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Acacia trees-legumes potential for phytoremediation of urban landfill soil in Bonoua (Côte d'Ivoire)

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ABSTRACT

Landfills in urban areas contribute to soil and water pollution with heavy metals. In Côte d'Ivoire, urban landfill soil is used to produce food, which presents health risks. This study evaluates the growth capacity of *Acacia* spp. trees-legumes (*Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa*) and their potential for landfill soil remediation and restorations. These trees-legumes were grown under controlled conditions for six months in polluted soils sampled from urban landfills located in southeastern Côte d'Ivoire. The study used a simple, completely randomized design with four treatments (*Acacia mangium*, *Acacia auriculiformis, Acacia crassicarpa,* and control) and five replicates. Growth parameters, soil pH, metal contents (bulk soil, leachate), and plants were measured during this experiment. The results indicated that *Acacia auriculiformis* and *Acacia mangium* displayed better growth indicators (dry biomass, heights, and number of phyllodes) compared to *Acacia crassicarpa*. The soil pH under the trees-legumes indicated a significant decrease compared to the control ($p < 0.05$). In addition, heavy metal contents significantly decreased in the leached solutions of the planted soil compared to the control ($p < 0.05$). In the exchangeable soil fraction, only the *Acacia auriculiformis* treatment showed a significant decrease in Zn compared to the control. Regarding the plants, *Acacia auriculiformis* showed the highest amounts of Pb (111 µg plant^{-1}) and Cd (54 µg plant^{-1}) in total biomasses. *Acacia crassicarpa* had the highest metal extraction capacity from the polluted soil (Pb: 24 µg plant^{-1}, Cr: 11 µg plant^{-1}, Cd: 14 µg plant^{-1}, and Zn: 83 µg plant^{-1}) compared to the two other species. The *Acacia crassicarpa* species appears to be the best one for the phytoremediation of landfill soils.

1. Introduction

In Côte d'Ivoire, the production of solid waste, mainly domestic and industrial, is constantly increasing due to population growth and the intensification of economic activities. Managing this urban solid waste remains a major challenge for the administrative authorities

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because there are no waste sorting centers, and the treatment of household waste is almost non-existent. As a result, this solid waste is dumped in open-air dumps in most Ivorian communes. In some cities, solid waste is burned or dumped in the shallows on the outskirts of the cities [1]. Numerous reactions take place not only between the waste and the receiving environment (soil, rock, groundwater, etc.), but also within the waste itself [2]. Consequently, these waste management practices represent a significant risk of environmental contamination, mainly by organic compounds but also by inorganic compounds, such as trace metals (heavy metals) [3,4]. Many studies have also shown that the chemical composition of landfill waste contains high concentrations of heavy metals [2]. This is the case of the former Bonoua landfill, a city located in the southeast of Côte d'Ivoire. The landfill used to be on the outskirts of the town but is now in the center of the city due to rapid urbanization. Recent work conducted by [5] on this landfill revealed high levels of chromium (Cr), lead (Pb), cadmium (Cd) and zinc (Zn), which were higher than the WHO standards for soil levels. Their study revealed increasing heavy metal contents along the toposequence. This would be linked to a transfer of these metals, probably in connection with diffusion, percolation, and soil erosion processes [5]. The presence of metals in soils leads to the degradation of the quality of the environment with a consequent deterioration of the health of the surrounding populations. Indeed, the local population uses the landfill soils for agricultural production and consume the groundwater taken from wells in the immediate vicinity of the landfill. Similarly, in the district of Abidjan, the former Akouédo landfill (southeast of Abidjan) is used as a substrate for growing vegetables to supply the markets of Abidjan's communes. In addition, a permanent leaching solution with a high load of metals (Pb, Hg, Cr, and Cd) from this landfill is discharged into the M'Badon Bay, where local populations fish for their consumption. Therefore, it becomes essential to rehabilitate the soils of these landfills in order to restore their quality and reduce the risks of transferring these metals in the trophic chain. Several techniques exist for treating polluted soils, including physico-chemical techniques and biological methods, such as phytoremediation [6]. Phytoremediation is a well-known, efficient biological method but is rarely used in the decontamination of polluted anthropized soils in tropical zones. It is certainly slower but much more economical and ecological [7]. Phytoremediation is a soil remediation method that includes a set of techniques based on the use of plants, often in association with microorganisms [8]. In Africa, phytoremediation using plants with high phytoremediation potential is little practiced. Studies have presented some soil phytoremediation plants in sub-Saharan Africa, such as *Hibiscus cannabinus L., Andropogon gayanus, and Vetiveria nigritania* [9]. However, these plants have yet to be found very effective in extracting or stabilizing pollutants in soils. It is in this context that the present study was initiated with the objective of evaluating the efficiency and phytoremediation performance of three tropical shrub species in the phytoremediation of metal polluted soils: *Acacia mangium, Acacia auriculiformis,* and *Acacia crassicarpa*. Of these three species, *Acacia mangium* has been the subject of several works in soil phytoremediation to detect heavy metals in their vegetative parts [10-16]. The species *Acacia auriculiformis* is also cited in some recent works on the phytoremediation of polluted soil [17-20]. As for the *Acacia crassicarpa* species, the literature indicates few works regarding phytoremediation [21,22]. The *Acacia* spp. species can therefore be tested as soil phytoremediation plants [23,24]. However, their potential in a phytoremediation context are still poorly known, and there is no intercomparison in the effectiveness of these species in the phytoremediation of soils with high heavy metal contents. This study evaluated the growth capacity of *Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa* and their potential for landfill soil remediation and restorations. These trees-legumes were grown under controlled conditions for six months in polluted soils sampled from an urban landfill located in southeastern Côte d'Ivoire.

2. Materials and methods

2.1. Study site

The study site is near Bonoua, a town 59 km from Abidjan in the southeast of Côte d'Ivoire between latitudes 5°08'N and 5°33'N and longitudes 3°13'W and 3°51'W (Figure 1). The study site is a former dump located in the M'Ploussoué Park (coordinates 05°16'41.8''N and 03°36'03.2''W) with a surface area of 16 ha located southwest of Bonoua. The landfill is characterized by anthropogenic soil classified as fumic anthroposol according to the WRB global reference base system [5]. The landfill site, with an area of about 1135 m^2, consists of two parts. One part includes the actual municipal waste disposal pile, known as the landfill dome. The other part, the apparently bare lower area, consists of less waste and is located on the slope, southwest of the dome. The landfill shows the presence of various types of waste, such as plastic bags, damaged clothes, electronic waste, household batteries, electronic cards, car batteries, tyres, pharmaceutical or medical products (medicine bottles, expired medicines, syringes), paint cans, etc.

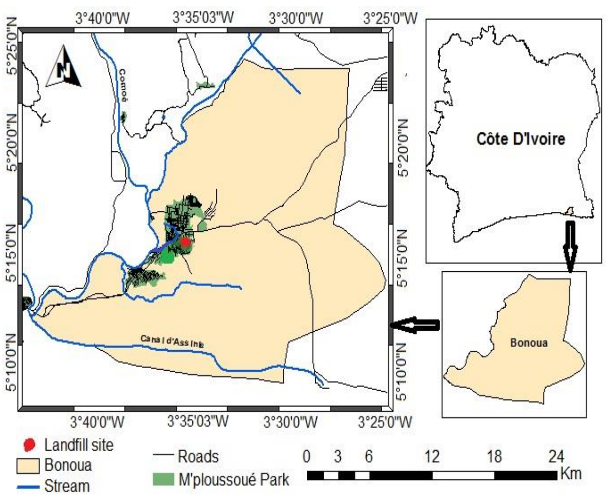

Fig. 1. Map of the location of the former Bonoua municipal dump.

2.2. Experimental plant growth

The biological material used in this study consists of three (3) species of trees-legumes, namely *Acacia mangium*, *Acacia auriculiformis* and *Acacia crassicarpa*. Table 1 shows the classical classification of the three *Acacia* species The Centre National de Recherche Agronomique (CNRA) of Côte d'Ivoire provided the seeds of these leguminous shrubs. These seeds of *Acacia* spp. were soaked in 95-97% concentrated sulfuric acid (H_2SO_4). Then, they were rinsed abundantly with sterile distilled water and soaked in sterile distilled water overnight at room temperature. The seeds were placed in Petri dishes containing an agar medium and incubated at 30 °C for 72 hours for germination. The germinated seeds of the different species of *Acacia* spp. were transplanted into pots containing 3 kg of landfill soil at a rate of three (3) seeds per pot. The cultivation set-up consisted of the culture pots perforated at the base to collect leachate by gravity. The experimental legume growth was carried out using a simple, completely randomized design with four treatments (*Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa* and control) and five replicates. The treatments are listed below:

- Treatment T: control (landfill soil)
- Treatment T_{am}: *Acacia mangium* + landfill soil
- Treatment T_{aa}: *Acacia auriculiformis* + landfill soil
- Treatment T_{ac}: *Acacia crassicarpa* + landfill soil

The trials were conducted under cover in natural light conditions and at room temperature. Throughout the experiment, each culture pot received 50 ml of distilled water twice a day at the beginning and end of the day. Leachates were collected from each treatment every two (2) weeks after transplanting. After one month of culture, the seedlings were dismantled to leave only the most vigorous foot to ensure homogeneous growth. The parameters measured were the plant height using a tape measure and the number of phyllodes by manual counting. At the end of the culture, the plants were stripped, and the roots of the plants were carefully extracted and rinsed with distilled water. The aerial part was separated from the roots before they were oven dried at 65 °C for 48 hours to determine the dry biomass. At the same time, the leachate samples were filtered using a Whatman™ type nylon filter membrane with a diameter of 47 mm and a porosity of 45 µm to determine their Pb, Cd, Cr and Zn contents. At the end of cultivation, the soils were dried at a temperature of 105 °C for 24 hours in an oven, then ground in a mortar and sieved to 50 µm for the determination of Pb, Cd, Cr and Zn contents. Also, the dry plant biomasses were finely ground for determining the Pb, Cd, Cr and Zn contents.

2.3. Chemical analysis of samples

2.3.1. Soils

The soil pH_{H2O} was determined in a soil-water suspension, according to the soil/solution weight ratio equal to 1/2.5, using a pH meter. In addition, a fine soil fraction initially taken was used for sequential extractions of different factions (exchangeable and acid soluble). The exchangeable heavy metal fraction was extracted first with a mixture of $MgCl_26H_2O$, followed by the acid soluble fraction that was extracted with a mixture of 0.05M HCl and 0.0125M H_2SO_4 in a m/v (g/ml) ratio of 1/5 [25]. After filtration, the heavy metal contents in these extracts were determined by mass spectrometry. Finally, the heavy metal contents in the total soil were analyzed by X-ray fluorescence (XRF) spectrometry (XRF NITON XL3T GOLDD+).

2.3.2. Leachate

After filtration of the leachates, the contents of Pb, Cd, Cr and Zn in these solutions were determined by mass spectrometry.

2.3.3. Plants

The previously dried and ground plant samples were mineralized in a mixture of 1 ml of hydrogen peroxide and 3 ml of nitric acid in Teflon tubes for 24 hours at cold temperature, then at hot temperature of 90 °C overnight. After cooling, the mineralization obtained was evaporated to dryness, and the residue was taken up in 1 ml of hydrochloric acid and heated to 75 °C. The solution obtained was filtered into 50 ml volumetric flasks. The volume of the solutions was adjusted to the gauge line, and the contents of Pb, Cd, Cr, and Zn in these mineralizations were determined by mass spectrometry.

2.4. Assessment of accumulation and translocation

In this study, the bioaccumulation factor and translocation factor were calculated to characterize the phytoremediation potential of the plants. The bioaccumulation or bioconcentration factor (BF) is used to assess the ability of plants to concentrate the heavy metals in their tissues. It is the ratio of the concentration of the heavy metals in the plant roots to their concentration in the soil [26]. The translocation factor (TF) is used to assess the phytoextraction capabilities of plants, specifically their ability to transport heavy metals from roots to stems and leaves. It corresponds to the ratio of the concentration of the heavy metals in the aerial parts of the plants to their concentration in the roots [26].

2.5. Statistical processing

In this study, statistical analyses were performed by XLSTAT 2016 software. Student- Newman-Keuls tests were used to compare the observed means on different measured parameters at $p < 0.05$.

3. Results and discussion

3.1. Landfill soil characterization and heavy metal contents

The landfill soil is described as anthroposol. The physical and chemical characteristics of this soil are presented in Table 1. It was sandy textured soil with a neutral pH. It had high nitrogen and organic carbon contents in the range of classical values in landfill soil, and the C/N ratio was lower than 11. The exchangeable base cations showed low contents of Ca, Mg, and Na but a high content of K compared to the normative values of landfill soil. The Cation Exchange Capacity (CEC) remained low compared to the normative values. The physico-chemical characteristics of the landfill soil indicated conditions conducive to the retention of heavy metals by organic matter, as suggested by several studies, indicating that pH and organic matter play a very important role in metal retention [27-29]. Heavy metal contents in the landfill soil showed that Pb and Cr levels were below the CCME (Canadian Council of Ministers of the Environment) limit (Table 1). Cadmium and Zn levels were respectively 10.65 and 1.4 times higher than the CCME standard, similar to literature results [30]. In addition, the total heavy metals (Zn and Cr) contents in soils under *Acacia* spp. were higher compared to the CCME standard [30], in contrast to Pb and Cd (Figure 2). The Cd contents for this experiment were below the detection limit value.

Table 1. Selected physicochemical characteristics of landfill soil.

Parameters		**Landfill soil**	**Standard**
Physical parameters (%)	Clay	14.93	
	Silt	6.05	
	Sand	79.03	
	pH	7.15	
Organic matter (g/kg)	C	16.55	12.6-25*
	N	2.25	1.2-2.2*
	OM	28.47	3.6-6.5*
	C/N	7.21	11-15*
Exchangeable bases ($cmol_c$/kg)	K^+	0.25	0.15-0.25*
	Ca^{2+}	3.48	5-8*
	Mg^{2+}	0.66	1.5-3*
	Na^+	0.19	0.3-0.7*
Cation Exchange Capacity ($cmol_c$/ kg)	CEC	6.55	10-20*
Heavy metal (mg/kg)	Pb	23	70**
	Cd	31.9	3**
	Cr	49.6	64**
	Zn	283.98	200**

*Reference threshold values [31-34].
**Canadian environmental quality criteria for contaminated sites recommendation [30].

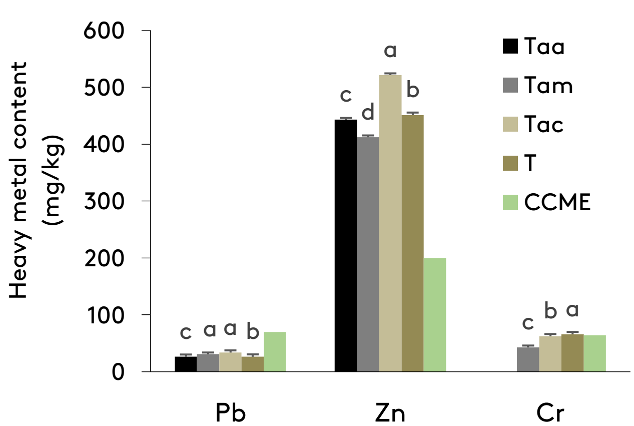

Fig. 2. Average heavy metals contents in the soil of the different treatments. T: control treatment; Tam: *Acacia mangium* treatment; Taa: *Acacia auriculiformis* treatment; Tac: *Acacia crassicarpa* treatment. a, b, c and d indicate different mean values. Histograms for each element followed by the same letter are not significantly different according to the Student Newman-Keuls (SNK) test at $p < 0.05$.

3.2. Exchangeable and soluble acid heavy metal contents

Heavy metal contents of soil exchangeable and soluble acid fractions from the sequential extractions are indicated in Figures 3 and 4. The exchangeable fraction showed that the Pb, Cd, and Cr contents of the soils under the *Acacia* spp. trees were not significantly different from the control (Figure 3). For Zn, *Acacia auriculiformis* treatment showed a significant decrease of 30.1% compared to the control. The control, *Acacia mangium,* and *Acacia crassicarpa* treatments remained statistically identical. Soluble acid fraction contents (Figure 4) indicated that Pb, Cd, and Cr contents did not present any significant difference between *Acacia* treatments and the control, while Zn soluble acid contents with species showed a significant decrease compared to the control. These decreases were about 69.57%, 59.66%, and 15.5% for *Acacia mangium*, *Acacia Auriculiformis,* and *Acacia crassicarpa,* respectively. These results suggest that the heavy metals analyzed in this study are potentially bioavailable and mobile in soil. Many early studies demonstrated that the fraction of bioavailable heavy metals is generally higher in the rhizosphere than in the non-rhizosphere soil [35-37], suggesting more intense heavy metal mobilization processes in the rhizosphere than in the bulk soil [38-40]. Although the bioavailability of heavy metals is often best predicted by their dissolved concentration, solid-phase heavy metals are important components because some plants uptake most of their nutrients from the less available fractions [41] and because the replenishment of metals in the soil solution is ultimately controlled by the solid-phase pools [42,43]. In addition, despite the high levels of heavy metals (Pb, Cd, Cr, and Zn) in the soil, it did not appear to have affected the growth of the species of *Acacia* spp.

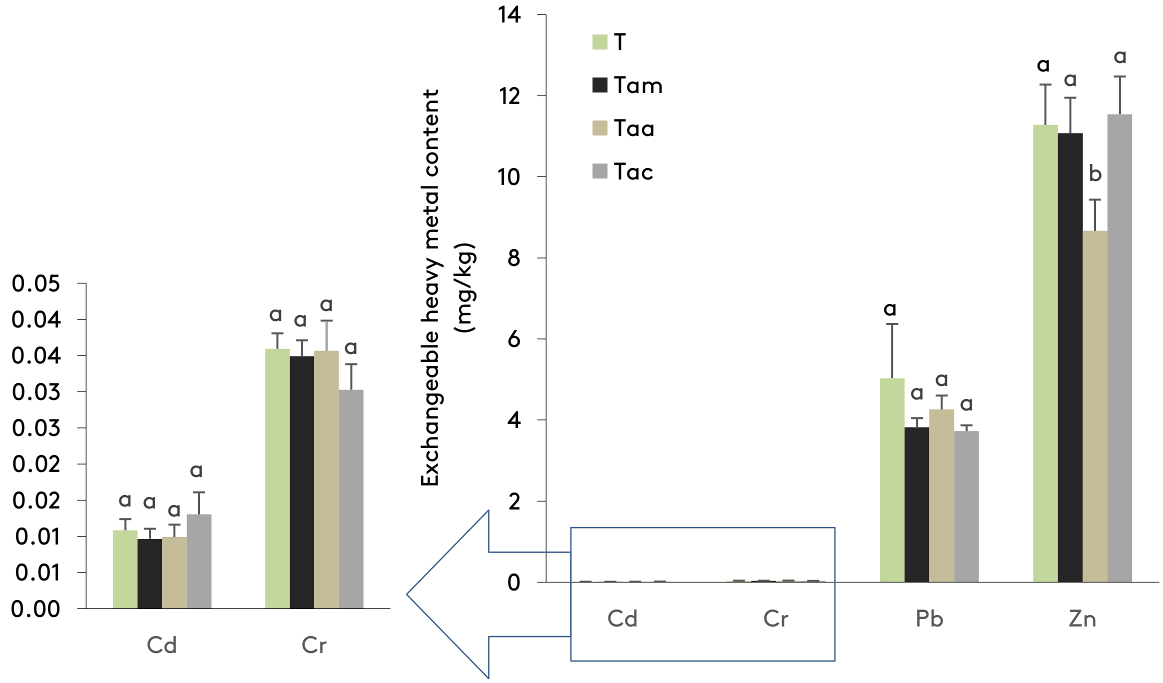

Fig 3. Soil exchangeable fraction contents in heavy metals (Pb, Cd, Cr and Zn) after *Acacia* spp. trees-legume growth experiment for 180 days. T: control treatment; Tam: *Acacia mangium* treatment; Taa: *Acacia auriculiformis* treatment; Tac: *Acacia crassicarpa* treatment. a and b indicate different mean values. Histograms for each element followed by the same letter are not significantly different according to the Student Newman-Keuls (SNK) test at $p < 0.05$.

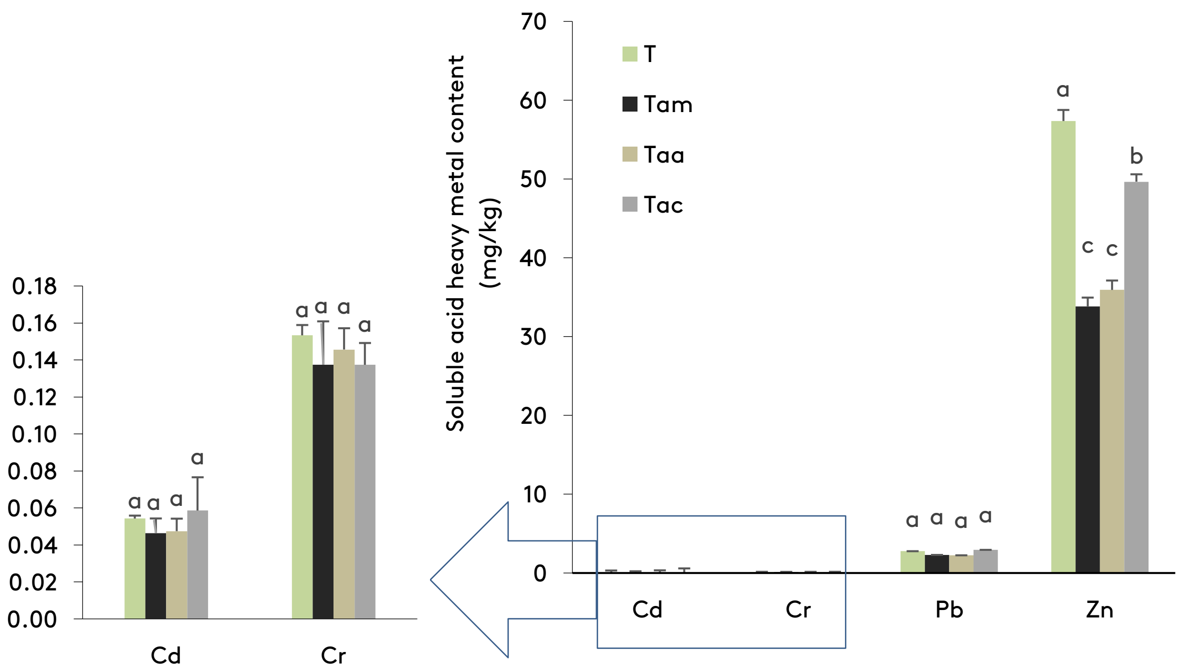

Fig. 4. Soil soluble acid fraction contents in heavy metals (Pb, Cd, Cr, and Zn) after *Acacia* spp. trees-legume growth experiment during 180 days. T: control treatment; Tam: *Acacia mangium* treatment; Taa: *Acacia auriculiformis* treatment; Tac: *Acacia crassicarpa* treatment. a, b and c indicate different mean values. Histograms for each element followed by the same letter are not significantly different according to the Student Newman-Keuls (SNK) test at $p < 0.05$.

3.3. Growth performance of *Acacia spp.* in landfill soil

The height measurements of the species were used to determine the growth rate of the plants (Table 2). The results show that *Acacia crassicarpa* had the lowest average growth rate, significantly followed by *Acacia mangium* (0.22±0.06 cm/day). *Acacia auriculiformis* showed the highest average growth rate of 0.29±0.14 cm/day. These average growth rates are in the ranges of values reported in the literature, which vary from 0.06 to 0.6 cm/day for *Acacia auriculiformis* and from 0.06 to 0.34 cm/day for *Acacia mangium* [11,44,45]. As for *Acacia crassicarpa*, the value obtained in this study remains lower than that obtained in one of the few works using this species for phytoremediation [22]. These variations in the growth rate could be due to the culture time and the physicochemical composition of the substrates used for the culture. Bolou et al. [40] showed better results with growth rates varying from 0.42 to 0.75 cm day^{-1} using the same three species of *Acacia* spp. These different works make it more likely that the differences in growth rate could be related to the conditions of the culture of the plants. Previous studies have shown that these species are able to grow in soils with high metal contents [10,24], with highly variable biomass productions. These differences in growth rate resulted in a difference in biomass production. Thus, *Acacia auriculiformis* presented the highest value of total biomass, significantly higher by 362.76% of the biomass of *Acacia crassicarpa* and statistically similar to the biomass of *Acacia mangium* (Table 2). The shoot biomass of the plant species represented between 78.72% and 83.37% of the total biomass with a root/shoot ratio of 0.19 and 0.25 less than unity, similar to previous results [46]. These ratios indicated good plant growth in this polluted environment. *Acacia* spp. plants are leguminous plants known to be efficient in adapting to unfertile soil and improving the physico-chemical characteristics of these soils [47,48]. In addition, this study reveals that *Acacia mangium, Acacia auriculiformis* and *Acacia crassicarpa* were able to grow in polluted soil. This adaptation of *Acacia* species in soils polluted with heavy metals is closely associated with the establishment of mechanisms and processes (excretion of proton and organic acids, metal reduction) in the rhizosphere [40,49]. The difference between the biomass of plants could reflect the difference between these plants in the implementation of these mechanisms in the rhizosphere and affecting the rate of heavy metals leaching from the root zone.

3.4. Soil pH and heavy metal contents in leachate

After plant cultivation, the pH of the soils under the treatments indicated a significant decrease compared to the control (Figure 5), however, with a similar pH value in leachates from *Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa* soil. These species of *Acacia* spp. influenced their rhizosphere condition *via* various mechanisms during their growth. It has been shown that the symbiotic nitrogen-fixing plants, during their nutrition, would acidify the soils [50,51]. This phenomenon would be related to the release of H^+ ions in the rhizosphere during nitrogen-fixation [52-54]. In addition, the decreasing pH could also be explained by the release of different organic acids in the rhizosphere [40,54].

Table 2. Growth rate (cm/day), biomass (g), and ratio of root biomass to shoot biomass of *Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa* plants. BA: above-ground biomass; BR: root biomass; BT: total biomass. a, b and c indicate different mean values. Values followed by the same letter in the same line are not significantly different according to the Student Newman-Keuls (SNK) test at p< 0.05.

	A. mangium	*A. auriculiformis*	*A. crassicarpa*
Growth rate (cm/day)	0.22±0.06b	0.28±0.14a	0.1±0.03c
Total biomass (g)	4.03±0.94a	4.35±1.45a	0.94±0.41b
Shoot biomass BA (g)	3.36±0.98a	3.53±1.25a	0.74±0.26b
Root biomass BR (g)	0.67±0.03a	0.82±0.23a	0.19±0.15b
BR/BA ratio	0.19	0.23	0.25

The release of organic acids is considered one of the mechanisms of tolerance to crop stress, such as soil metal content [55]. The results of the above-mentioned studies support findings on the acidification of the rhizosphere. This acidification trend could lead to solubilization by hydrolysis, releasing these metals in ionic forms and, thus, potentially bioavailable to plants [40,56]. In leached solutions, the results showed a significant decrease of heavy metal content at the end of plant growth (Figure 6). The highest decrease was observed with the zinc contents in the leachates, and the Cd contents highlighted the lowest decrease. The two other heavy metals had decreasing contents between Zn and Cd. The significant decrease in Zn levels in the leachates may be linked to a high mobilization of this element by the plant. Zinc is one of the essential micronutrients and an important constituent of several enzymes and proteins. It is only needed by plants in small quantities. However, it is crucial to plant development, as it plays a significant part in a wide range of processes. Conversely, a slight decrease in Pb, Cd, and Cr levels may be correlated with a low mobilization of these elements for plant growth. These metals are not essential micronutrients for plants and can be immobilized in the soil as organometallic compounds in *Acacia* spp. in their rhizosphere [39].

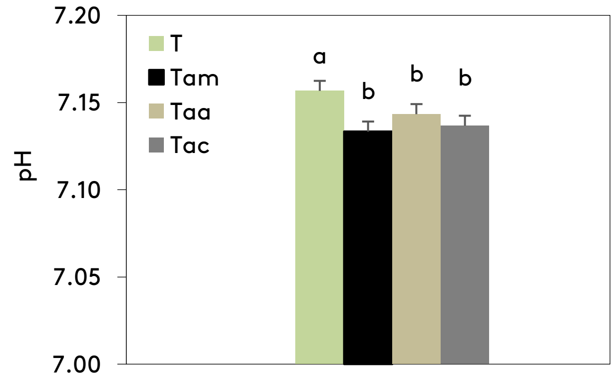

Fig. 5. Soil pH of the different treatments during the cultivation period with the dump soil. T: control treatment; Tam: *Acacia mangium* treatment; Taa: *Acacia auriculiformis* treatment; Tac: *Acacia* crassicarpa treatment. a and b indicate different mean values. Histograms followed by the same letter are not significantly different according to the Student Newman-Keuls (SNK) test at $p < 0.05$.

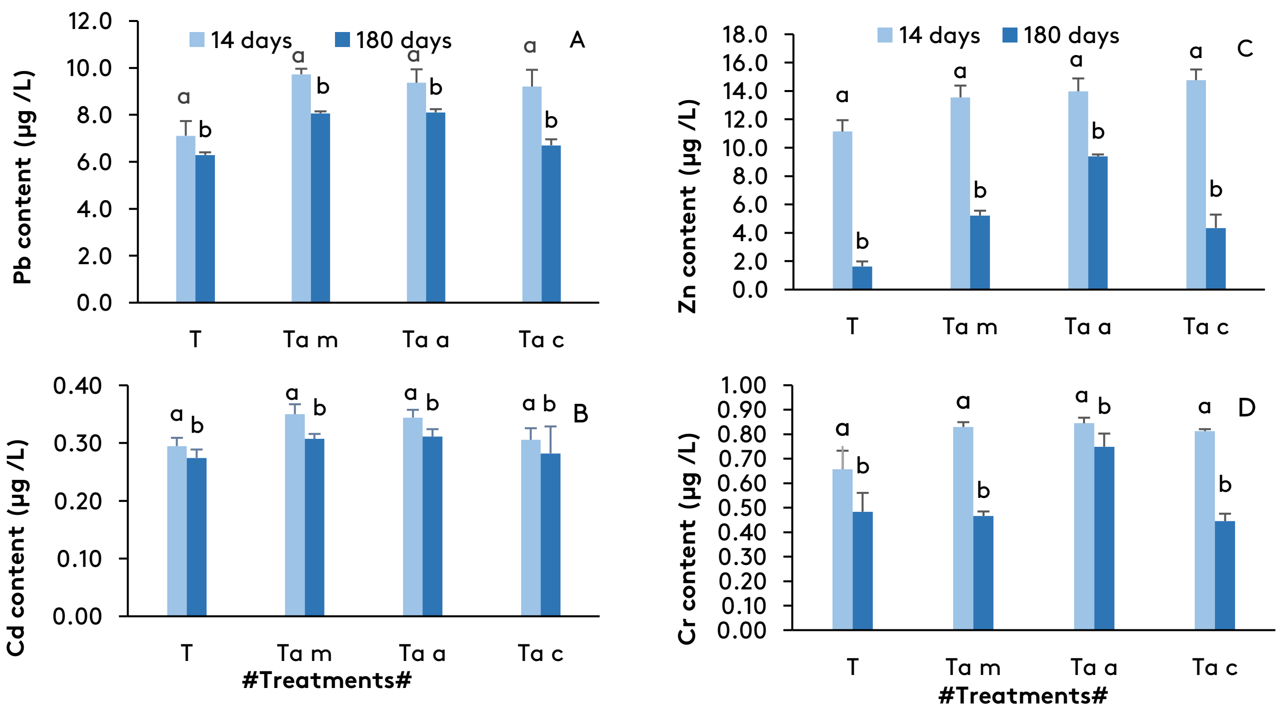

Fig. 6. Soil leachate content in Pb (A), Cd (B), Zn (C) and Cr (D) with different treatments at the beginning (14 days) and at the end (180 days) of *Acacia* spp. trees-legumes growth experiment. T: control treatment; Tam: *Acacia mangium* treatment; Taa: *Acacia auriculiformis* treatment; Tac: *Acacia crassicarpa* treatment. a and b indicate different mean values. Histograms for each treatment followed by the same letter are not significantly different according to the Student Newman-Keuls (SNK) test at $p < 0.05$.

3.5. Efficiency of Acacia spp. in phytoremediation

Table 3 presents the results of Pb, Cd, Cr, and Zn contents in the shoot, root, and total biomass of *Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa*. In the total biomass, *Acacia auriculiformis* had the highest Pb uptake, with 15.63% and 362.5% higher content compared to *Acacia mangium* and *Acacia crassicarpa,* respectively. For Cd, the content in the total biomass of *Acacia auriculiformis*

was also 14.89% and 390.91% higher than those of *Acacia mangium* and *Acacia crassicarpa,* respectively. Cr was only detected in the *Acacia crassicarpa* biomass. Zinc was analyzed in the *Acacia crassicarpa* biomass with a content of 83 µg plant^{-1}, higher than the *Acacia auriculiformis* content (57 µg plant^{-1}). Zinc was not detected in the biomass of the *Acacia mangium*. The different species of *Acacia* spp. showed variability in the stock of Pb, Cd, Cr, and Zn. *Acacia crassicarpa* showed low total content for Pb and Cd, which was related to its low biomass production. A similar study indicated opposite results, showing the efficiency of *Acacia crassicarpa* in the removal of Pb and Cd [22]. *Acacia crassicarpa* remains the only species that stores chromium, mainly in its biomass. Comparatively, Manikandan et al. [11] showed that *Acacia auriculiformis* was able to accumulate large amounts of Cr in its biomass. The calculated bioaccumulation factors for each heavy metal are given in Table 4. The results indicate that Pb recorded a bioaccumulation factor greater than one in all three species. Zn and Cr also exhibited a BF greater than one in *Acacia crassicarpa* but less than one in *Acacia mangium* and *Acacia auriculiformis*. Cd showed a BF of less than one in all three species. The calculated translocation factors are also listed in Table 4. The results indicate that Pb and Cd had factors greater than one in *Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa*. The TF of Cr remained below one in *Acacia crassicarpa*. Zn also indicated a TF less than one in *Acacia auriculiformis* and *Acacia crassicarpa*. Bioaccumulation and translocation factor values are also important in estimating the phytoremediation potential of plants [26,57-59]. In this study, the bioaccumulation factors helped to indicate that *Acacia mangium, Acacia auriculiformis* and *Acacia crassicarpa* could be classified as lead accumulating plants. For Cd, these can be classified as exclusionary plants. *Acacia mangium* and *Acacia auriculiformis* were excluded for chromium and zinc. As for *Acacia crassicarpa,* it showed an accumulation towards these two elements. Concerning translocation factors, *Acacia mangium, Acacia auriculiformis,* and *Acacia crassicarpa* showed a capacity to transfer Pb and Cd, making them phytoextracting plants. Even if Cr and Zn were accumulated by the plants, they remained mainly stored in the roots. Therefore, *Acacia mangium* and *Acacia auriculiformis* could be classified as phytostabilizing plants for Zn. *Acacia crassicarpa* also had a phytostabilizing capacity for Cr.

Table 3. Heavy metal (Pb, Cd, Cr and Zn) contents in shoot and root biomass (mg/kg) and total biomass (mg/plant) of *Acacia mangium*, *Acacia auriculiformis* and *Acacia crassicarpa*. BA: above-ground biomass; BR: root biomass; BT: total biomass

	Heavy metal content								
	A. mangium			*A. auriculiformis*			*A. crassicarpa*		
	BA (mg/kg)	BR (mg/kg)	BT (µg/plant)	BA (mg/kg)	BR (mg/kg)	BT (µg/plant)	BA (mg/kg)	BR (mg/kg)	BT (µg/plant)
Pb	48.3	23.8	96	51.8	23.8	111	52.5	27.3	24
Cd	23.1	11.9	47	24.5	11.2	54	24.5	13.3	11
Cr	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	70	14
Zn	<LOD	<LOD	<LOD	<LOD	70	57	<LOD	427	83

Table 4. Calculated bioaccumulation factors and translocation factors of Pb, Cd, Cr and Zn from *Acacia mangium*, *Acacia auriculiformis,* and *Acacia crassicarpa.*

Acacia species	Heavy metal	BF	TF
Acacia mangium	Pb	1.05	2.03
	Cd	0.37	1.94
	Cr	0.00	n.d
	Zn	0.00	n.d
Acacia auriculiformis	Pb	1.05	2.18
	Cd	0.35	2.19
	Cr	0.00	n.d
	Zn	0.25	0.00
Acacia crassicarpa	Pb	1.20	1.92
	Cd	0.42	1.84
	Cr	1.41	0.00
	Zn	1.50	0.00

n.d: not determined

4. Conclusions

The objective of this study was to evaluate the potential of three trees-legumes for the phytoremediation of soils with a high heavy metal loading in an urban landfill. The species *Acacia mangium* and *Acacia auriculiformis* showed the best growth performance and produced the highest biomass compared to *Acacia crassicarpa*. According to the results, lead and cadmium were mostly removed from above-ground biomass, while chromium and zinc remained stored only in the root biomass of *Acacia auriculiformis* and *Acacia crassicarpa*. In view of the performances presented, *Acacia crassicarpa* would be the best species for the phytoremediation of polluted soils compared to *Acacia mangium* and *Acacia auriculiformis*. *Acacia crassicarpa* has the capacity to lower soil pH and a versatile capacity to remove Pb, Cd, Cr, and Zn, mainly in its root part; it can be recommended for use in phytoremediation studies of soils polluted with heavy metals.

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