
Published January 29, 2025

(mainly heavy metals and organics) from contaminated soils and waters at the site level with little or no disturbance to the landscape [5,9]. It equally reduces the cost of alternatively disposing of hazardous wastes in a landfill or an off-site storage facility [5].

Phytoremediation can be grouped into techniques viz phytoextraction [2], hemofiltration (hemofiltration), phytodegradation, phytovolatilization, and phytostabilisation [10]. Phytoextractionalso, also known as phytoaccumulation, is a phytoremediation application that utilizes plants to remove heavy metals from water, soil, and sediments. It is also a promising soil remediation process that can quickly absorb heavy metals and clear the soil of toxins [11,12, 13]. Phytoextraction removes pollutants from the soil without adversely affecting the soil properties [13]. Plants have been shown to directly affect contaminant levels through phytoextraction, which concentrates heavy metals from the environment into plant tissues [14]. To be eligible for phytoremediation, plants are usually highly productive and good bioaccumulators with tolerance to increased pollution levels [14-16]. Many research groups have explored the potential of various species for the phytoextraction of heavy metal-contaminated areas [17-19]. In addition, aquatic plants such as water hyacinth (*Eichhornia crassipes*), pennyworth (*Hydrocotyle umbellate*), duckweed (*Lemna minor*), and water velvet (*Azollapinnata*) have been shown to be effective in rhizofiltration, phytoextraction and phytodegradation [20,21].

In this study, the metal uptake potentials of eight plants found in Nigeria were investigated. The plants are *Jatropha curcas* (a species of flowering plant in the spurge family, Euphorbiaceae, found in tropical and subtropical regions), *Ixora coccinea* (a genus of flowering plant in the Rubiacea family), *Codiaeum variegatum* –both male and female species (another flowering plant belonging to the Euphorbiaceae family, which are salinity resistant plants), *Andropogon tectorium*, *Panicum maximum* (Guinea grass), *Zea mays* (corn) and *Cajanus cajan* (Pigeon Pea, an annual or semi-perennial shrub legume).
These plants were chosen for this study for reasons that include ready availability, widespread distribution, vast knowledge base, rapid growth, and plant commodity values. Herein, we report the potential of these plants as suitable phytoremediators for soil matrix polluted with Zinc (Zn), Cobalt (Co), Cadmium (Cd), and Lead (Pb) at 0.1M and 0.5M concentrations, and at 8 and 12 weeks of inoculation.

2. Methods

Four hundred and thirty-two (432) seedlings of *Jatropha curcas (Jc), Ixora coccinea (Ic), Codiaeum variegatum* (male (Cm) and female (Cf)), *Andropogon tectorium(At)* and *Panicum maximum(Pl)* were collected from the premises of Nnamdi Azikiwe University, Awka Nigeria, while the seedlings of *Zea mays(Zm)* and *Cajanus cajan(Cc)* were collected from an already prepared nursery. The seeds and seedlings were identified at the Department of Botany Herbarium, Nnamdi Azikiwe University, Awka. The seeds and seedlings were later authenticated at the same Herbarium. Exactly 0.1 M and 0.5 M solutions of $Zn(NO_3)_2·6H_2O$, $Co(NO_3)_2·6H_2O$, $Pb(NO_3)_2$ and $Cd(NO_3)_2·4H_2O$ were prepared using the methods described by Anarado *et al*., 2019 [22]. Briefly, 0.1 M solutions of $Co(NO_3)_2·6H_2O$, $Zn(NO_3)_2·6H_2O$, $Cd(NO_3)_2·4H_2O$, and $Pb(NO_3)_2$ were prepared dissolving 29.103g, 29.748 g, 30.848 g and 33.121 g respectively in 0.7 dm^3 of distilled water and each made up to 1 dm^3 mark with distilled water. 0.5 M solutions of $Co(NO_3)_2·6H_2O$, $Zn(NO_3)_2·6H_2O$, $Cd(NO_3)_2·4H_2O$, and $Pb(NO_3)_2$ were prepared to dissolve 145.516 g, 148.74 g, 154.24 g, and 165.605 g respectively in 0.7 dm^3 of distilled water and each made up to 1 dm^3 mark with distilled water. Fifty-four seedlings of each plant were grown in isolated polyethylene bags; forty-eight seedlings were inoculated with 0.1M and 0.5M solutions of the salt, while six of each plant were left uninoculated. The plants were harvested after 8 and 12 weeks of inoculation, washed, air-dries, washed, and digested with aqua regia, and concentrations of Pb^{2+}, Zn^{2+}, $Cd^{2+,}$ and Co^{2+} absorbed by the inoculated and uninoculated plants were determined using VARIAN AA240 Atomic Absorption Spectrophotometer, Tables 1,2,3,4.

1. Results and Discussions

1.1. Lead Ion (Pb^{2+}) Absorption by Plants

Table 1. Absorption of Pb^{2+} (mg/kg) by plants at different concentrations and harvest times.

	8 Weeks		12 Weeks	
Plants	0.1M	0.5M	0.1M	0.5M
Jc	0.35 ± 0.11^d	1.85 ± 0.48^c	0.65 ± 0.11^c	0.59 ± 0.18^c
Cf	5.94 ± 0.20^a	7.49 ± 1.27^a	5.25 ± 0.37^a	9.33 ± 0.27^a
Cm	2.35 ± 0.36^c	6.51 ± 0.81^a	5.21 ± 0.75^a	3.90 ± 0.70^b

At	0.46 ± 0.10^{d}	0.86 ± 0.41^{d}	4.70 ± 0.21^{a}	2.94 ± 0.64^{b}
Pl	3.22 ± 0.39^{b}	3.88 ± 0.12^{b}	4.34 ± 0.38^{a}	3.49 ± 0.22^{b}
Ic	1.13 ± 0.26^{d}	0.76 ± 0.10^{d}	2.35 ± 0.35^{b}	0.31 ± 0.08^{c}
Zm	0.60 ± 0.24^{d}	0.00 ± 0.00^{d}	0.16 ± 0.05^{c}	0.18 ± 0.07^{c}
Cc	0.19 ± 0.06^{d}	0.12 ± 0.04^{d}	0.19 ± 0.09^{c}	0.19 ± 0.05^{c}

*Data are expressed as mean ± standard deviation (n = 3)
*Means in the same column with different superscripts are significantly different at $p < 0.05$
*Plant species: *Jatropha curcas* – Jc, *Codiaeum variegatum* (female) – Cf, *Codiaeum variegatum* (male) – Cm, *Andropogon tectorium* – At, *Panicum maximum* – Pl, *Ixora coccinea* – Ic, *Zea mays* – Zm, *Cajanus cajan* – Cc

The two-factor analysis of variance (ANOVA) was used to examine the effect of the concentration of metal ions and the harvest time of plants on the absorption of selected metal ions (Pb^{2+}, Cd^{2+}, Co^{2+}, and Zn^{2+}) by the plants. Where an interaction effect exists between concentration and harvest time, a pairwise comparison of means was made using Tukey's test at a 0.05% significance level. Results with P < 0.05 were considered statistically significant. The analysis was done using R, version 3.5.3

Table 2. Absorption of Cd^{2+} (mg/kg) by plants at different concentrations and harvest times.

	8 Weeks		12 Weeks	
Plants	0.1M	0.5M	0.1M	0.5M
Jc	0.05 ± 0.07^{d}	0.42 ± 0.10^{e}	0.20 ± 0.18^{c}	0.78 ± 0.03^{e}
Cf	12.79 ± 1.36^{a}	35.23 ± 1.07^{a}	33.09 ± 4.08^{a}	36.22 ± 3.99^{a}
Cm	2.44 ± 0.50^{c}	3.03 ± 0.34^{d}	3.05 ± 0.08^{b}	3.88 ± 0.71^{c}
At	2.43 ± 0.63^{c}	14.76 ± 0.60^{b}	6.11 ± 0.58^{b}	1.88 ± 0.36^{d}
Pl	5.21 ± 0.97^{b}	0.26 ± 0.17^{e}	1.55 ± 0.20^{c}	1.60 ± 0.28^{d}
Ic	1.39 ± 0.74^{c}	9.40 ± 0.58^{c}	0.36 ± 0.10^{c}	27.71 ± 4.74^{b}
Zm	0.02 ± 0.01^{d}	0.16 ± 0.08^{e}	0.01 ± 0.01^{c}	0.01 ± 0.00^{e}
Cc	0.01 ± 0.01^{d}	0.19 ± 0.06^{e}	0.06 ± 0.05^{c}	0.05 ± 0.03^{e}

*Data are expressed as means ± standard deviation (n = 3)
*Means in the same column with different superscripts are significantly different at $p < 0.05$
*Plant species: *Jatropha curcas* – Jc, *Codiaeum variegatum* (female) – Cf, *Codiaeum variegatum* (male) – Cm, *Andropogon tectorium* – At, *Panicum maximum* – Pl, *Ixora coccinea* – Ic, *Zea mays* – Zm, *Cajanus cajan* – Cc

Table 3. Absorption of Zn^{2+} (mg/kg) by plants at different concentrations and harvest times.

	8 Weeks		12 Weeks	
Plants	0.1M	0.5M	0.1M	0.5M
Jc	0.15± 0.09^{c}	0.69± 0.15^{e}	1.05± 0.49^{d}	1.16± 0.14^{c}
Cf	5.02± 1.02^{a}	10.02± 0.39^{a}	8.24± 0.67^{b}	7.37± 2.02^{b}
Cm	3.90± 0.89^{b}	10.00± 0.27^{a}	9.33± 0.47^{a}	10.10± 0.39^{a}
At	4.55± 1.19^{a}	5.35± 1.26^{c}	7.67± 0.75^{b}	9.79± 0.38^{a}
Pl	4.68± 0.48^{a}	8.43± 1.17^{b}	7.16± 0.73^{b}	9.96± 0.54^{a}
Ic	1.97± 0.36^{c}	8.55± 0.97^{b}	3.95± 0.98^{c}	10.96± 1.45^{a}
Zm	3.88 ± 0.80^{b}	3.06 ± 0.96^{d}	0.54 ± 0.21^{d}	0.40 ± 0.25^{c}
Cc	3.02 ± 0.09^{b}	2.10 ± 0.38^{d}	1.65 ± 0.12^{d}	1.44 ± 0.42^{c}

*Data are expressed as means ± standard deviation (n = 3)
*Means in the same column with different superscripts are significantly different at $p < 0.05$
*Plant species: *Jatropha curcas* – Jc, *Codiaeum variegatum* (female) – Cf, *Codiaeum variegatum* (male) – Cm, *Andropogon tectorium* – At, *Panicum maximum* – Pl, *Ixora coccinea* – Ic, *Zea mays* – Zm, *Cajanus cajan* – Cc

Table 4. Absorption of Co^{2+} (mg/kg) by plants at different concentrations and harvest times.

	8 Weeks		12 Weeks	
Plants	0.1M	0.5M	0.1M	0.5M
Jc	0.06 ± 0.05^{b}	0.15 ± 0.09^{d}	0.81 ± 0.60^{c}	0.60 ± 0.14^{d}
Cf	1.31 ± 0.03^{b}	13.29 ± 1.94^{b}	3.05 ± 0.58^{a}	19.75 ± 0.63^{a}
Cm	1.02 ± 1.02^{b}	0.49 ± 0.04^{d}	1.56 ± 0.31^{b}	2.47 ± 0.52^{c}
At	0.82 ± 0.25^{b}	1.54 ± 0.33^{d}	2.83 ± 0.44^{a}	2.29 ± 0.28^{c}
Pl	6.07 ± 1.45^{a}	4.20 ± 0.48^{c}	0.82 ± 0.38^{c}	0.99 ± 0.03^{d}
Ic	1.15 ± 0.32^{b}	20.37 ± 2.05^{a}	3.66 ± 0.50^{a}	13.12 ± 0.67^{b}
Zm	0.01 ± 0.02^{b}	0.04 ± 0.03^{d}	0.06 ± 0.01^{c}	0.13 ± 0.05^{d}
Cc	0.06 ± 0.03^{b}	0.02 ± 0.02^{d}	0.04 ± 0.01^{c}	0.06 ± 0.03^{d}

*Data are expressed as means ± standard deviation (n = 3)
*Means in the same column with different superscripts are significantly different at $p < 0.05$
*Plant species: *Jatropha curcas* – Jc, *Codiaeum variegatum* (female) – Cf, *Codiaeum variegatum* (male) – Cm, *Andropogon tectorium* – At, *Panicum maximum* – Pl, *Ixora coccinea* – Ic, *Zea mays* – Zm, *Cajanus cajan* – Cc

3.2. Effects of concentration and harvest time on Pb^{2+} absorption by Jc Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Pb^{2+} by Jc plant at a given concentration depends on the harvest time. The highest Pb^{2+} absorption (1.85 mg/kg) was observed at 0.5M concentration in Jc plants harvested on week 8. This was significantly higher than the absorption observed at 0.5M concentration in Jc plants harvested on week 8(0.35 mg/kg) and at 0.1M and 0.5M concentrations in Jc plants harvested on week 12(0.59 mg/kg and 0.69 mg/kg, respectively), which were not significantly different (Figure 1). *Jatropha curcas* had earlier been reported to be a suitable sorbent of lead ions in an aqueous solution [23].

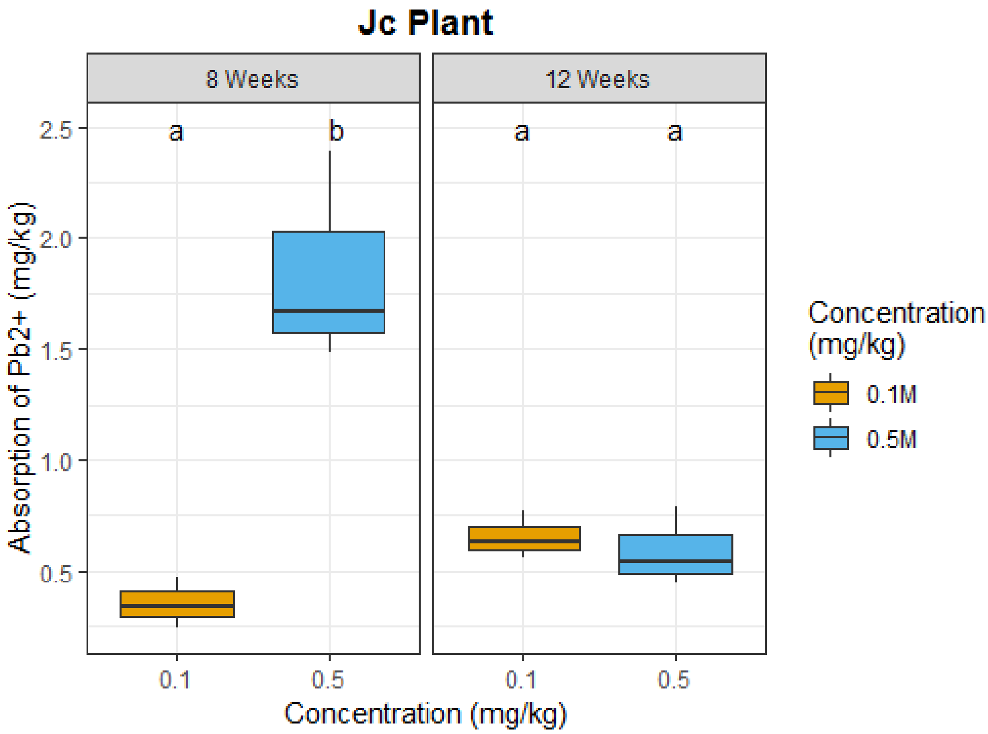

Figure 1. Effect of concentration and harvest time on Pb^{2+} absorption by Jc Plant

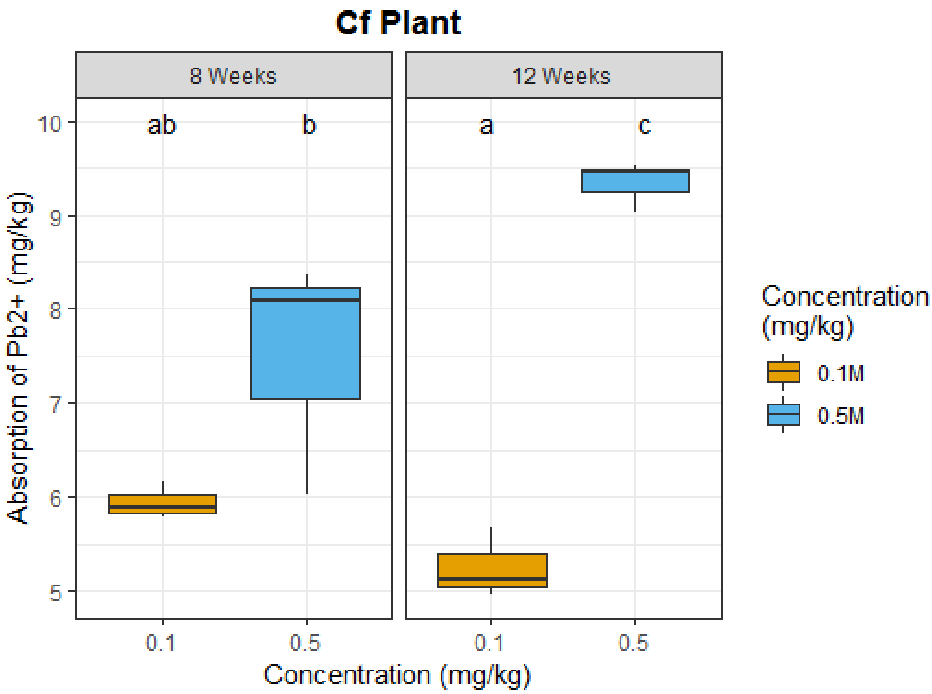

Figure 2. Effect of concentration and harvest time on Pb^{2+} absorption by Cf Plant

3.3. Effects of concentration and harvest time on Pb^{2+} absorption by Cf Plant

The observed interaction between concentration and time of harvest of Cf plants implies that the absorption of Pb^{2+} by Cf plant at a given concentration depends on the harvest time. Figure 2 shows that the highest Pb^{2+} absorption (9.34 mg/kg) was observed at 0.5M concentration in Cf plants that were harvested on week 12. Unsurprisingly, this plant absorbed this high lead concentration, as lead in the soil can establish many ionic bonds. It is categorized as a weak Lewis acid with a strong covalent character. Lead distribution in the soil is from combinations of factors that include chemical processes such as oxidation and reduction reactions, adsorption of cations on the exchange complex, chelation by organic matter, metal oxides, and cycling by vegetation. Because of its strong binding with organic and colloidal materials, soil lead is soluble and is available for plant uptake [24]. This was significantly higher than the absorption observed at 0.5M concentration in Cf plants harvested on week 12 and at 0.1M and 0.5M concentrations in Cf plants harvested on week 8. The lowest Pb^{2+} absorption (5.25 mg/kg) was observed at 0.1M concentration in Cf plants harvested on week 12, which was not significantly different from the Pb^{2+} absorption (5.9 mg/kg) at 0.1M concentration in Cf plants harvested on week 8.

3.4. Effects of concentration and harvest time on Pb^{2+} absorption by Cm Plant

The observed interaction effect between concentration and time of harvest of Cm plants implies that the absorption of Pb^{2+} by Cm plant at a given concentration depends on the harvest time. Figure 3 shows that the highest Pb^{2+} absorption (6.51 mg/kg) was observed at 0.5M concentration in Cm plants harvested on week 8. This was, however, not significantly higher than the absorption (5.21 mg/kg) observed at 0.1M concentration in Cm plants harvested on week 12. The lowest Pb^{2+}absorption (2.35 mg/kg) was observed at 0.1M concentration in Cm plants harvested on week 8, which was not significantly different from the Pb^{2+} absorption (3.90 mg/kg) at 0.5M concentration in Cm plants harvested on week 12. Both male and female species of *Codiaeum variegatum* exhibited the capacity as hyperaccumulators of lead. Our result validates the work of Agustin and Hamidah (2019), who reported that *C. variegatum* could potentially be a Pb emission reduction plant [25].

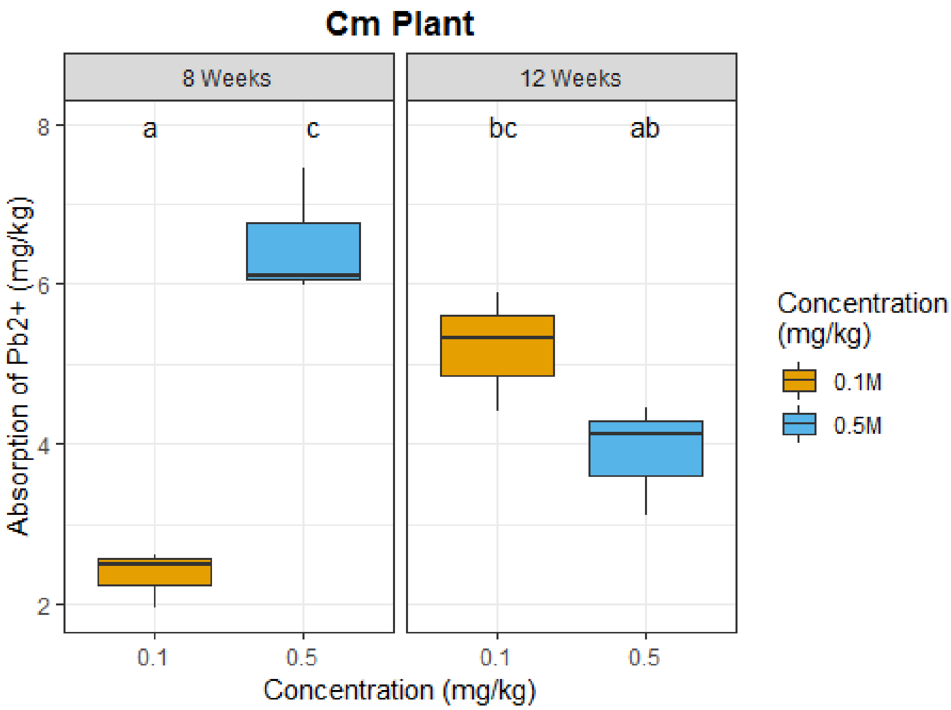

Figure 3. Effect of concentration and harvest time on Pb^{2+} absorption by Cm Plant

3.5. Effect of concentration and harvest time on Pb^{2+} absorption by At plant

The observed interaction effect between concentration and time of harvest of At plants implies that the absorption of Pb^{2+} by At plants at a given concentration depends on the harvest time. Figure 4 shows that the highest Pb^{2+} absorption (4.70 mg/kg) was observed at 0.1M concentration in At plants harvested on week 12. This was significantly higher than the absorption observed at 0.5M concentration in At plants harvested on week [12] and at 0.1M and 0.5M concentrations in At plants harvested on week 8. The lowest Pb^{2+} absorption (0.45 mg/kg) was observed at 0.1M concentration in At plants harvested on week 8, which was not significantly different from the Pb^{2+} absorption (0.86 mg/kg) at 0.5M concentration in At plants harvested on week 8. The led ion's absorption increased with an increase in concentration at 8 weeks. However, absorption was decreased at 12 weeks with an increase in concentration. Another species of *Andropogon*- *A. gayanus* was reported to have absorbed lead, which aligns with our report [26].

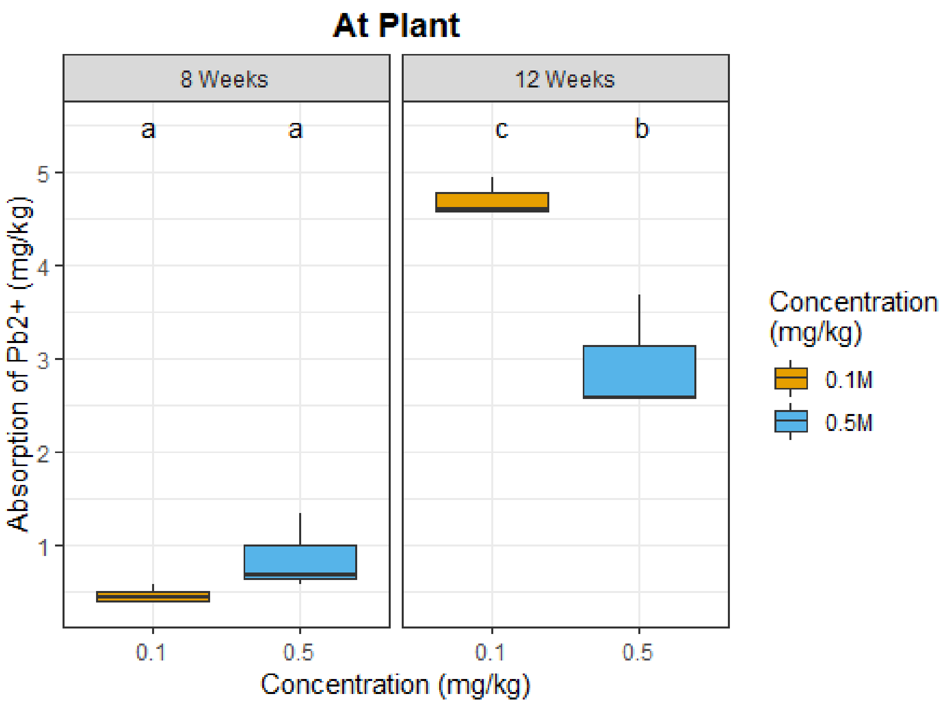

Figure 4. Effect of concentration and harvest time on Pb^{2+} absorption by At plant

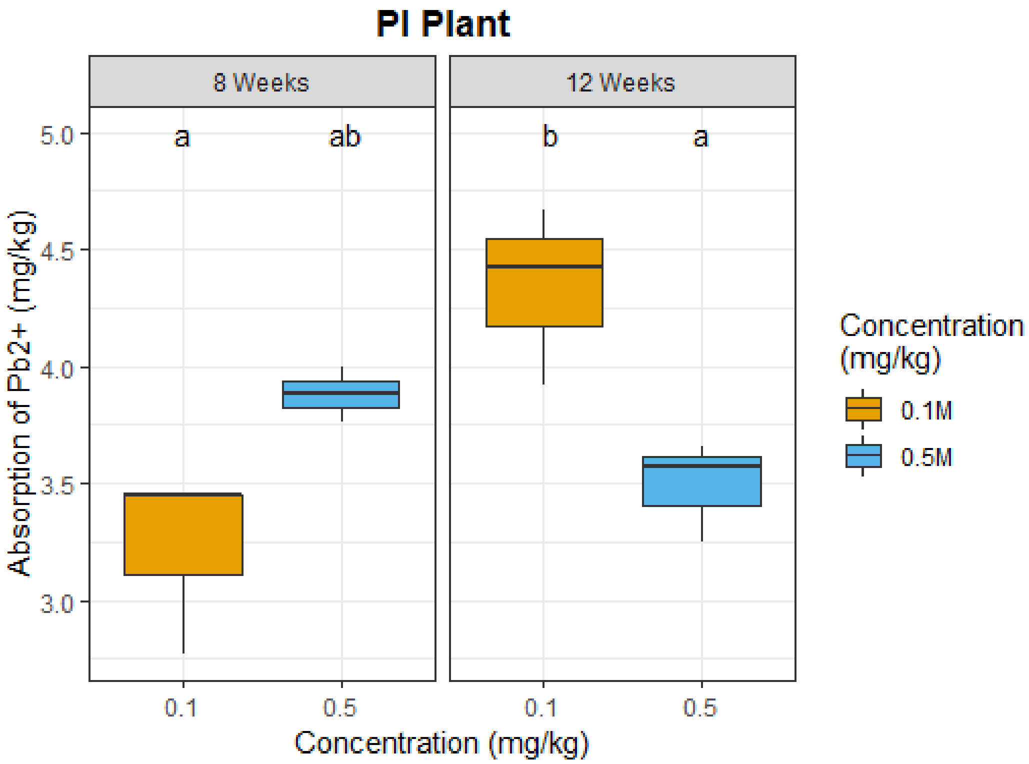

Figure 5. Effect of concentration and harvest time on Pb^{2+} absorption by Pl Plant

3.6. Effects of concentration and harvest time on Pb^{2+} absorption by Pl Plant

The observed interaction between concentration and time of harvest of Pl plants implies that the absorption of Pb^{2+} by Pl plants at a given concentration depends on the harvest time. Figure 5 shows that the highest Pb^{2+} absorption (4.34 mg/kg) was observed at 0.1M concentration in Pl plants that were harvested on week 12. This was significantly higher than the absorption observed at 0.5M concentration in Pl plants harvested on week 12 and at 0.1M concentration in Pl plants harvested on week 8, but not at 0.5M concentration for plants harvested on week 8. The lowest Pb^{2+} absorption (3.22 mg/kg) was observed at 0.1M concentration in Pl plants harvested on week 8, which was not significantly different from the Pb^{2+} absorption at 0.5M concentration in Pl plants harvested on week 8 and week 12 (3.88 mg/kg and 3.48 mg/kg, respectively). *Panicum maximum* had earlier been reported to be used in absorbing lead, which aligns with our findings, as the plants could absorb 4.34 mg/kg of lead [27].

3.7. Effects of concentration and harvest time on Pb^{2+} absorption by Ic Plant

The observed interaction between concentration and time of harvest of Ic plants implies that the absorption of Pb^{2+} by Ic plants at a given concentration depends on the harvest time. Figure 6 shows that the highest Pb^{2+} absorption (2.34 mg/kg) was observed at 0.1M concentration in Ic plants harvested on week 12. This was significantly higher than the absorption observed at 0.5M concentration in Ic plants harvested on week 12 and at 0.1M and 0.5M concentrations in Ic plants harvested on week 8. The lowest Pb^{2+} absorption (0.31 mg/kg) was observed at 0.5M concentration in Ic plants harvested on week 12, which was not significantly different from the Pb^{2+} absorption (0.76 mg/kg) at 0.5M concentration in Ic plants harvested on week 8. An increase in the concentration of lead ions decreased the lead ion absorption by Ixora coccinea at both harvest times. *I. coccinea, an ornamental plant*, has the advantage because the flowers may be reused after remediation [28].

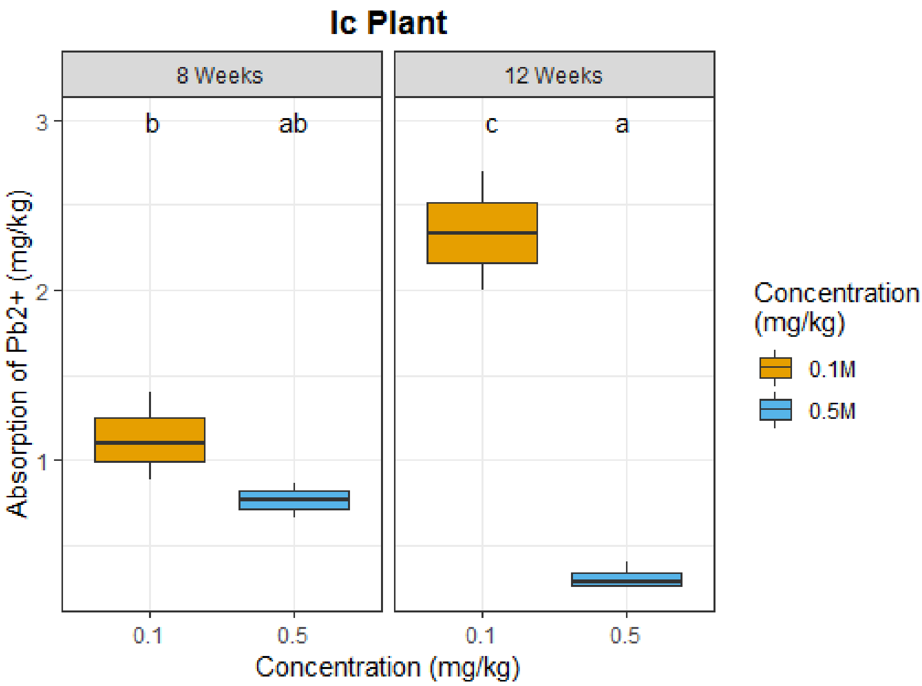

Figure 6. Effect of concentration and harvest time on Pb^{2+} absorption by Ic Plant

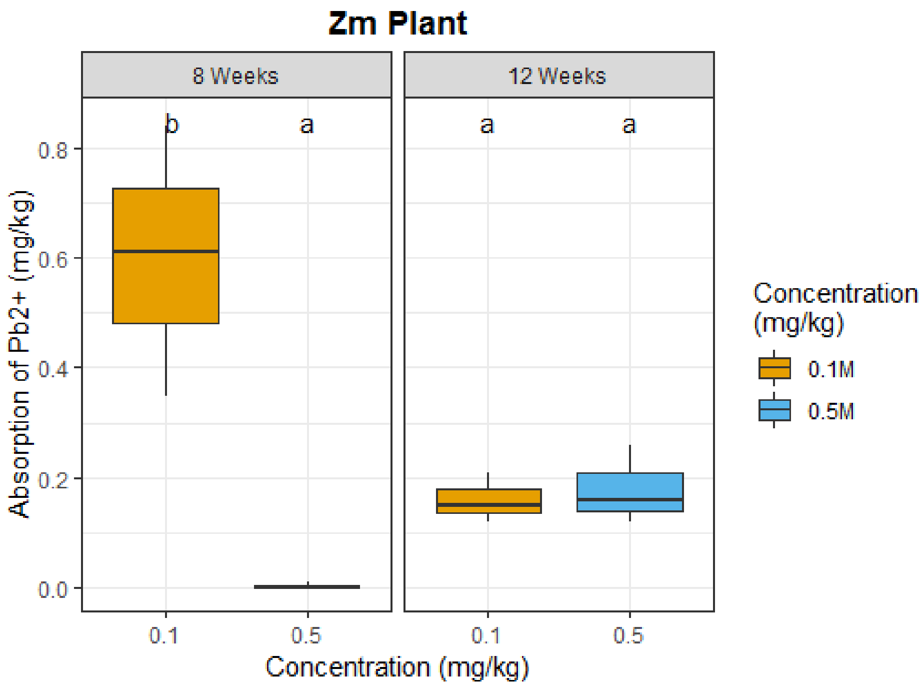

Figure 7. Effect of concentration and harvest time on Pb^{2+} absorption by Zm Plant

3.8. Effects of concentration and harvest time on Pb^{2+} absorption by Zm Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Pb^{2+} by the Zm plant at a given concentration depends on the harvest time. The highest Pb^{2+} absorption (0.60 mg/kg) was observed at 0.1 M concentration in Zm plants harvested on week 8. This was significantly higher than the absorption observed at 0.5 M concentration in Zm plants harvested on week 8 (0.003 mg/kg) and at 0.1M and 0.5 M concentrations in Zm plants harvested on week 12 (0.16 mg/kg and 0.18 mg/kg, respectively), which were not significantly different (Figure 7). The absorption of lead by *Zea mays* decreased when the concentration was increased from 0.1M to 0.5M at 8 weeks. Our result is against the report of Chiwetalu *et al.* (2020), who reported that lead absorption by *Zea mays* increased with increased lead concentration in the soil [29].

3.9. Effects of concentration and harvest time on Pb^{2+} absorption by Cc Plant

No interaction effect was observed between the concentration of ions and the harvest time. Figure 8 shows that concerning the concentration of ions, the highest Pb^{2+} absorption of 0.19 mg/kg was observed at 0.1M, which was not significantly different from that of 0.5M concentration (0.12 mg/kg). Similarly, the Pb^{2+} absorption of 0.19 mg/kg recorded in Cc plants harvested on week 12 was not significantly higher than the Pb^{2+} absorption of 0.12 mg/kg recorded in plants harvested on week 8. This work aligns with the report of Chikele and Sharma (2008), who reported that *C. cajan* plant could accumulate lead in lead-inoculated soil [30].

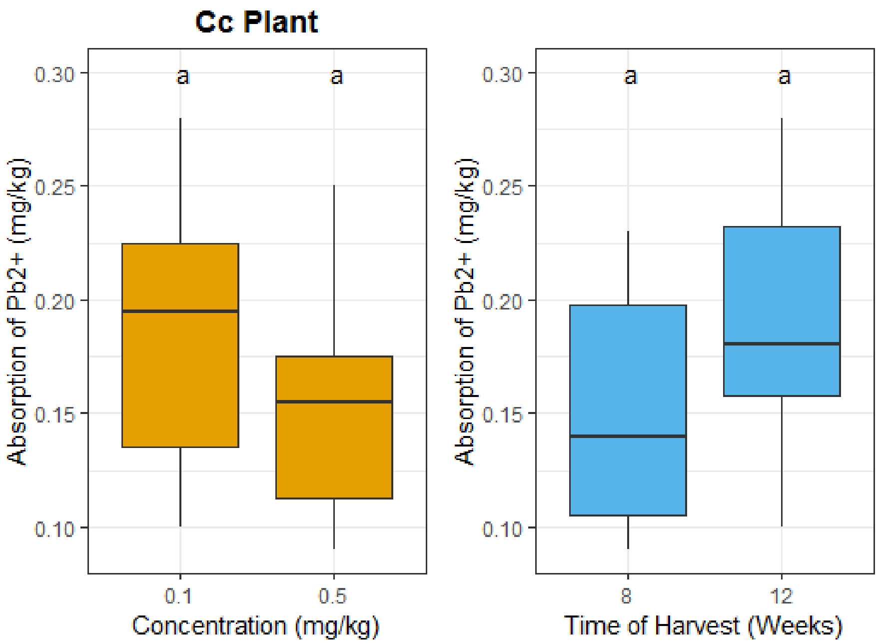

Figure 8. Effect of concentration and harvest time on Pb^{2+} absorption by Cc Plant

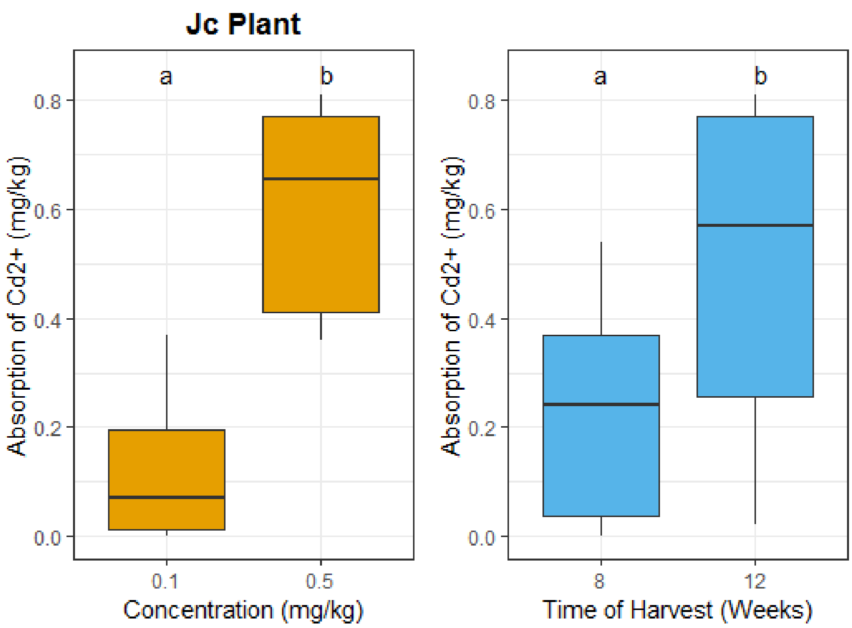

Figure 9. Effect of concentration and harvest time on Cd^{2+} absorption by Jc Plant

3.10. Cadmium Ion (Cd^{2+}) Absorption by Plants

3.10.1. Effects of concentration and harvest time on Cd^{2+} absorption by Jc Plant

The result showed that increased concentration increased the absorption of cadmium ions at both harvest times. The Cd^{2+} absorption of 0.42 mg/kg by Jc plants recorded at 0.5M was significantly higher than the absorption (0.05 mg/kg) at 0.1M on week 8. The highest absorption was observed at 0.5 M on week 12 (Figure 9). *J. curcas* had earlier been shown to exhibit the best absorption capability for Cd by Chang et al. (2014) [31], which justified the absorption of the metal ion based on our findings.

3.10.2. Effects of concentration and harvest time on Cd^{2+} absorption by Cf Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Cd^{2+} by Cf plants at a given concentration depends on the harvest time. The highest Cd^{2+} absorption (36.22 mg/kg) was observed at 0.1M concentration in Cf plants that were harvested on week 8. This was significantly higher than the lowest absorption of 12.79 mg/kg, observed at 0.1M concentration in Cf plants harvested on week 8. The highest Cd2+ absorption observed at 0.1M concentration in Cf plants that were harvested on week 8 was, however, neither significantly different from the absorption recorded in Cf plants that were harvested on week 8 and exposed to 0.5M concentration nor from that of plants that were harvested on week 12 and exposed to 0.1M concentration (Figure 10). The result showed *Codiaeum variegatum* as a hyperaccumulator of cadmium ion. As the metal concentration increased, the metal ion's absorption increased in both male and female species.

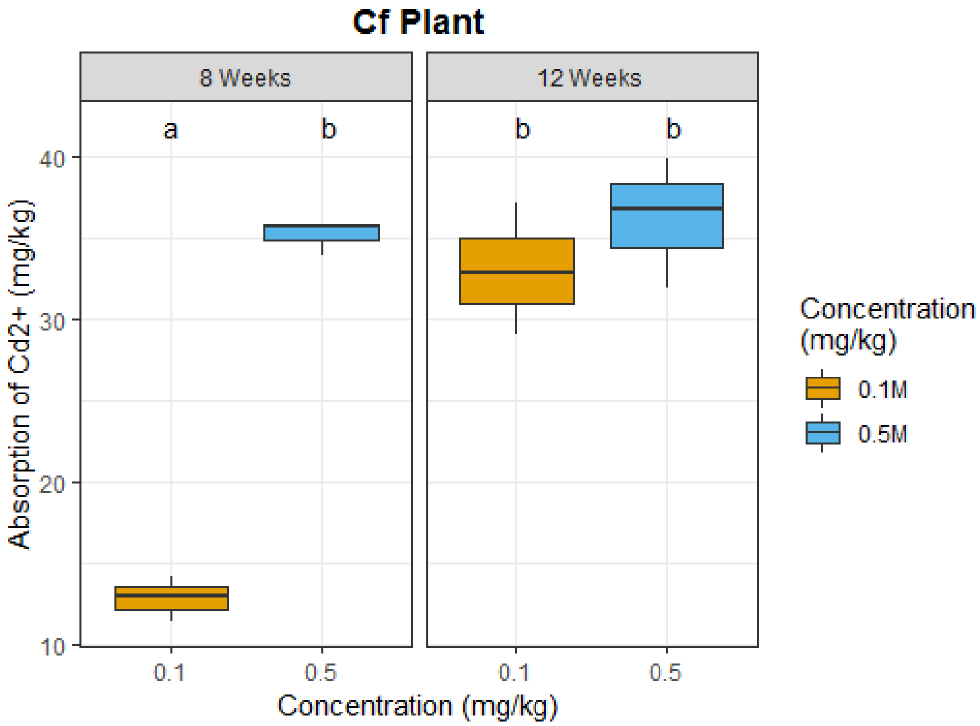

Figure 10. Effect of concentration and harvest time on Cd^{2+} absorption by Cf Plant

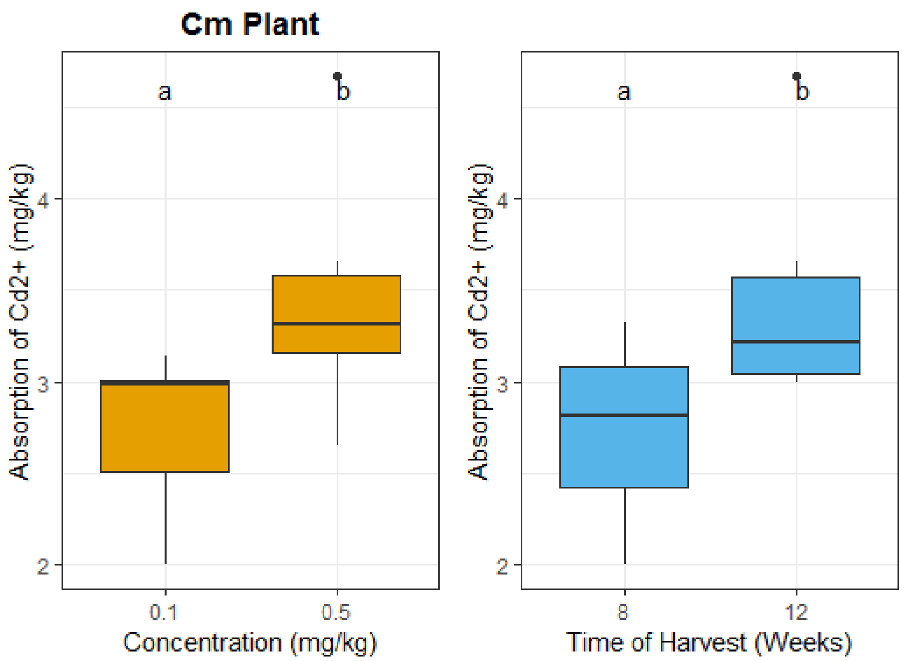

Figure 11. Effect of concentration and harvest time on Cd^{2+} absorption by Cm Plant

3.10.4. Effects of concentration and harvest time on Cd^{2+} absorption by At plant

The observed interaction effect between concentration and time of harvest of At plants implies that the absorption of Cd^{2+} by At plants at a given concentration depends on the harvest time. Figure 12 shows that the highest Cd^{2+} absorption of 14.76 mg/kg was observed at 0.5M concentration in At plants harvested on week 8. This was significantly higher than the absorption observed at 0.5M concentration in At plants harvested on week 8 and at 0.1M and 0.5M concentrations in At plants harvested on week 12. The lowest Cd^{2+} absorption of 1.88 mg/kg was observed at 0.5M concentration in At plants harvested on week 12, which was not significantly different from the Cd^{2+} absorption of 2.43 mg/kg in At plants harvested on week 8 and exposed to 0.5M concentration. As the time of harvest increased, absorption of cadmium ions decreased. Andropogon grass has been reported to have absorbed the metal ion by other authors [33], validating our findings.

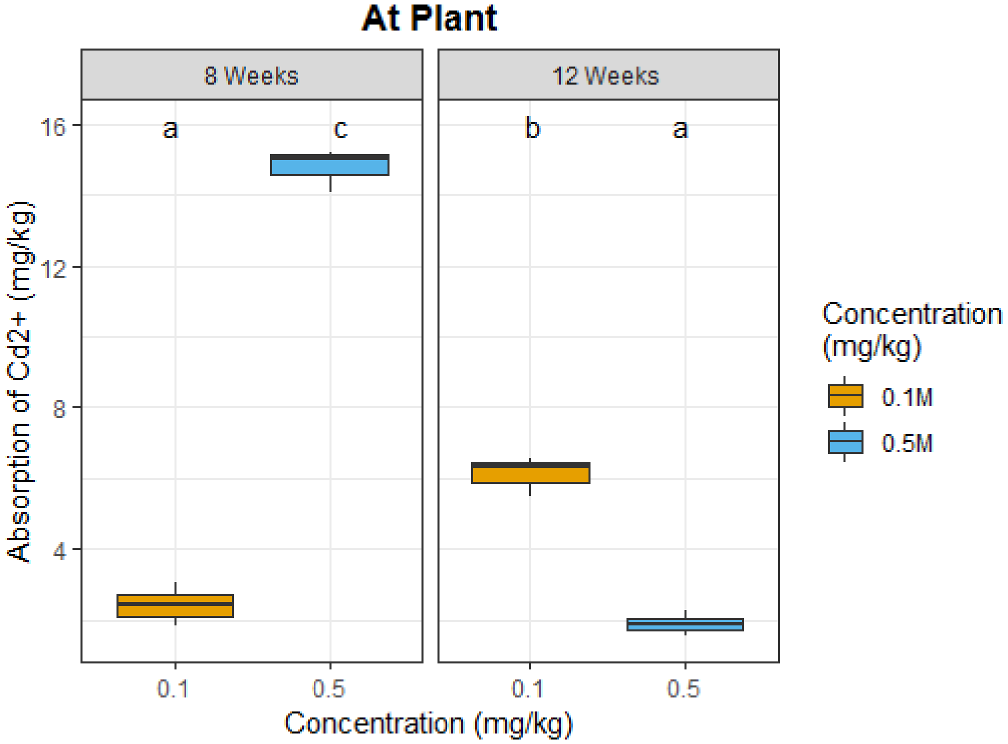

Figure 12. Effect of concentration and harvest time on Cd^{2+} absorption by At Plant

3.10.3. Effects of concentration and harvest time on Cd^{2+} absorption by Cm Plant

The hyperaccumulating capacity of both species of *Codiaeum variegatum* shown from this work is against the findings of Widyasari *et al. (2024), who reported that C. variegatum is not a phytoremediation* agent for cadmium [32]. Cadmium ions are absorbed more with an increase in the concentration. The highest absorption of cadmium ion (3.88 mg/kg) was observed at 0.5 M at week 12, whereas the lowest absorption was 2.44 mg/kg. The absorption at 0.5 M at 8 weeks is significantly higher than at 0.1 M at the same harvest time (Figure 11).

3.10.5. Effects of concentration and harvest time on Cd^{2+}absorption by Pl Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Cd^{2+} by Pl plant at a given concentration depends on the harvest time. The highest Cd^{2+} absorption of 5.21 mg/kg was observed in Pl plants harvested on week 8 and exposed to 0.1M concentration. This was significantly higher than the absorptions observed at 0.5M concentration in Pl plants that were harvested on week 8 (0.26 mg/kg) and at 0.1M and 0.5M concentrations in Pl plants that were harvested on week 12 (1.55 mg/kg and 1.60 mg/kg, respectively), which were not significantly different (Figure 13). The cadmium absorption by *P. maximum* was unsurprising as some authors had earlier supported our findings [34-35].

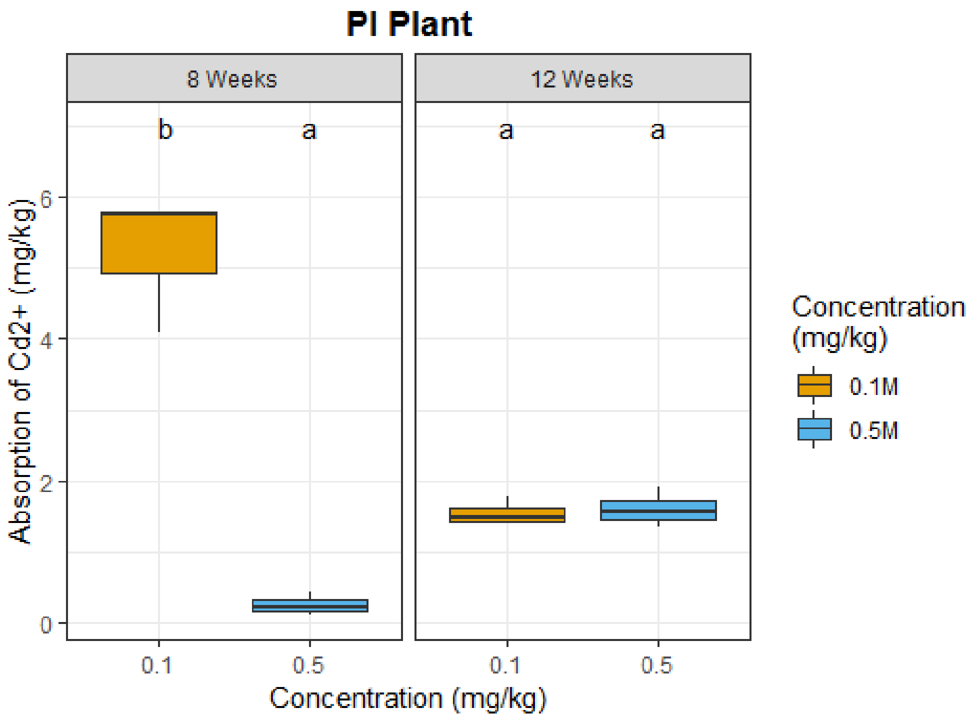

Figure 13. Effect of concentration and harvest time on Cd^{2+} absorption by Pl Plant

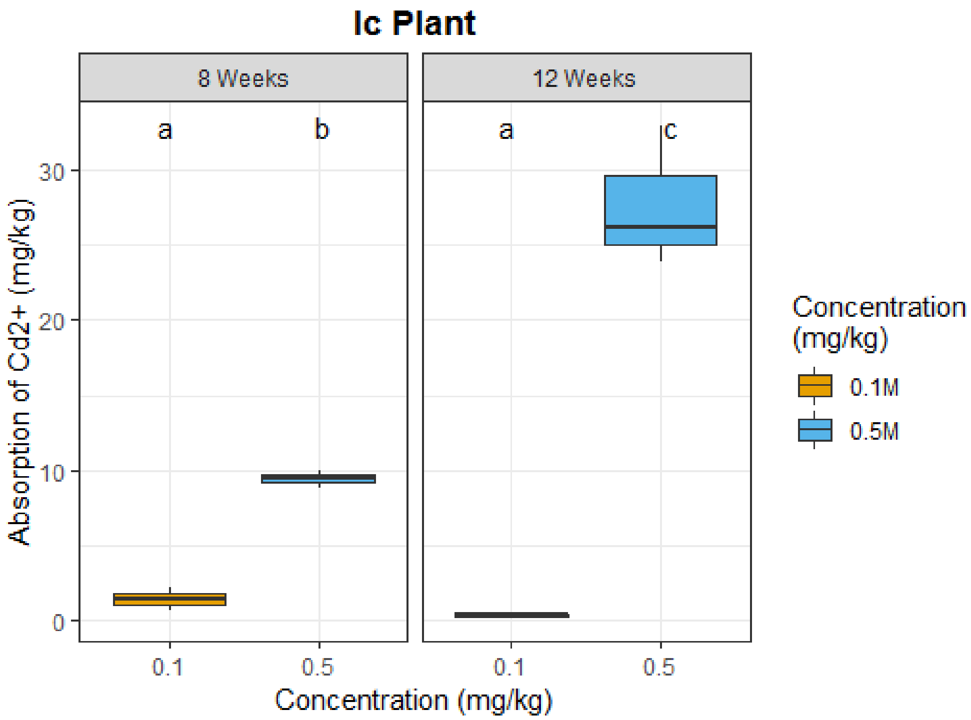

Figure 14. Effect of concentration and harvest time on Cd^{2+} absorption by Ic Plant

3.10.6. Effects of concentration and harvest time on Cd^{2+} absorption by Ic Plant

The observed interaction effect between concentration and time of harvest of Ic plants implies that the absorption of Cd^{2+} by Ic plants at a given concentration depends on the harvest time. Figure 14 shows that the highest Cd^{2+} absorption of 27.71 mg/kg was observed in Ic plants harvested on week 12 and exposed to 0.5M concentration. This was significantly higher than the absorption observed at 0.1M concentration in Ic plants harvested on week 12 and at 0.1M and 0.5M concentrations in Ic plants harvested on week 8. The lowest Cd^{2+} absorption of 0.36 mg/kg was observed at 0.1M concentration in Ic plants that were harvested on week 12, which was not significantly different from the Cd^{2+} absorption of 1.39 mg/kg in Ic plants that were harvested on week 8 and exposed to 0.1M concentration. An increase in the concentration of cadmium ions increased the absorption of the metal ion. At 0.5 M, *I. coccinea* absorbed up to 27.71 mg/kg of the metal ion at 12 weeks. Consequently, I. coccinea could be regarded as a hyperaccumulating agent of cadmium ion. Our work validated the report of Ching *et al.* (2013) [36].

3.10.7. Effects of concentration and harvest time on Cd^{2+} absorption by Zm Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Cd^{2+} by Zm plants at a given concentration depends on the harvest time. The highest Cd^{2+} absorption of 0.16 mg/kg was observed in Zm plants harvested on week 8 and exposed to 0.5M concentration. This was significantly higher than the absorptions observed at 0.1M concentration in Zm plants that were harvested on week 8 (0.02 mg/kg) and at 0.1M and 0.5M concentrations in Zm plants that were harvested on week 12 (0.02 mg/kg and 0.01 mg/kg, respectively), which were not significantly different (Figure 15). *Z. mays* was earlier reported to be hyperaccumulator of cadmium by some researchers [37].

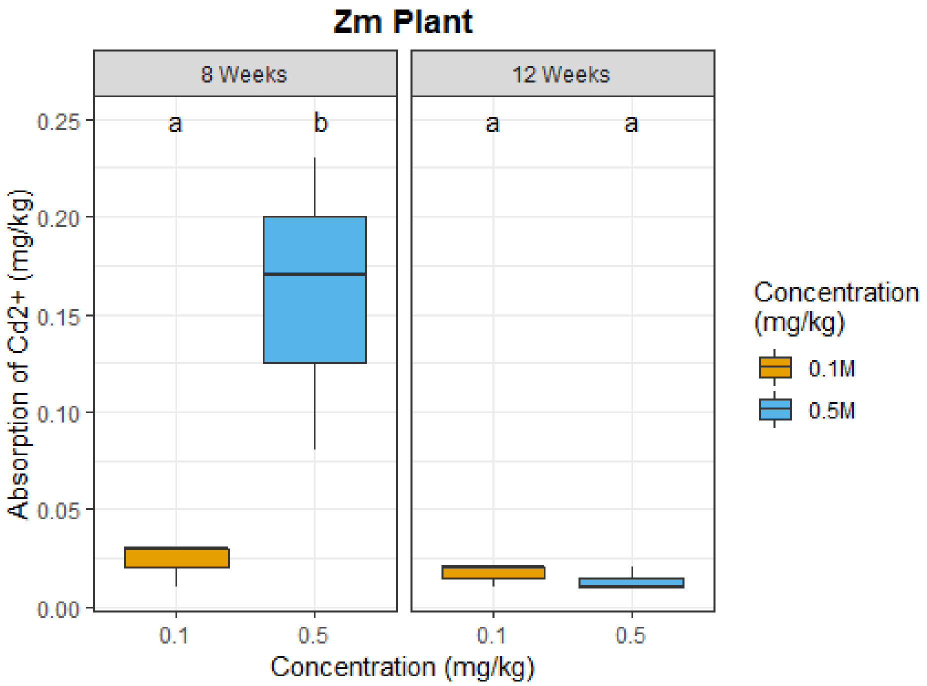

Figure 15. Effect of concentration and harvest time on Cd^{2+} absorption by Zm Plant

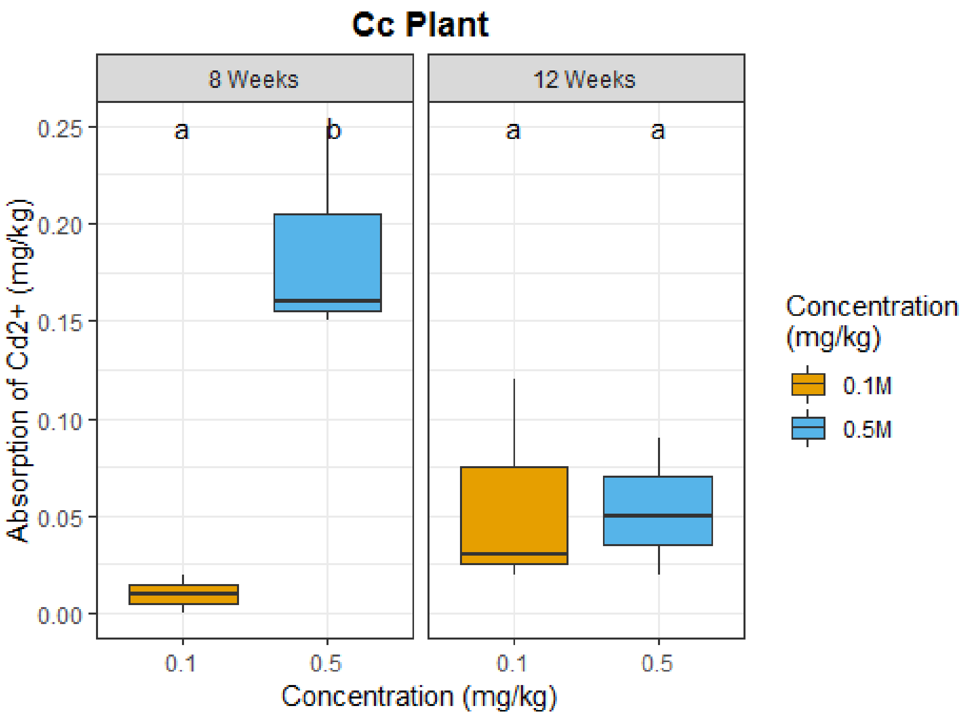

Figure 16. Effect of concentration and harvest time on Cd^{2+} absorption by Cc Plant

3.10.8. Effects of concentration and harvest time on Cd^{2+} absorption by Cc Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Cd^{2+} by Cc plants at a given concentration depends on the harvest time. The highest Cd^{2+} absorption of 0.19 mg/kg was observed in Cc plants harvested on week 8 and exposed to 0.5M concentration. This was significantly higher than the absorptions observed at 0.1M concentration in Cc plants that were harvested on week 8 (0.01 mg/kg) and at 0.1M and 0.5M concentrations in Cc plants that were harvested on week 12 (0.06 mg/kg and 0.05 mg/kg, respectively), which were not significantly different (Figure 16). *Cajanus cajan* absorbed cadmium ions in low concentrations *C. cajan* has been reported as a potential phytoremediation agent for cadmium [38].

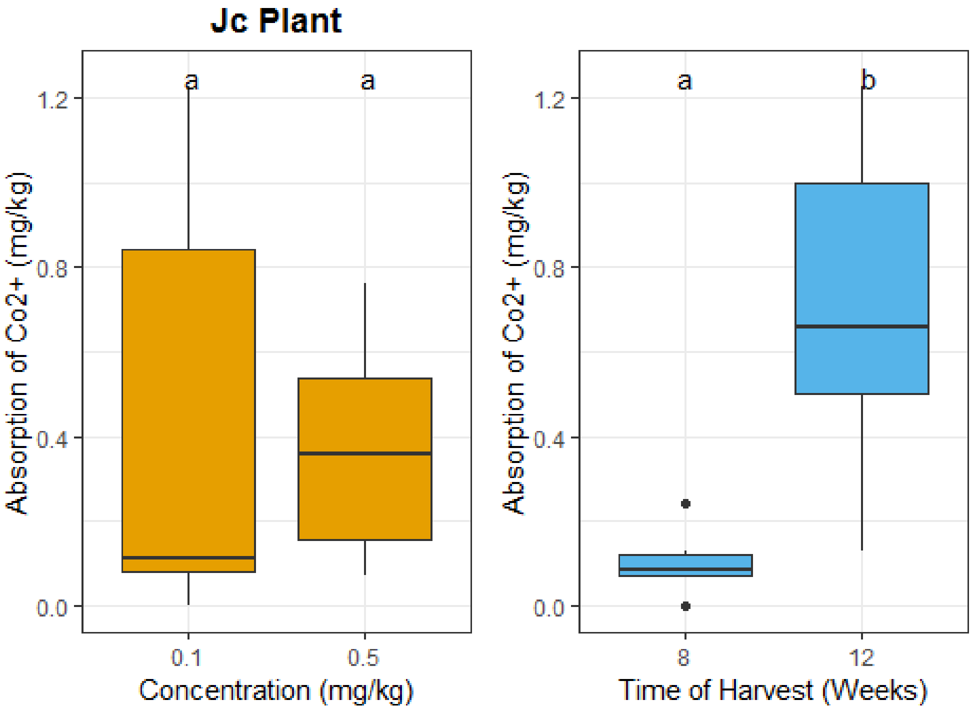

Figure 17. Effect of concentration and harvest time on Co^{2+} absorption by Jc Plant

3.11. Cobalt Ion (Co^{2+}) Absorption by Plants

3.11.1. Effects of concentration and harvest time on Co^{2+} absorption by Jc Plant

No interaction effect was observed between the concentration of ions and the harvest time. Figure 17 shows that concerning the concentration of ions, the highest Co2+ absorption of 0.81 mg/kg was observed at 0.1M over 12 weeks, which was t significantly different from that of 0.5M concentration (0.60 mg/kg). Conversely, the Co^{2+} absorption of 0.06 mg/kg recorded in Jc plants harvested on week 8 was significantly lower than the Co^{2+} absorption of 0.81 mg/kg recorded in plants harvested on week 12. At week 8, an increase in concentration increased the absorption of cobalt ions by J. curcas; however, as the harvest time was increased to 12 weeks, an increase in the concentration of metal ions decreased the absorption of the metal ion. It has been shown that Co at lower concentrations (>200 mg kg-1) favors the gas exchange parameters and photosynthetic pigmentation in *J. curcas* [39].

3.11.2. Effects of concentration and harvest time on Co^{2+} absorption by Cf Plant

The observed interaction between concentration and time of harvest of Cf plants implies that the absorption of Co^{2+} by Cf plants at a given concentration depends on the harvest time. Figure 18 shows that the highest Co^{2+} absorption of 19.75 mg/kg was observed in Cf plants harvested on week 12 and exposed to 0.5M concentration. This was significantly higher than the absorption observed at 0.1M concentration in Cf plants harvested on week 12 and at 0.1M and 0.5M concentrations in Cf plants harvested on week 8. The lowest Co^{2+} absorption of 1.31 mg/kg was observed at 0.1M concentration in Cf plants that were harvested on week 8, which was not significantly different from the Co^{2+} absorption of 3.05 mg/kg in Cf plants that were harvested on week 12 and exposed to 0.1M concentration.

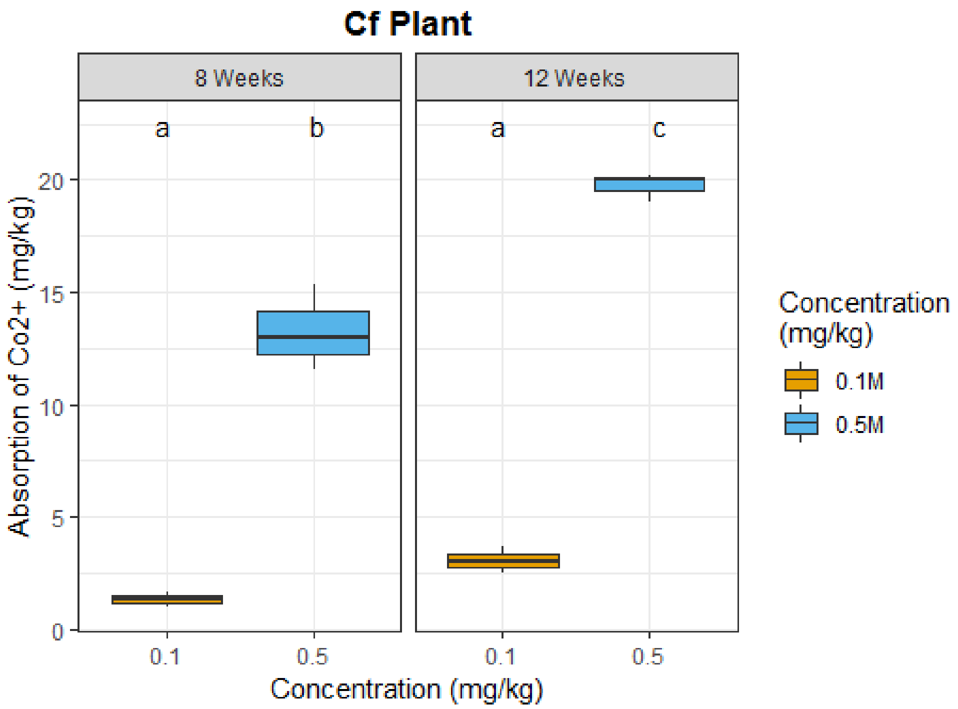

Figure 18. Effect of concentration and harvest time on Co^{2+} absorption by Cf Plant

3.11.3. Effects of concentration and harvest time on Co^{2+} absorption by Cm Plant

No interaction effect was observed between the concentration of ions and the harvest time. Figure 19 shows that, concerning the concentration of ions, the highest Co2+ absorption of 2.47 mg/kg was observed at 0.5M on week 12, significantly different from that of 0.1M concentration (1.56 mg/kg). On the other hand, the Co^{2+} absorption of 1.02 mg/kg recorded in Cm plants that were harvested on week 8 was significantly lower than the Co^{2+} absorption of 1.56 mg/kg recorded in plants harvested on week 12.

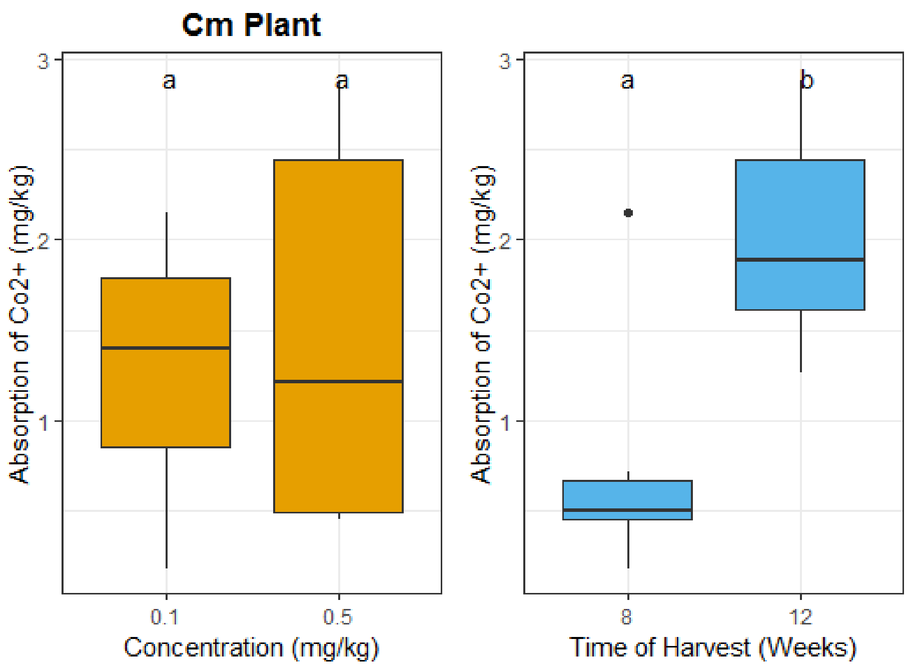

Figure 19. Effect of concentration and harvest time on Co^{2+} absorption by Cm Plant

3.11.4. Effects of concentration and harvest time on Co^{2+} absorption by At plant

The observed interaction effect between concentration and time of harvest of At plants implies that the absorption of Co^{2+} by At plants at a given concentration depends on the harvest time. Figure 20 shows that the highest Co^{2+} absorption (2.83 mg/kg) was observed at 0.1M concentration in At plants that were harvested on week 12. This was, however, not significantly higher than the absorption (2.29 mg/kg) observed at 0.5M concentration in At plants that were harvested on week 12. The lowest

Pb^{2+} absorption (0.82 mg/kg) was observed at 0.1M concentration in At plants that were harvested on week 8, which was not significantly different from the Co^{2+} absorption (1.54 mg/kg) at 0.5M concentration in At plants harvested on week 8.

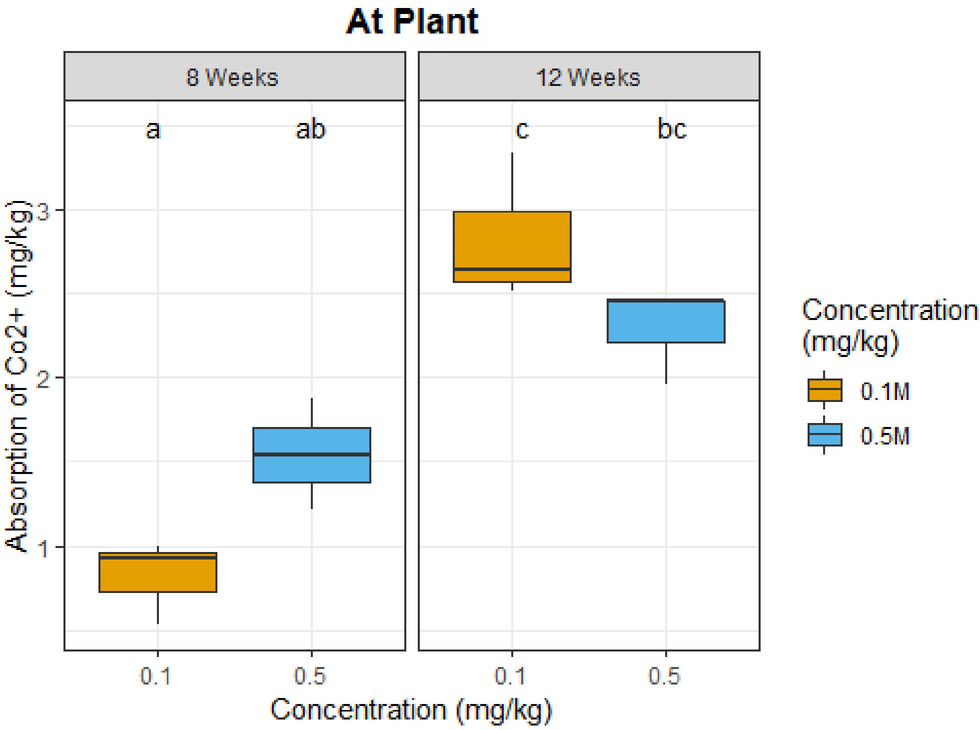

Figure 20. Effect of concentration and harvest time on Co^{2+} absorption by At plant

3.11.5. Effects of concentration and harvest time on Co^{2+}absorption by Pl Plant

The concentration of ions and the time of harvest had no interaction effect. Figure 21 shows that, concerning the concentration of ions, the highest Co2+ absorption of 6.07 mg/kg was observed at 0.1M, significantly different from that of 0.5M concentration (4.20 mg/kg). On the other hand, the Co^{2+} absorption of 0.82 mg/kg recorded in Pl plants harvested on week 12 was significantly lower than the Co2+ absorption of 4.20 mg/kg recorded in plants harvested on week 8.

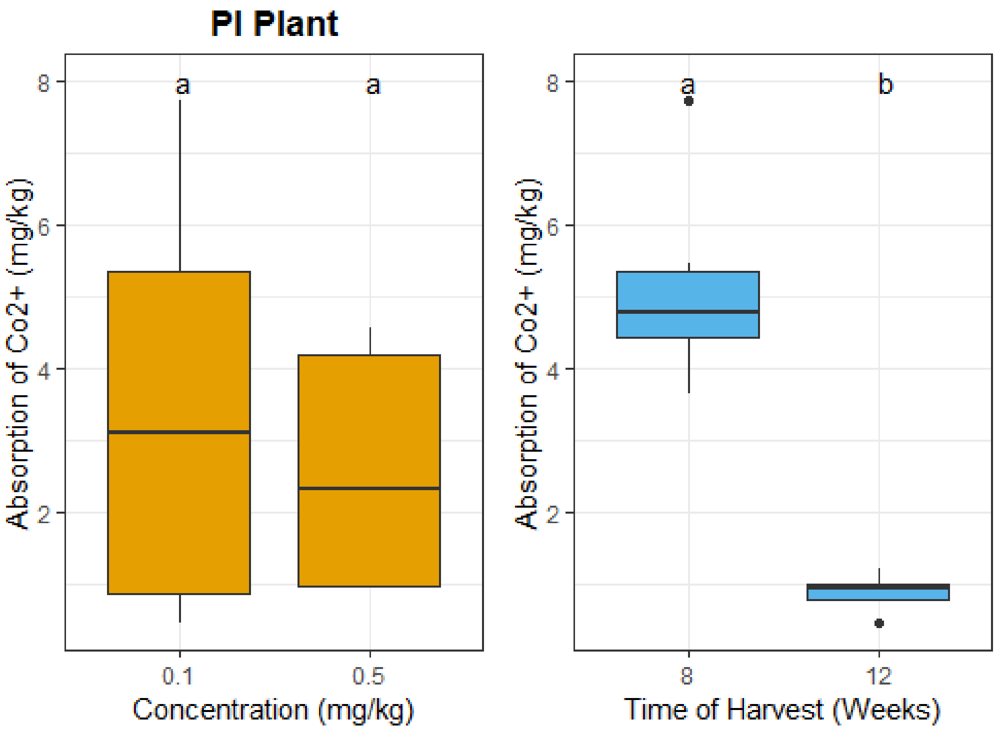

Figure 21. Effect of concentration and harvest time on Co^{2+} absorption by Pl Plant

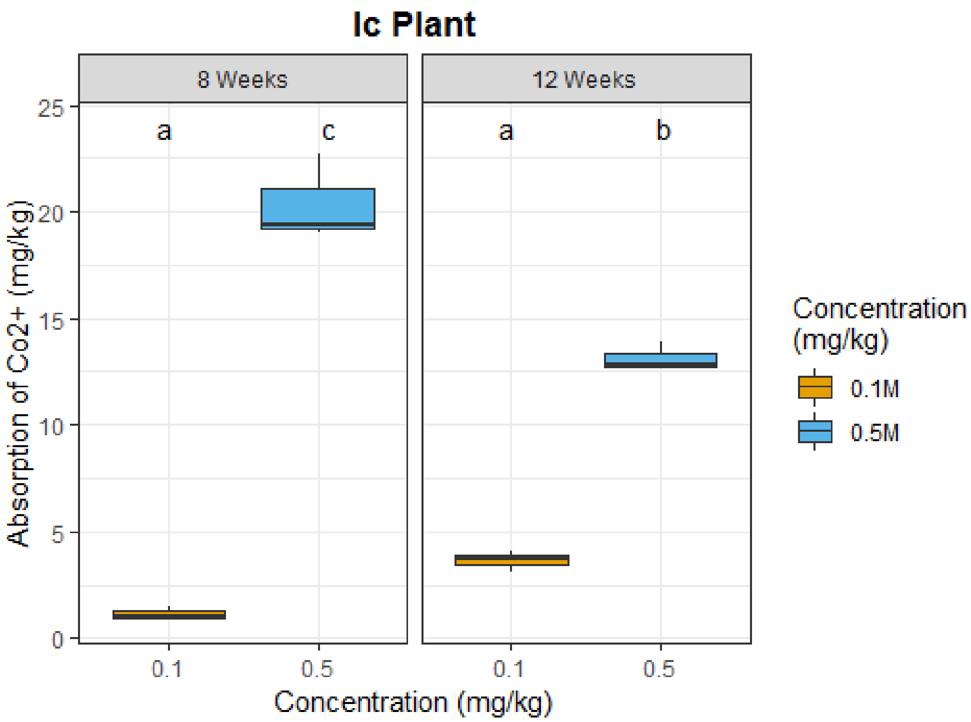

Figure 22. Effect of concentration and harvest time on Co^{2+} absorption by Ic Plant

3.11.6. Effects of concentration and harvest time on Co^{2+} absorption by Ic Plant

The observed interaction effect between concentration and time of harvest of Ic plants implies that the absorption of Co^{2+} by Ic plants at a given concentration depends on the harvest time. Figure 22 shows that the highest Co^{2+} absorption of 20.37 mg/kg was observed in Ic plants harvested on week 8 and exposed to 0.5M concentration. This was significantly higher than the absorption observed at 0.1M concentration in Ic plants harvested on week 8 and at 0.1M and 0.5M concentrations in Ic plants harvested on week 12. The lowest Co^{2+} absorption of 1.15 mg/kg was observed at 0.1M concentration in Ic plants that were harvested on week 8, which was not significantly different from the Co^{2+} absorption of 3.65 mg/kg in Ic plants that were harvested on week 12 and exposed to 0.1M concentration. At a high concentration of 0.5 M, *I. coccinea* absorbed cobalt up to 20 mg/kg, so at a high concentration, *I. coccinea* could be a hyperaccumulating agent for cobalt.

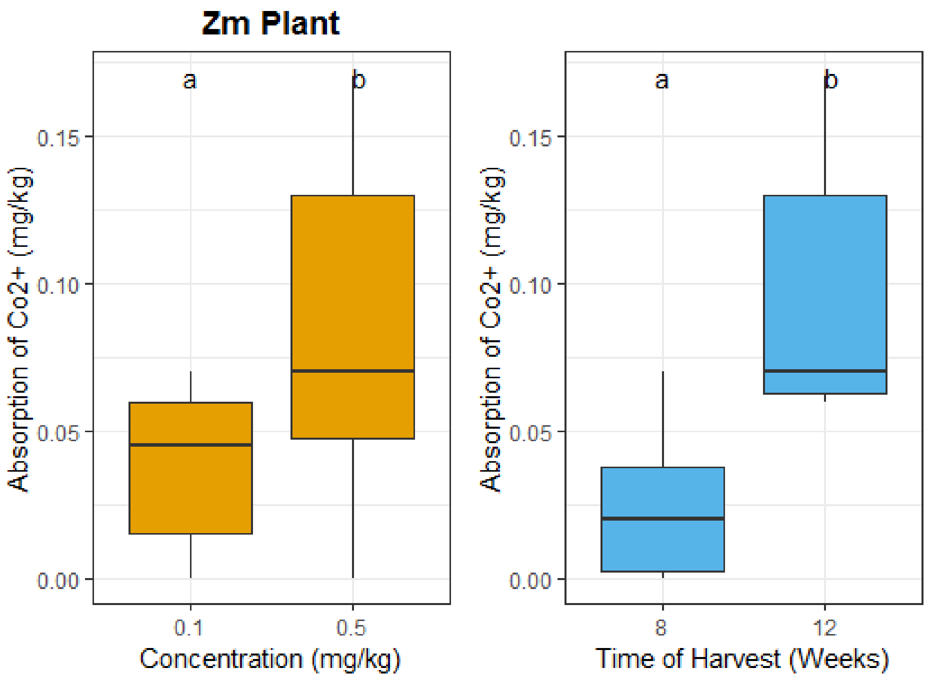

Figure 23. Effect of concentration and harvest time on Co^{2+} absorption by Zm Plant

3.11.7. Effects of concentration and harvest time on Co^{2+} absorption by Zm Plant

No interaction effect was observed between the concentration of Co^{2+} and the time of harvest. The Co^{2+} absorption of 0.13 mg/kg by Zm plants recorded at 0.5M concentration was significantly higher than that of 0.06 mg/kg observed at 0.1M concentration. Concerning the harvest time, Zm plants that were harvested on week 12 had a significantly higher Co2+ absorption than those harvested on week 8 (Figure 23). The low absorption of cobalt was earlier reported to be beneficial to *Z. mays* as cobalt was said to be an essential micronutrient [40]. and could be helpful for plant growth [41].

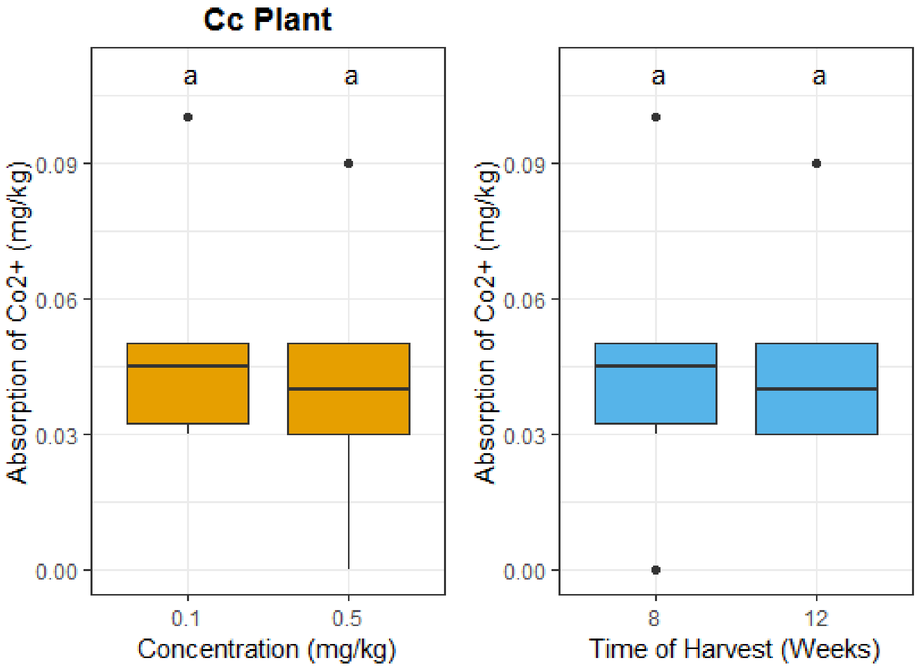

Figure 24. Effect of concentration and harvest time on Co^{2+} absorption by Cc Plant

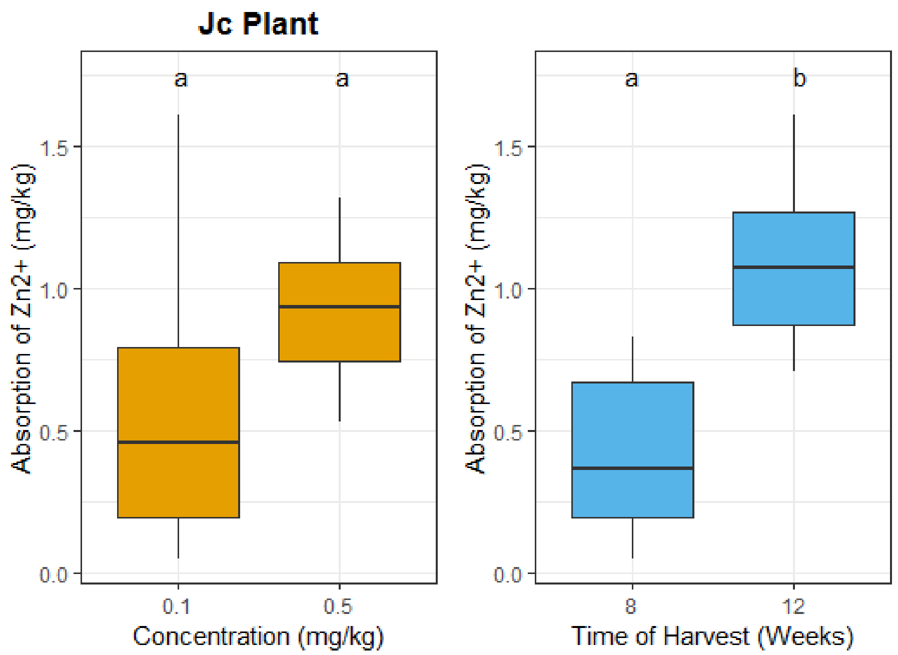

Figure 25. Effect of concentration and harvest time on Zn^{2+} absorption by Jc Plant

3.11.8. Effect of concentration and harvest time on Co^{2+} absorption by Cc Plant

Figure 24 shows that, for the concentration of ion, the highest Co^{2+} absorption of 0.06 mg/kg was observed at 0.1M and 0.5 M at 8 and 12 weeks, respectively, which was not significantly different from that of 0.5M concentration (0.02 mg/kg) at 8 weeks. Similarly, the Co^{2+} absorption of 0.04 mg/kg recorded in Cc plants harvested on week 12 was not significantly higher than the Co^{2+} absorption of 0.02

mg/kg recorded in plants harvested on week 8. It was observed that *C. cajan* absorbed cobalt in a very high concentration and cannot be a phytoremediation agent for cobalt.

3.12. Zinc Ion (Zn^{2+}) Absorption by Plants

3.12.1. Effects of concentration and harvest time on Zn^{2+} absorption by Jc Plant

Figure 25 shows that, for the ion concentration, the highest Zn^{2+} absorption of 1.16 mg/kg was observed at 0.5M, which was not significantly different from that of 0.1M concentration (0.15 mg/kg). On the other hand, the Zn^{2+} absorption of 1.05 mg/kg recorded in Jc plants harvested on week 12 was significantly higher than the Zn2+ absorption of 0.15 mg/kg recorded in plants harvested on week 8. At both harvest times, an increase in the concentration of zinc ions increased the absorption. *J. curcas* reportedly absorbed zinc in the root part [42].

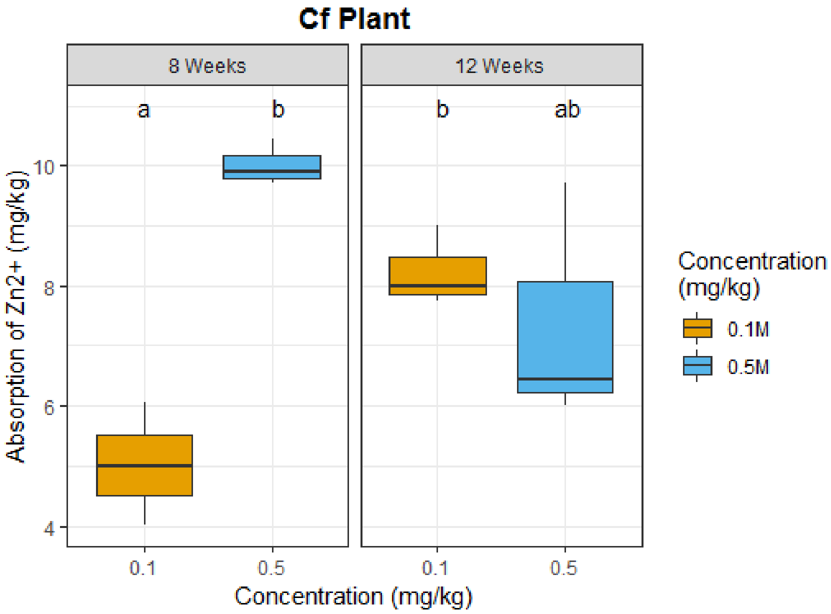

Figure 26. Effect of concentration and harvest time on Zn^{2+} absorption by Cf Plant

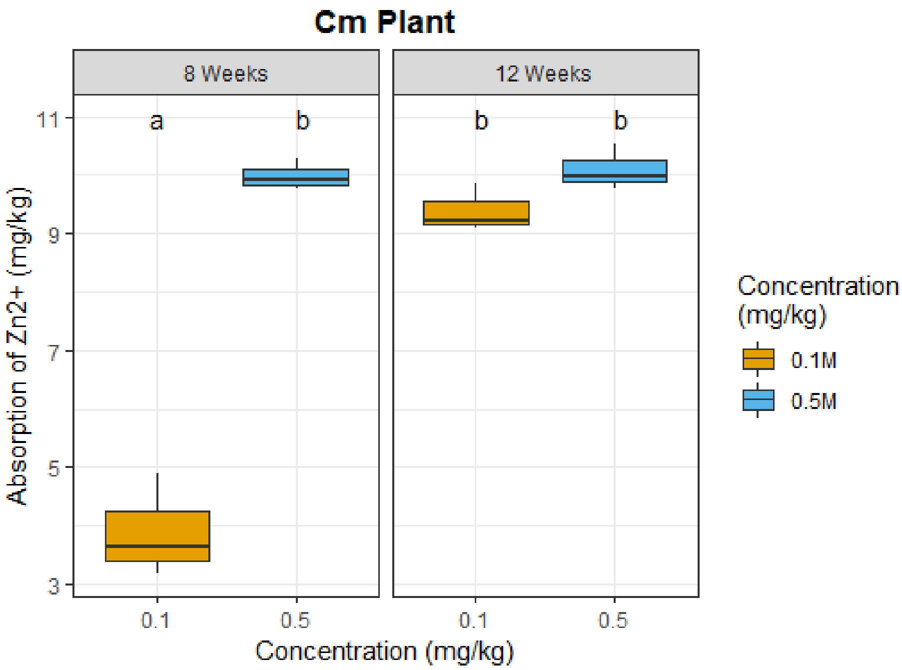

Figure 27. Effect of concentration and harvest time on Zn^{2+} absorption by Cm Plant

3.12.2. Effects of concentration and harvest time on Zn^{2+} absorption by Cf Plant

The observed interaction between concentration and time of harvest of Cf plants implies that the absorption of Zn^{2+} by Cf plants at a given concentration depends on the harvest time. Figure 26 shows that the highest Zn^{2+} absorption (10.02 mg/kg) was observed at 0.5M concentration in Cf plants that were harvested on week 8. This was significantly higher than the absorption observed at 0.1M concentration in Cf plants harvested on week 8, but not at 0.1M and 0.5M concentrations for Cf plants harvested on week 12. The lowest Zn^{2+} absorption of 5.02 mg/kg recorded in Cf plants that were harvested on week 8 was not significantly different from the Zn^{2+} absorption of 7.38 recorded at 0.5M concentration in plants harvested on week 12.

3.12.3. Effects of concentration and harvest time on Zn^{2+} absorption by Cm Plant

The observed interaction effect between concentration and time of harvest implies that the absorption of Zn^{2+} by Cm plants at a given concentration depends on the harvest time. The highest Zn^{2+} absorption (10.10 mg/kg) was observed at 0.5M concentration in Cm plants that were harvested on week 12. This was significantly higher than the lowest absorption of 3.90 mg/kg, observed at 0.1M concentration in Cm plants harvested on week 8. The highest Zn^{2+} absorption observed at 0.5M concentration in Cm plants that were harvested on week 12 was, however, neither significantly different from the absorption recorded in Cm plants that were harvested on week 12 and exposed to 0.1M concentration nor from that of plants that were harvested on week 8 and exposed to 0.5M concentration (Figure 27). The high zinc absorption is in line with the work of Okunlola *et al.* (2021), who reported the phytoremediation of zinc by the plant [43].

3.12.4. Effects of concentration and harvest time on Zn^{2+} absorption by At plant

No interaction effect was observed between concentration and time of harvest. The Zn^{2+} absorption of 9.79 mg/kg by At plants recorded at 0.5M concentration was significantly higher than that of 7.67 mg/kg observed at 0.1M concentration at week 12, concerning harvest time, At plants that were harvested on week 12 had a significantly higher Zn^{2+} absorption of 9.79 mg/kg than plants harvested on week 8, which had an absorption of 5.35 mg/kg (Figure 28). The metal ion absorption by *A. tectorium* was increased as the zinc ion concentration was increased at both harvest times.

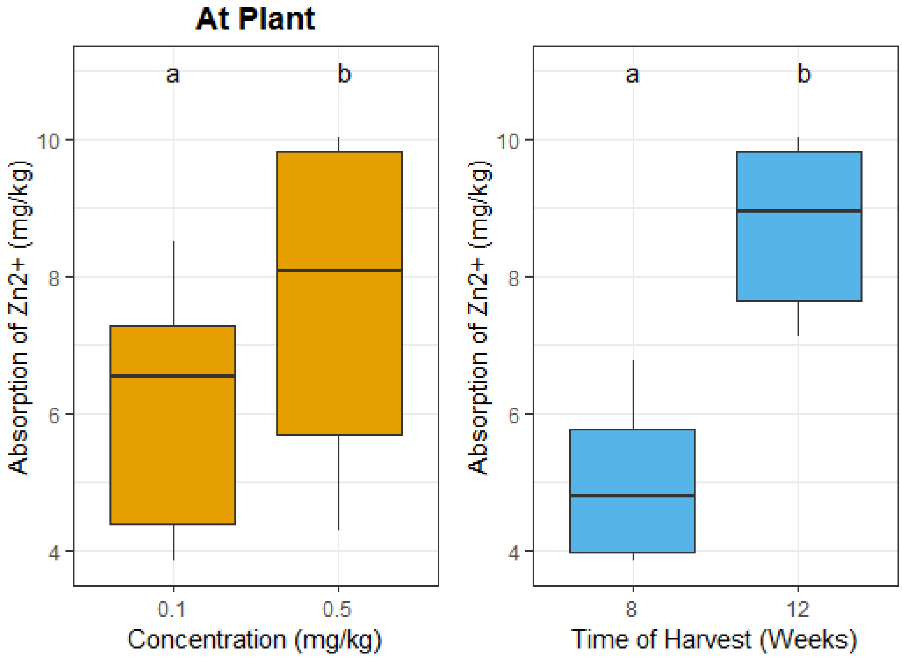

Figure 28. Effect of concentration and harvest time on Zn^{2+} absorption by At plant

3.12.5. Effects of concentration and harvest time on Zn^{2+} absorption by Pl Plant

The Zn^{2+} absorption of 9.96 mg/kg by Pl plants recorded at 0.5M concentration was significantly higher than that of 7.16 mg/kg observed at 0.1M concentration. Concerning the harvest time, a significant difference was observed between the highest absorption of 9.96 mg/kg recorded in week 12 Pl plants and week 8 plants, with an absorption of 8.43 mg/kg (Figure 29). *P. maximum* has been reported to have absorbed 5.08 mg/kg of zinc around Selected Industries in Lagos State, Nigeria. The absorption of zinc ions is in line with the authors' report [44]. The zinc absorption by *P. maximum* is also in line with the earlier work on the metal ion absorption by the plant in Rivers State, Nigeria [45].

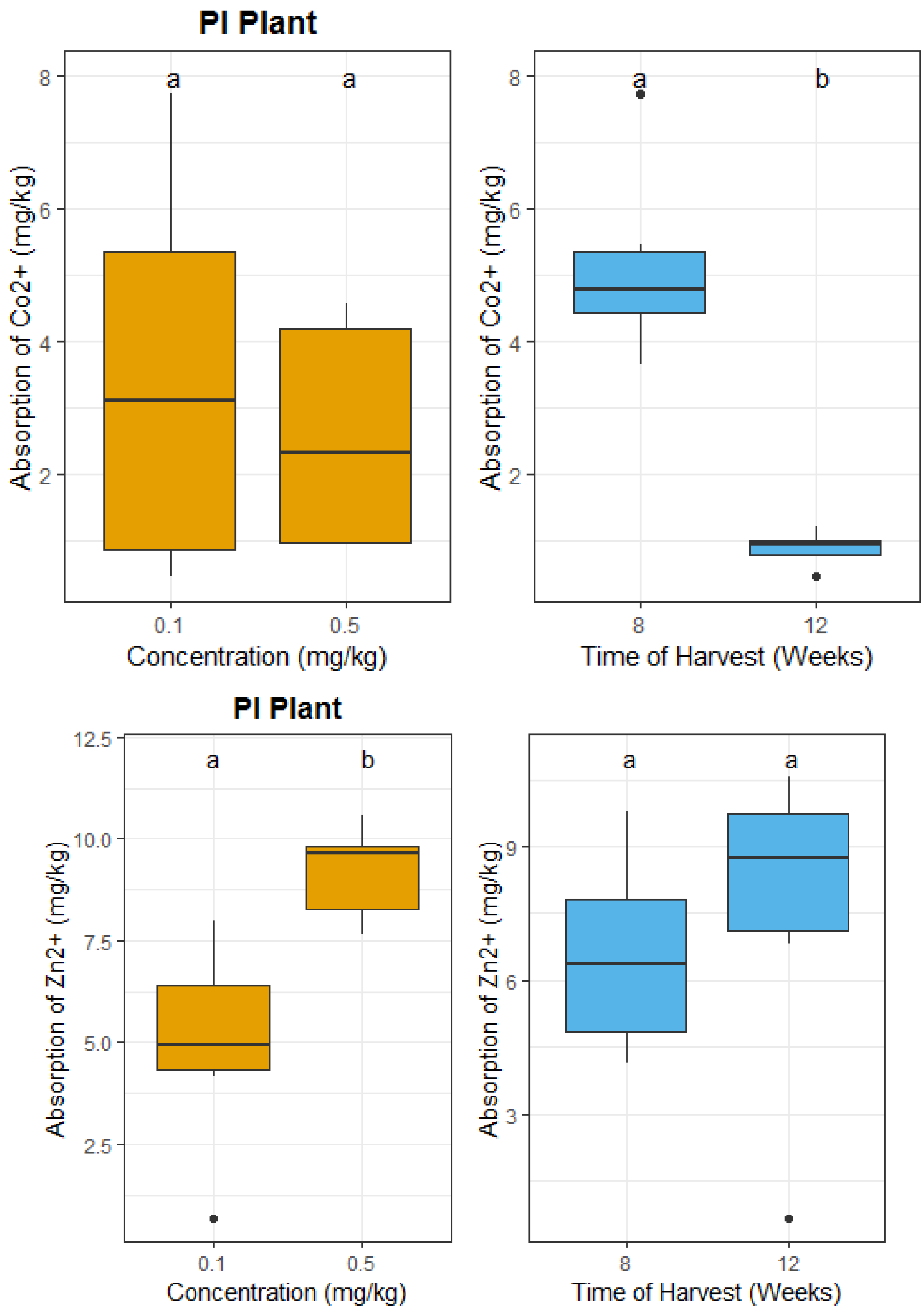

Figure 29. Effect of concentration and harvest time on Zn^{2+} absorption by Pl Plant

3.12.6. Effects of concentration and harvest time on Zn^{2+} absorption by Ic Plant

The Zn^{2+} absorption of 10.96 mg/kg by Ic plants recorded at 0.5M concentration was significantly higher than that of 3.95 mg/kg observed at 0.1M concentration at week 12. Concerning harvest time, Ic plants harvested on week 12 had a significantly higher Zn^{2+} absorption of 10.96 mg/kg than plants harvested on week 8, which had an absorption of 8.55 mg/kg (Figure 30). As the concentration of zinc ions was increased, the metal ion absorption increased at both harvest times.

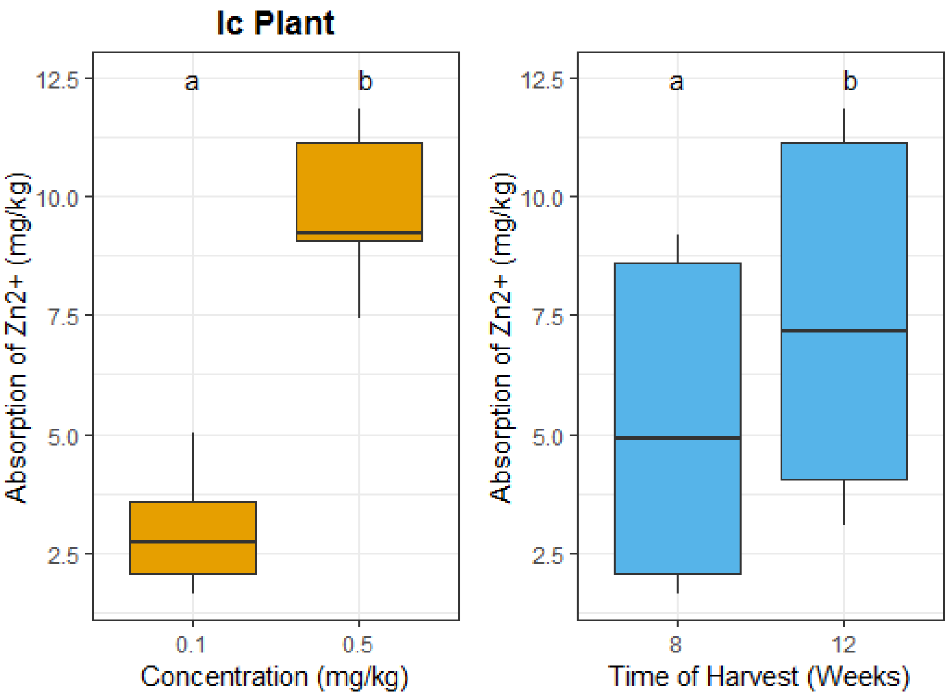

Figure 30. Effect of concentration and harvest time on Zn^{2+} absorption by Ic Plant

3.12.7. Effects of concentration and harvest time on Zn^{2+}absorption by Zm Plant

Figure 31 shows that, concerning the concentration of ions, the highest Zn2+ absorption of 3.88 mg/kg was observed at 0.1M, significantly different from that of 0.5M concentration (3.06 mg/kg) at week 8. On the other hand, the Zn^{2+} absorption of 3.06 mg/kg recorded in Zm plants harvested on week 8 was significantly higher than the Zn2+ absorption of 0.40 mg/kg recorded in plants harvested on week 12. *Z. mays* has also been reported to be a good Zn^{2+} absorber by some researchers [46].

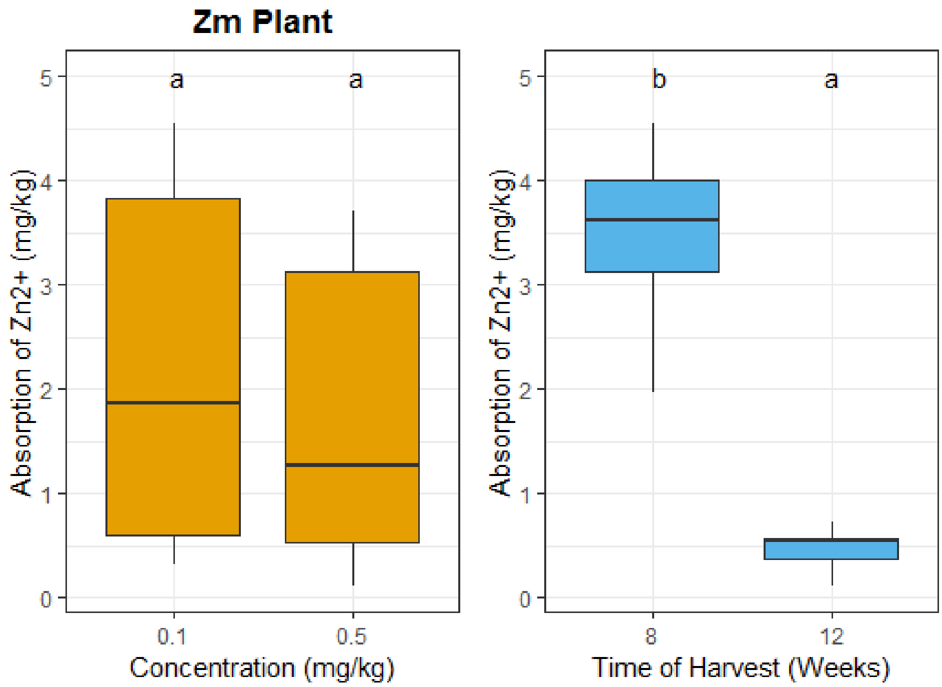

Figure 31. Effect of concentration and harvest time on Zn^{2+} absorption by Zm Plant

3.12.8. Effects of concentration and harvest time on Zn^{2+} absorption by Cc Plant

The Zn^{2+} absorption of 3.02 mg/kg by Cc plants recorded at 0.1M concentration was significantly higher than that of 2.10 mg/kg observed at 0.5M concentration at week 8. Concerning harvest time, Cc plants harvested on week 8 had a significantly higher Zn^{2+} absorption of 2.10 mg/kg than plants harvested on week 12, which had an absorption of 1.44 mg/kg (Figure 32). Absorption of zinc ion by *C. cajan* decreased as the concentration of the metal ion increased.

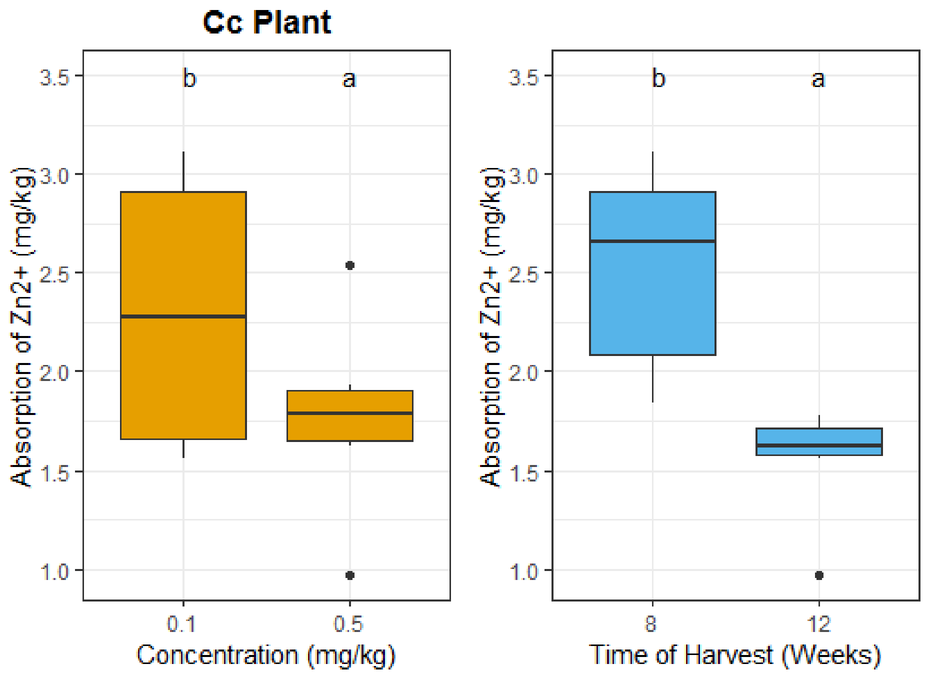

Figure 32. Effect of concentration and harvest time on Zn^{2+} absorption by Cc Plant

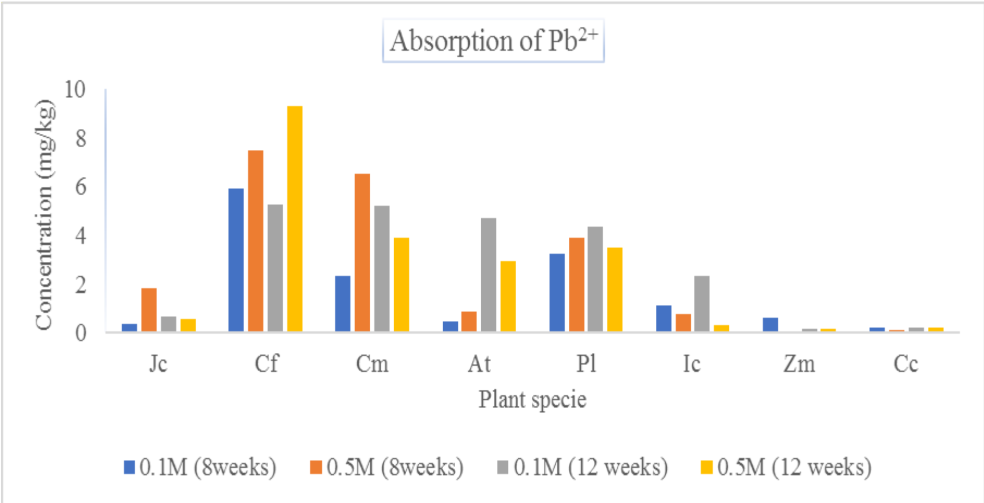

Figure 33. The mean concentration of Pb^{2+} in all plant species

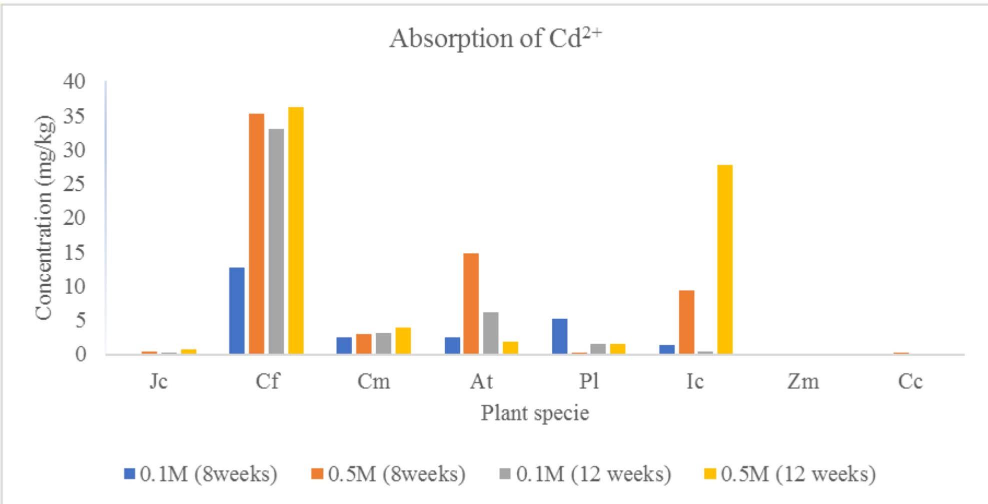

Figure 34. The mean concentration of Cd^{2+} in plant species

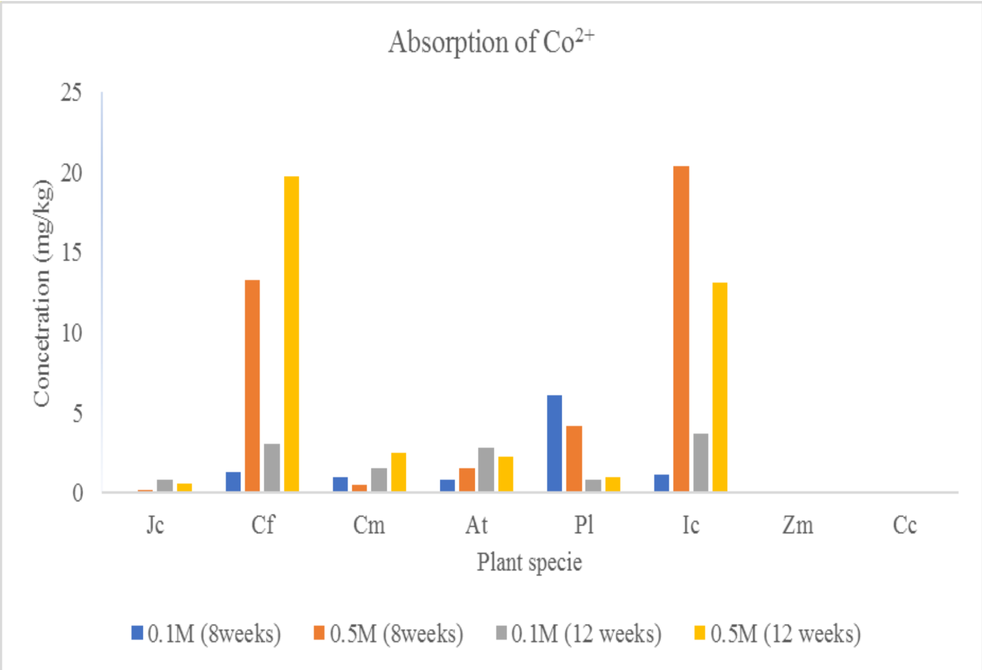

Figure 35. The mean concentration of Co^{2+} in plant species

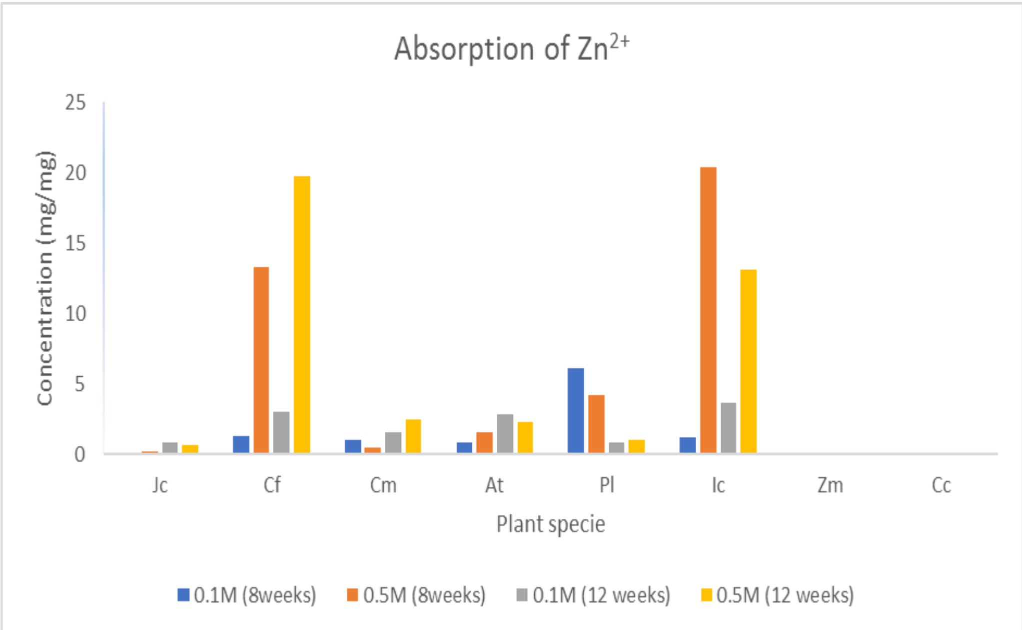

Figure 36. The mean concentration of Zn^{2+} in plant species

Comparing the mean concentrations of Pb^{2+}, Cd^{2+}, Co^{2+} and Zn^{2+} in all the plant species (Figures 33-36), it was observed that at concentration of 0.1M at 8 weeks, Cf plant absorbed Pb^{2+} the most followed by Pl, the Cm plants. Cc plant absorbed the least. At 12 weeks, same concentration, Cf and Cm plants absorbed the most, Zm absorbed the least. At the concentration of 0.5M at both 0.1M and 0.5M concentrations, both Cf and Cm plants showed greater absorption than all other plant species.

Comparison was also made on the absorption of Cd^{2+} by all the plant species, the order of absorption at 0.1M and 0.5M at both harvest times was observed to be: Cf >Ic >At >Cm >Pl >Jc >Cc >Zm. In contrast, the order of absorption of Co^{2+} at both concentrations at both harvest times was observed to be: Ic >Cf >Pl >At >Cm >Jc >Cc >Zm.

Zn^{2+} was most absorbed by At Cf plants, and Cc and Zm plants absorbed the least. The low absorption of all the metal ions by Cc and Zm plants could be seen as good since both plants are edible plants consumed by humans.

Conclusion

The concentrations of the metal ions inoculated with, as well as the time of harvest, played critical roles in the absorption of the metals by the plants. The flowering plants- *Codiaeum variagatum* (male and female) and *Ixora coceinea* showed better absorption of the metal ions than all other plants. The potential demonstrated by the flowering plants indicated that they could serve both aesthetic and phytoremediation functions at the same time.

The authors declare no competing interest in this work.

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