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Uptake of Heavy Metals by *Jatropha curcas* L. Planted in Soils Containing Sewage Sludge

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Abstract: Problem statement: The chemical pollution of soil has become a major source of concern and has posed serious health problems within the last few years in many developed nations. A variety of organic and inorganic pollutants, including heavy metals, are being mixed in with the cultivated soil and water. Sewage sludge was one of the major sources of enrichment of heavy metals. These pollutants are eventually transported to the natural vegetation and cultivated crops and concentrated in food chains, with possible detrimental effects on human health and wild-life. Thus, soil contaminants need to be cleaned up to improve environmental safety. **Approach:** Research was conducted to elucidate the potential of *Jatropha curcas* L. to clean toxic heavy metals derived from sewage sludge. *J. curcas* seedlings were planted on six different planting media T0 (100% soil-control), T1 (80% soil and 20% sewage sludge), T2 (60% soil and 40% sewage sludge), T3 (40% soil and 60% sewage sludge), T4 (20% soil and 80% sewage sludge) and T5 (100% sewage sludge) for a period of three months. The growth performance, including height and diameter, of *J. curcas* was measured using diameter tape, while the basal diameter was measured using a venier caliper every two weeks. Plant samples were collected after harvest and soil samples were collected before and after planting. The ICP-MS was used to determine the concentration of heavy metals in the planting medium and plant parts. **Results:** According to the growth parameters, the composition of 60% sewage sludge mixed with 40% soil was suitable for achieving optimum *J. curcas* growth. This plant was able to remove heavy metals (Zn, Pb, Cr, Cd and Cu) effectively from the medium containing 100% sewage sludge and after harvesting, the concentrations of Zn, Pb, Cr, Cd and Cu in T5(100% sewage sludge medium) were decreased by 67.7, 78.3, 77.2, 78.5 and 75.0%, respectively from the initial values. The highest levels of Zn (29.5 mg kg^{-1}), Cu (0.44 mg kg^{-1}) and Cd (8.35 mg kg^{-1}) accumulation were found in the roots, whereas the highest Pb and Cr concentrations were observed in the leaves and stem, respectively. **Conclusion/Recommendations:** The roots of *J. curcas* were found to be suitable for the uptake of heavy metals in sewage sludge, especially Zn. Cr was also adsorbed effectively by the leaves. Thus, *J. curcas* was a suitable plant to use as a phytoremediator to clean heavy metals, in particular Zn, Cu and Cr. However, a study determining, the short term effects of the large scale use of sewage sludge on trees /-field crops/-leafy vegetables and environmental its impact needs to be carried out.

Key words: Heavy metals, *Jatropha curcas*, phytoremediation, plant growth, sewage sludge

INTRODUCTION

Soil pollution, a very important environmental problem, has been attracting considerable public attention over the last few decades. Parts of our world have been contaminated with organic and inorganic pollutants for ages and the pollutants are released into our environment through numerous ways, including oil spills and the production of waste from agricultural and industrial activities (Zubillaga and Lavada, 2008;

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Zubillaga *et al*., 2008). Environmental pollutants include numerous types of solvents such as Trichloroethylene (TCE), atrazine, Trinitrotoluene (TNT), oil, gasoline, benzene, Polycyclic Aromatic Hydrocarbons (PAHs) and fuel additives (Hong *et al*., 2001; Batiha *et al*., 2008). Other than that, plant macronutrients and micronutrients include nitrates and phosphate, Cr, Fe, Mn, Mo, Ni, Zn and Cu and the non-essential elements such as As, Cd and Hg can be categorized as inorganic pollutants. Bridge (2004) stated that organic and inorganic pollutants greatly impact human health and agricultural productivity and also disrupt the world's ecological biodiversity system. These harmful inorganic pollutants, such as heavy metals in plants, can be eliminated through phytoremediation techniques. In areas with high soil concentrations of minerals, they often are also contaminated with heavy metals. The sources of the enrichment of metal in the soil include sewage sludge, incinerators, fertilizers, urban compost and mining residues (Adhikari *et al*., 2004; Dobra *et al*., 2006; Patel and Pandey, 2009).

Sewage sludge can be described as the solid waste products from wastewater treatments, mining residues and agricultural waste. It contains numerous heavy metals that possess characteristics pollutants. Thus, when the metals are released or channeled into the soil, it may cause hazardous effects to the crops and also the consumers who utilize the products produced from the crops. Jones and Johnson (1989); Sánchez *et al*. (2005) and Zakir *et al*. (2008) also observed that the heavy metals, such as Cd, Mn and Zn, in the soil and plant tissues increased after sewage sludge was applied and contributes to the waterways and soils pollution. Kabata-Pendias and Pendias (2001) determined that Pb, Cd, Cr, Hg, Zn and Cu are the most common heavy metal contaminants. These heavy metals, when ingested by humans, may cause several health problems, such as anemia and skin allergies (Yadav *et al*., 2009).

Therefore, the soil must be cleaned up. Phytoremediation, a green technology, has been used to develop approaches that facilitate the removal of heavy metals from soil into plants that are planted on it. Phytoremediation is the use of vegetation for the *in situ* or *ex situ* treatment of contaminated soils, sediments and polluted water to detoxify inorganic and organic metals (Salt *et al*., 1995; Damian and Damian, 2007; Afkar *et al*., 2010). Alkorta and Garbisu (2001) found that phytoremediation works by accumulating the metals in certain parts of the plant. However, Hansen and Tjell (1983) indicated that the success of phytoremediation in sludge-amended soils also depends greatly on the type of species being planted and the characteristics of the sludge contents.

In this study, the plant species *J. curcas* L. (Family: Euphorbiaceae) was selected for the study of its efficacy to clean up toxic materials from the sewage sludge promising characteristics, including its robust nature, rapid gestation period and excessive recovery. Anatomically, the plant has a straight trunk with reddish grey bark and is able to grow up to 5 m tall. The leaves of *J. curcas* are about 6-5 cm long and 5-7 cm and are usually crowded at the apex of the twig. Yadav *et al*. (2009), in their studies on the uptake of As, Cr and Zn by *J. curcas,* concluded that this plant exhibits the ability to recover and reclaim the contaminated soils. Not only does *J. curcas* act as an important alternative biofuel, this plant can grow in diverse types of soil conditions. Furthermore, the study performed by Agamuthu *et al*. (2010) suggested that *J. curcas* is suitable to be used as a phytoremediator for removing hydrocarbon from contaminated soil. In addition, Chehregani and Malayeri (2007) observed that *J. curcas* has the capability to remove Cd and Pb. Although some studies of concerning the bioremediation of contaminated soils have carried out, current knowledge regarding the potential phytoremediation of sewage sludge by *J. curcas* is limited. Therefore, this study was undertaken to elucidate the potential of *J. curcas* to clean toxic heavy metals in soils treated with sewage sludge.

MATERIALS AND METHODS

The study was conducted at the greenhouse at the Faculty of Forestry, University Putra Malaysia (2° 59' 18.24" N latitude and 101°42' 45.45" E longitude) from April to July 2009. Relative humidity in this area was 65%. The seedlings of the *J. curcas* mother tree collected by the Malaysia Department of Agriculture, Serdang were germinated from cuttings of the mature stem and planted in polybags (16.0×16.0 cm). The proportions used for the growing medium for the *J. curcas* seedlings were, soil: organic matter: river sand in a 3:2:1 ratio. The seedlings were transplanted into suitable plastic pots (32.0 cm height, 106.0 cm upper diameter and 69.0 lower diameter) that were filled up with the mixture of soil and sewage sludge after one month.

The Completely Randomized Design (CRD) was used and the pots were labeled according to their compositions: T0-control (100% soil), T1 (80 soil and 20% sewage sludge), T2 (60 soil and 40% sewage sludge), T3 (40 soil and 60% sewage sludge), T4 (20 soil and 80% sewage sludge) and T5 (100 sewage sludge). The heights and diameters of the *J. curcas* plants were measured every two weeks during the study period with diameter tape, while the basal diameter was measured using a venier caliper every two weeks. Soil samples were collected from each pot before, kept in a standard plastic container after planting and air-dried before physico-chemical analyses. The ICP-MS was used (Sahoo *et al*., 2009) for analyzing the concentrations of heavy metals in the planting medium and plant parts. Hydrochloric acid (HCl) and nitric acid (HNO_3) were used as extractants. The sample solutions were analyzed with ICP-MS. Total carbon was determined with conventional method, with a Los on Ignition analyzer and 5 g of air dried soil were kept in an oven for 8 h at 550°C.

The analyses of variance for the growth and heavy metals in the soil, sludge and plant parts were done following the ANOVA technique and the mean values were adjusted using Tukey's test ($p<0.05$). A comparison using the Student's t-test at a 5% level was done to detect any significant differences between samples taken before planting and after harvesting.

RESULTS

Growth performance of *J. curcas* cultivated in a soil containing sewage sludge: The *J. curcas* planted in the T3 medium had the tallest average height (8.79 cm), while T2 had the shortest height increment (6.98 cm). After 12 weeks, the *J. curcas* planted in T4 (20% soil+ 80% sewage sludge) showed the largest increment in basal diameter (3.95 cm) compared to that planted in the 100% soil medium. The 100% soil (control) allowed for the highest number of leaves, followed by T2 and T1. Except for T4 and T5, the leaf numbers increased every week. The *J. curcas* planted in T4 and T5 had less leaves.

General properties of the soils: The particle-size analysis that was carried out to evaluate the soil textural class revealed that only treatment 5 exhibited a clay loam texture, while the other treatments, including the control, showed the same clay soil texture. The soil pH values before planting and after harvesting were significantly different ($p\leq0.05$); in all five treatments (T1 through T5), the pH of the soil after harvesting was lower compared to before planting, but; the pH of the soil after harvesting in the control treatment was slightly higher compared to before planting. In the *J. curcas* growth medium the highest total carbon level was found in T5 (0.24 g kg^{-1}) followed by T4 (0.23 g kg^{-1}).

Heavy metal concentrations in *J. curcas* growth medium before planting and after harvesting: The concentrations of heavy metals before planting and after harvesting are shown in Fig. 1-5. The *J. curcas* was found to be able to efficiently remove the heavy metals, such as Zn, Pb, Cr, Cd and Cu especially in T5 where the planting medium contained 100% sewage sludge. The Zn content of the sewage sludge was 366.23 mg kg^{-1} before planting in T5 and after harvesting, the Zn level was 117.97 mg kg^{-1} (Fig. 1).

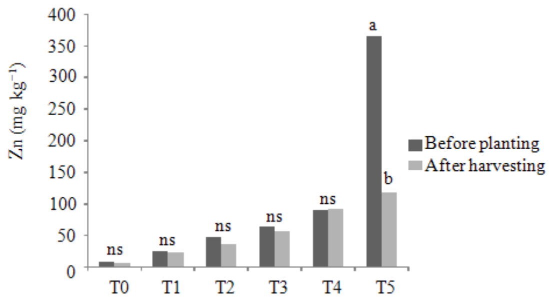

Fig. 1: Concentrations of Zn in growth medium before planting and after harvesting. Different letters indicate significant difference between means at each treatment before planting and after harvesting according to a Student's t-test ($p<0.05$) ns, not significant difference ($p<0.05$). T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

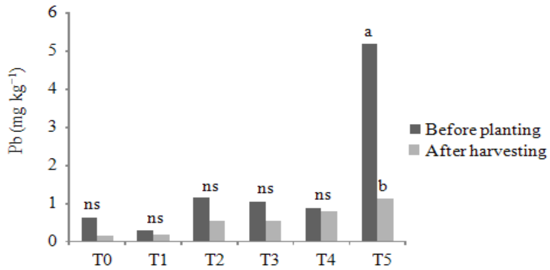

Fig. 2: Concentrations of Pb in growth medium before planting and after harvesting. Different letters indicate significant difference between means at each treatment before planting and after harvesting according to a Student's t-test ($p<0.05$) ns, not significant difference ($p<0.05$). T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

The level of Pb in T5 also decreased after harvesting (1.12 mg kg^{-1}) compared to initial Pb level (5.18 mg kg^{-1}) as shown in Fig. 2. The highest decrease in Cr levels in the *J. curcas* growth medium was observed in T5 in which the level of Cr after harvesting was 7.69 mg kg^{-1}, while the initial level of Cr was 33.86 mg kg^{-1} (Fig. 3).

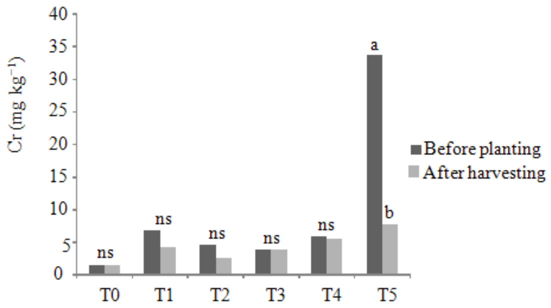

Fig. 3: Concentrations of Cr in growth medium before planting and after harvesting. Different letters indicate significant difference between means at each treatment before planting and after harvesting according to a Student's t-test ($p<0.05$) ns, not significant difference ($p<0.05$). T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

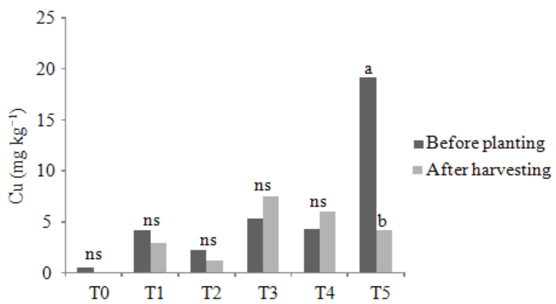

Fig. 4: Concentrations of Cu in growth medium before planting and after harvesting. Different letters indicate significant difference between means at each treatment before planting and after harvesting according to a Student's t-test ($p<0.05$) ns, not significant difference ($p<0.05$). T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

The initial value of Cu was 19.18 mg kg^{-1} and only 4.13 mg kg^{-1} was found to be left in medium (Fig. 4). Cadmium uptake was also found to be effective in T5, where the initial value was 0.16 mg kg^{-1} and the final level after harvest was 0.04 mg kg^{-1} (Fig. 5).

Heavy metal concentrations in plant parts: The concentrations of Zn, Pb, Cr, Cu and Cd in plant parts (leaves, stem and roots) at three months after planting are shown in Table 1-3. The highest Zn accumulation (29.53 mg kg^{-1}) was observed in the roots of *J. curcas* in T5 (Table 3). Furthermore, the roots of *J. curcas* were found to absorb high levels of Zn compared to the stem and leaves. The accumulation of Pb was only observed in the leaves of the plants, with the highest level observed in T4 (4.63 mg kg^{-1}).

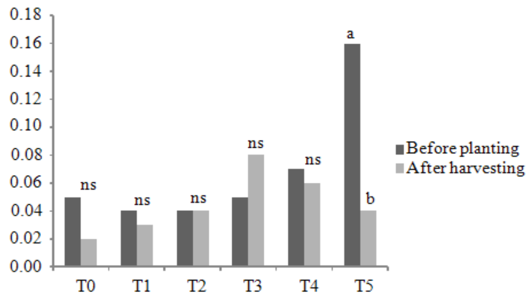

Fig. 5: Concentrations of Cd in growth medium before planting and after harvesting. Different letters indicate significant difference between means at each treatment before planting and after harvesting according to a Student's t-test ($p<0.05$) ns, not significant difference ($p<0.05$). T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

Table 1: Heavy metal concentrations in leaves of *J. curcas* at three months after planting

	Concentration (mg kg^{-1})				
Treatment	Zn	Pb	Cr	Cu	Cd
T0	0.42^{d}	0.06^{d}	0.01^{a}	0.06^{a}	nd
T1	1.34^{c}	1.34^{cd}	0.02^{a}	0.08^{a}	nd
T2	5.04^{a}	3.27^{b}	0.03^{a}	0.09^{a}	nd
T3	1.97^{a}	4.05^{ab}	0.03^{a}	0.06^{a}	nd
T4	4.30^{bc}	4.63^{a}	0.04^{a}	0.09^{a}	nd
T5	3.147^{b}	2.51^{c}	0.02^{a}	0.08^{a}	nd

Note: Different letters within a column indicate significant difference between means at a 5% level according to Tukey's test, nd: not determined. T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

Table 2: Heavy metal concentrations in stem of *J. curcas* at three months after planting

Treatment	Concentration (mg kg^{-1}) Zn	Pb	Cr	Cu	Cd
T0	1.13^{d}	nd	0.18^{b}	0.13^{b}	nd
T1	4.94^{c}	nd	0.33^{a}	0.23^{a}	nd
T2	8.00^{a}	nd	0.17^{b}	0.13^{b}	nd
T3	9.18^{a}	nd	0.20^{ab}	0.10^{b}	nd
T4	5.02^{bc}	nd	0.15^{b}	0.16^{ab}	nd
T5	6.21^{b}	nd	0.18^{b}	0.13^{b}	nd

Note: Different letters within a column indicate significant difference between means at a 5% level according to Tukey's test, nd: not determined. T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

Table 3: Heavy metal concentrations in roots of *J. curcas* at three months after planting

Treatment	Concentration (mg kg^{-1}) Zn	Pb	Cr	Cu	Cd
T0	1.02^{e}	nd	0.09^{a}	0.20^{b}	0.00^{d}
T1	6.48^{d}	nd	0.12^{b}	0.16^{bc}	3.15^{c}
T2	15.96^{b}	nd	0.11^{b}	0.14^{c}	8.35^{a}
T3	14.78^{bc}	nd	0.14^{ab}	0.22^{b}	2.03^{c}
T4	12.40^{c}	nd	0.11^{b}	0.44^{a}	5.13^{b}
T5	29.53^{a}	nd	0.18^{a}	0.32^{ab}	8.20^{a}

Note: Different letters within a column indicate significant difference between means at a 5% level according to Tukey's test, nd: not determined. T0, (100% soil-control); T1, (80% soil and 20% sewage sludge); T2, (60% soil and 40% sewage sludge); T3, (40% soil and 60% sewage sludge); T4, (20% soil and 80% sewage sludge); T5, (100% sewage sludge)

The stem of *J. curcas* in the T1 medium accumulated the highest amount of Cr (0.33 mg kg^{-1}), while the lowest (0.11 mg kg^{-1}) concentration was noted in T4. The highest Cu uptake (0.44 mg kg^{-1}) was found in the roots in T4, followed by T5 (0.32 mg kg^{-1}) and the minimum (0.06 mg kg^{-1}) concentration was noted in the leaves of the control and T3. Only the root of *J. curcas* absorbed and accumulated Cd, having the highest value (8.55 mg kg^{-1}) in T2, followed by T5 (8.20 mg kg^{-1}), T4 (5.13 mg kg^{-1}), T1 (3.15 mg kg^{-1}) and T3 (3.15 mg kg^{-1}), while Cd was not present in the control (Table 3).

Relationship between heavy metal concentrations in the soil and plant parts: The highest concentrations of Zn, Cu, Cr, Pb and Cd in 100% sewage sludge contributed to the increased basal area in the T4 and T5 treatments and the height increase in T3, which consisted of 40% soil and 60% sewage sludge and this proportion may have allowed for optimal plant growth stimulation. Efficient Pb uptake was found in the leaves, having the highest numbers in T4. The high uptake of Pb in T4 compared to T5 may actually be the maximum uptake of Pb that is able to be absorbed by *J. curcas*. Next to Pb, Zn was the most prominent heavy metal that was absorbed by *J. Curcas*. The maximum Zn accumulation was observed in the roots in comparison to the stems and leaves, showing the highest concentration in T5 (29.53 mg kg^{-1}) and the lowest in the control. The Cd level was found to be low in the soil before planting and remained lower after the *J. curcas* had been harvested, with the highest uptake of Cd observed in T5 (0.12 mg kg^{-1}) in the roots, with lesser amounts observed in the stem and leaves. All parts of *J. curcas* were able to absorb and store Cr, especially the stem, with the highest level of Cr uptake (0.33 mg kg^{-1}) recorded in T2.The pattern of Cu uptake by *J. curcas* was not proportional because the levels of Cu in the soil after harvest were lower compared to the soil before planting in the control, T1 and T2, while in T3 and T4, the levels of Cu were higher in the soil after *J. curcas* has been harvested compared to before planting.

DISCUSSION

Growth performance of *J. curcas* and effects of sewage sludge on soil acidity: The highest average height increase (8.79 cm) was found in T3, while T2 showed the lowest increase in height (6.98 cm). These results indicate that the composition of 60% sewage mixed with 40% soil is suitable and ideal for achieving optimum *J. curcas* growth. The *J. curcas* planted in T_4 showed the highest increase in basal diameter (3.95 cm) compared to that planted in the 100% soil medium. The growth or increase in the basal diameter of *J. curcas* was found to be slow in the first 2 weeks, which likely occurred due to the plants attempting to acclimatize themselves to their new growing medium. The highest number of leaves was observed in the 100% soil medium (control), followed by T2 and T1. With the exception of T4 and T5, the numbers of leaves increased every week. The *J. curcas* planted in T4 and T5 had less leaves, which may have been caused by the high heavy metal level in the soil, creating an acidic state in the growing medium.

Heavy metal concentrations in *J. curcas* growth medium: *J. curcas* can uptake heavy metals such as Zn, Pb, Cr, Cd and Cu efficiently, especially in T5, in which the planting medium contained 100% sewage sludge (Table 1). Before planting, the concentrations of Cd, Cu and Pb in the sewage-sludge containing soils were within- the permissible limits stated by World Health Organization (1998), except for Zn, which showed levels of 366.23 mg kg^{-1} before planting in T5. The Zn level from the T5 harvest was 117.97 mg kg^{-1}, showing a 67.7% decrease compared to the initial level. The level of Pb in T5 also showed the highest decrease compared to the other treatments and control medium, with 78.37% less in the growth medium after harvesting (5.18 mg kg^{-1}) compared to the initial Pb level (1.12 mg kg^{-1}). The success of *J. curcas* in taking up Pb and Cd from soil is paralleled with the capacities of *Euphorbia cheinrandenia*, which comes from the same family (Chehregani and Malayeri, 2007). The highest decrease in Cr levels in the *J. curcas* growth medium was observed in T5, in which the level of Cr after harvesting was 7.69 mg kg^{-1}, while the initial level was 33.86 mg kg^{-1}, indicating a 77.19% loss. The initial value of Cu was 19.18 mg kg^{-1} and only 4.13 mg kg^{-1} remained in the medium. Cadmium uptake was also found to be effective in T5, where the initial level was 0.16 mg kg^{-1} and the final level after harvesting was 0.04 mg kg^{-1} (75.0% decrease from the initial value).

Treatment 5 exhibited a clay loam texture, while the other treatments, including the control, had a clay soil texture; these results indicated that the soil was clay in nature. Before planting and after harvesting, the pH value was significantly different ($p \leq 0.05$) in all treatments. (T1 through T5); the pH of the soil after harvesting was lower compared to before planting. However, the control treatment showed a slightly higher pH after harvesting compared to before planting. The greatest decrease in soil pH levels after planting was observed in T4. The availability of sewage sludge in the soil contributes to a lower soil pH, the highest total carbon level was found in the *J. curcas* growth medium in T5 (0.24 g kg^{-1}) followed by T4 (0.23 g kg^{-1}). The nature of the sewage sludge and the rate of decomposition of the organic materials affect the time necessary to release certain heavy metals into the soil and thus help to improve soil fertility (Rice, 2009).

Heavy metal concentrations in plant parts: The highest Zn accumulation (29.53 mg kg^{-1}) was recorded in *J. curcas* in T5 (Table 2). Furthermore, the roots of *J. curcas* were found to absorb high levels of Zn compared to the stems and leaves. Pb accumulation was only found in the leaves of the plants, with the highest level observed in T4 (4.63 mg kg^{-1}). The *J. curcas* is not a good Pb accumulator because it absorbs very small amounts of it in comparison to the other elements. The stem of *J. curcas* in the T1 medium exhibited the highest Cr (0.33 mg kg^{-1}) accumulation, while the lowest (0.11 mg kg^{-1}) was noted in T4. The highest Cu uptake (0.44 mg kg^{-1}) was found in the roots in T4, followed by T5 (0.32 mg kg^{-1}) and the minimum (0.06 mg kg^{-1}) was noted in the leaves of the control and T3. Only the root of *J. curcas* absorbed and accumulated Cd, showing the highest concentration (8.55 mg kg^{-1}) in T2, followed by T5 (8.20 mg kg^{-1}), T4 (5.13 mg kg^{-1}), T1 (3.15 mg kg^{-1}) and T3 (3.15 mg kg^{-1}), while the control contained negligible amounts of Cd concentration was.

Relationship between heavy metal concentrations in the growth medium and plant parts: The higher concentrations of Zn, Cu, Cr, Pb and Cd in the 100% sewage sludge contributed to increased basal area in the T4 and T5 treatments and the height increase in T3, which consisted of 40% soil and 60% sewage sludge, this proportion may have allowed for optimal plant growth stimulation. Yadav *et al*. (2009) reported that the soil or sewage sludge containing higher amounts of Zn compared to the other metals tended to reduce the increase in plant growth. Similar results were also observed in T5 treated *J. curcas* where the growth quite slow or poor compared to other *J. curcas,* in which the growth markedly slowed compared to the *J. curcas* planted in the lower proportions of sewage sludge. Moreover, Cooke and Johnson (2002) found that low nutrient and water holding capacities, toxic substances, salinity, stability, nutrient deficiencies (especially N, P and K), poor physical properties and excess acidity and alkalinity are some of the contributing factors that inhibit or disrupt plant growth in soil containing high amounts of heavy metals. Macnair (1987) and Baker (1987) reported that the *J. curcas* plant has the capability to grow well in soil with high heavy metals concentrations of heavy metals. The higher uptake of Pb in T4 compared to T5 may actually be the maximum uptake of Pb that was able to be absorbed by *J. curcas*. Next to Pb, Zn was the most prominent heavy metal that was absorbed by *J. Curcas*. The maximum Zn accumulation was observed in the roots in comparisons to the stems and leaves, with the highest concentrations in T5 (29.53 mg kg^{-1}) and the lowest in the control. Baker (1981) reported that some plants are able to hasten the transportation of heavy metals from their roots to shoots, which may be related to the rate of Zn uptake by *J. curcas*. Similarly, the restriction of heavy metals in *J. curcas* also affects the uptake of Cd. The Cd level was found to be low in the soil before planting and remained low after *J. curcas* been harvested, with the highest uptake of Cd observed in T5 (0.12 mg kg^{-1}) in the roots and the stems and leaves to a lesser degree; this finding was supported by Keller *et al.* (2003), who illustrated that plants with extensive root systems have the advantage of being able to absorb greater amounts of heavy metals due to better soil penetration.

Regarding the potential use of *J. curcas* for the phytoremediation of coal fly ash, we have discerned that *J. curcas* is very efficient in accumulating heavy metals, causing no damaging effects to the root biomass. *J. curcas* was also found to be effective in taking up Cr from the soil. All parts of *J. curcas* were able to absorb and store Cr, especially the stems, which showed the highest levels of Cr uptake (0.33 mg kg^{-1}) in T2. The pattern of Cu uptake by *J. curcas* was not proportional because the Cu levels in the soil after harvesting were lower compared to soil before planting in the control, T1 and T2, while in T_3 and T_4, the levels of Cu were higher in the soil after *J. curcas* has been harvested compared to before planting. Alkorta and Garbisu (2001) found that the plant metabolites of the pollutant may be more toxic compared to the original environmental pollutant. The accumulation of heavy metals in *J. curcas* tends to occur mainly in the roots and to a lesser degree in the leaves and stems. Palmroth *et al*. (2002) also agreed that plant roots stimulate the degradation of toxic organic materials. Furthermore, roots act as a medium for soil microorganisms to speed up the organic pollutant biodegradation rates. Therefore, the efficiency of heavy metal uptake by plant parts is as follows:

$$\text{stem} < \text{leaves} < \text{roots}$$

CONCLUSION

The roots of *J. curcas* were found to be suitable for taking up heavy metals from sewage sludge, especially Zn. Cr was found to be effectively absorbed by the leaves of *J. curcas*. In a nutshell, *J. curcas* is a suitable plant to use as a phytoremediator due its ability to accumulate high levels heavy metals in sewage sludge, especially Zn, Cu and Cr. Nevertheless, phytoremediation encompasses a much broader model and thus, additional more lengthy studies are needed to support the claim that *J. curcas* is a hyper-accumulator of heavy metals. An evaluation of the short-term effects the large-scale use of sewage sludge on tree growth and the environment also needs to be carried out.

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