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Phytoremediation Efficiency of Arsenic from Contaminated Soil by *Ricinus communis* and *Aloe barbadensis*

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ABSTRACT

This study investigated the phytoremediation efficiency of the plants *Aloe barbadensis* and *Ricinus communis* for the removal of arsenic (As) from contaminated soil. The experiment was conducted in a Completely Randomized Block Design (CRBD) to assess arsenic (As) uptake across plant parts and residual soil after four weeks of exposure to 200, 600, and 1000 mg As treatments. Atomic Absorption Spectrophotometry (AAS) was utilized to determine Arsenic accumulation and concentration. Both plant species exhibited dose-dependent accumulation, with *A. barbadensis* showing significantly higher root uptake (606.51 ± 1.88 mg kg^{-1} at 1000 mg) compared to *R. communis* (393.46 ± 3.09 mg kg^{-1}). Total arsenic removal efficiencies reached 89.7% for A. barbadensis and 76.5% for R. communis, confirming arsenic removal from contaminated soils. However, the uptake efficiency was found to decline slightly at higher As concentrations. Statistical analysis revealed significant differences ($p < 0.001$) between species, tissues, and treatment levels. The findings indicated that *A. barbadensis* is an excellent phytostabilizer of arsenic and recommend its use for eco-friendly remediation of As-polluted soils.

INTRODUCTION

Phytoremediation is a cost-effective and environmentally sustainable strategy for As remediation [1]. The practical application of this technique depends heavily on the uptake efficiency, stress tolerance, and adaptability of the plant species to their local conditions [2]. Although some plant species, such as Pteris vittata, have been documented for their high arsenic (As) extraction from contaminated soil [3], there is a growing interest in alternative species for application in environments where extreme conditions or co-contamination hinder the efficacy of traditional hyperaccumulators. *R. communis* have shown resistance to heavy metals in contaminated mine tailings, with effective arsenic accumulation by the roots and minimal translocation to aerial tissues [4,5]. The translocation factors below 0.25 reported for this plant, along with the high root retention point, indicate significant rhizospheric interactions. Its phytoremediation mechanisms indicate tolerance, the production of exudation enzymes, and the activation of stress-responsive genes [4,6,7]. As a native shrub, it has been co-planted with hyperaccumulators to achieve synergy and enhance As extraction from contaminated soil [8,3]. At the same time, *A.barbadensis* has exhibited moderate As accumulation in arid or erosion-prone environments [9].

The growth exhibited by the plant for 6-9 months in heavy metal-contaminated soil depicts high tolerance to heavy metal contamination [10]. However, limited translocation of As from its root to the shoot system limits its detoxification efficiency. Despite the rising interest in phytoremediation of heavy metals,

studies have not compared the arsenic (As) potentials of *R. communis* and *A. barbadensis*. The integration of adaptation through high biomass production [11] and the stabilization of heavy metals by plants can complement their phytoremediation role in the cleanup process. However, further research is pertinent to clarify the accumulation and removal efficiency of various parts, as well as dispersion within the shoot system for evaporation, given the limited research on the use of non-native plant species for reclaiming contaminated soils in Nigeria, particularly in Gombe State, which has endured significant heavy metal pollution. This study aims to evaluate the As phytoremediation efficiency of *R. communis* and *A. barbadensis*.

MATERIALS AND METHODS

Study Area

The study was conducted at the Botanical Garden of Gombe State University, situated in Tudun Wada, Shamaki Ward, Gombe State, Nigeria. Geographically, the location is positioned at approximately 10.30° N (10° 18′ 16″) and 11.17° E (11° 10′ 32″). This site offers an ideal environment for evaluating the phytoremediation potential in natural settings that resemble those found in Nigeria's semi-arid regions.

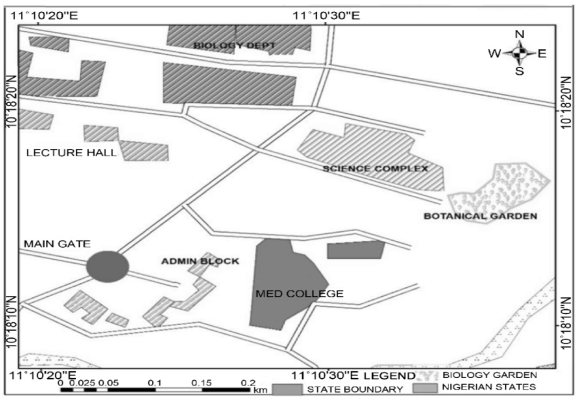

Fig. 1. Map of Gombe State University showing the study area (Botanical Garden).

Research Design

The study was conducted to evaluate the phytoremediation efficiency of Aloe barbadensis and Ricinus communis in removing arsenic (As) from contaminated soil. A Completely Randomized Block Design (CRBD) was adopted. This is to minimize environmental and sampling bias while evaluating As uptake in various plant organs and residual soil fractions. This design facilitates a robust statistical comparison among experimental groups and allows for equal treatment exposure [2,12].

Plant Materials

Two plant species, *Aloe barbadensis* (Aloe vera) and *Ricinus communis* (castor bean), which have established heavy metal tolerance and remediation potential, were selected. *R. communis* demonstrates high biomass production and efficient uptake of arsenic and other toxic metals [4,6]. *A. barbadensis* is known for its ability to stabilize and bioaccumulate trace metals under arid soil conditions [9,10]. Both plants exhibit strong rhizosphere adaptation. This makes them suitable candidates for phytoextraction and phytostabilization [13,14].

Sample Collection

Soil samples were collected from the Gombe State University Botanical Garden at a depth of 0–15 cm. This depth represents the active root zone, where arsenic bioavailability is highest [15, . Five-week-old healthy seedlings of *A. barbadensis* and *R. communis* were randomly obtained from the same nursery to ensure uniform genetic and physiological conditions. All samples were homogenized and air-dried at ambient temperature before use.

Phytoremediation Experiment

The homogenized soil was divided into three treatment subsets per plant species, and each subset was spiked with an arsenic trioxide (As_2O_3) solution to achieve nominal concentrations of 200, 600, and 1,000 mg As/kg soil, representing low, medium, and high contamination levels, respectively [8,17]. The treated soil was aged for seven days to equilibrate metal adsorption. Two kilograms of each contaminated soil subset were transferred into perforated plastic pots (n = 3 per treatment) and planted with one seedling per pot. Control pots contained uncontaminated soil of identical composition. All pots were monitored for four weeks and maintained under natural light, with water applied every two days to maintain a 70% field capacity (**Figs. 2** to **4**). These conditions were used to simulate realistic phytoremediation scenarios in tropical soils [17,18].

Digestion and Determination of Arsenic Concentration

After the exposure period, the plants were harvested, and roots, stems, and leaves were carefully separated, washed, and oven-dried at 60 °C. Dried tissues were ground into fine powder using a clean agate mortar and pestle. Arsenic quantification followed the AOAC Official Method 2016.06 [19]. One gram of each sample was digested with a 3:1 mixture of nitric and perchloric acids in a 100 mL beaker, heated to 50 °C for 15 minutes with constant stirring, and filtered into a 50 mL volumetric flask with distilled water. Soil samples were digested under the same conditions. The total As concentrations in plant tissues and soils were determined using Atomic Absorption Spectrophotometry (AAS) [20,21]. Quality control included reagent blanks and triplicate analyses to ensure precision and accuracy.

Data Analysis

The data obtained were statistically analyzed using two-way Analysis of Variance (ANOVA) to evaluate the effects of arsenic concentration and plant species on As accumulation across tissues and soil. Mean values, standard deviations, and percentage removal efficiencies were computed, and differences were considered significant at $p \leq 0.05$ [1,22]. The bioaccumulation factor (BAF) and translocation factor (TF) were derived to classify the phytoremediation mechanism as either phytoextraction or phytostabilization [23,24].

RESULTS

Determination of As in Soil before and after Treatment

The concentrations of arsenic (As) in soil samples before and after phytoremediation with *Aloe barbadensis* and *Ricinus communis* are presented in **Table 1**. The background As concentrations in uncontaminated soil were low, measuring 0.83 ± 0.01 mg/kg for *A. barbadensis* and 0.72 ± 0.03 mg/kg for *R. communis*. Following artificial contamination, soil arsenic (As) levels increased proportionally with the treatment concentration, confirming successful spiking. After the four-week phytoremediation period, substantial reductions in soil As were observed for both species. For *A. barbadensis*, the residual As concentrations in soil were 14.25 ± 0.32, 39.73 ± 0.47, and 103.77 ± 1.14 mg/kg at 200, 600, and 1000 mg As treatments, corresponding to removal efficiencies of 92.9%, 93.4%, and 89.6%, respectively. Similarly, in soils planted with *R. communis*, residual As concentrations were 19.39 ± 0.36, 63.21

± 0.51, and 225.65 ± 2.25 mg/kg, representing removal efficiencies of 90.3%, 89.5%, and 77.4%, respectively.

Table 1. As concentration in the soil before and after phytoremediation.

Soil / Plant species	As Treatment (mg/Kg)	As concentration residual in soil (mg/kg, mean ± SD)	As removal (%)
Before and after phytoremediation with *R. communis*	Control	0.72 ± 0.03	0.00
	200	19.39 ± 0.36	90.3
	600	63.21 ± 0.51	89.5
	1000	225.65 ± 2.25	77.4
Before and after phytoremediation with *A. barbadensis*	Control	0.83 ± 0.01	0.00
	200	14.25 ± 0.32	92.9
	600	39.73 ± 0.47	93.4
	1000	103.77 ± 1.14	89.6

Accumulation and Removal of As by *A. barbadensis*

The results of As accumulation and removal efficiency following the treatment of various parts of *A. barbadensis* and the surrounding soil are presented in **Table 2**.

The data indicate an increase in As in the leaves with treatment concentrations ranging from 52.79 mg/kg at 200 mg to 289.94 mg/kg at 1000 mg. The roots showed a significantly higher As accumulation (606.51 mg/kg) at the 1000 mg treatment level. In contrast, the soil showed a lower As accumulation (96.61 mg/kg) at the highest treatment level. While the roots showed the highest removal efficiency of 0.61% at a 1000 mg treatment, a 0.45% removal efficiency was maximally detected for leaves at a 200 mg treatment.

Furthermore, the soil removal efficiency remained relatively low across all treatment levels, indicating limited effectiveness in As removal compared with the plant parts. Statistical analysis revealed significant differences ($P < 0.001$) in both As accumulation and removal efficiency, as well as interactions between plant roots and soil following treatment.

Table 2. Accumulation and removal of As by *A. barbadensis* and soil after treatment.

As in plant parts	As accumulation in (mg/kg)				As removal (%)			
	Control	200	600	1000	Control	200	600	1000
Leaf	0.00 ± 0.00^{h}	52.79 ± 0.36^{fg}	166.35 ± 1.12^{d}	289.94 ± 1.69^{c}	0.00 ± 0.00^{e}	26.4	27.7	29.0
Root	0.00 ± 0.00^{h}	122.18 ± 2.12^{e}	386.80 ± 2.44^{b}	606.51 ± 1.88^{a}	0.00 ± 0.00^{e}	61.1	64.5	60.7
Soil	0.83 ± 0.01^{h}	21.26 ± 1.47^{g}	41.59 ± 1.70^{fg}	96.61 ± 3.37^{e}	0.00 ± 0.00^{e}	10.6	6.9	9.7

Key; a, b, c, d, e, f, g, and h represent significant differences($p < 0.001$) between treatments. Same letters indicate no significant difference, while different letters indicate significant differences.

Table 3. Accumulation and removal of As by *R. communis* and soil after treatment.

As in plant parts	As accumulation in (mg/kg)				As removal (%)			
	Control	200	600	1000	Control	200	600	1000
Leaf	0.00 ± 0.00^{h}	22.50 ± 0.91^{g}	86.83 ± 2.58^{e}	135.84 ± 2.53^{d}	0.00 ± 0.00^{f}	11.3	14.5	13.6
Root	0.00 ± 0.00^{h}	95.95 ± 2.62^{ef}	259.96 ± 3.38^{ab}	393.46 ± 3.09^{a}	0.00 ± 0.00^{f}	48.0	43.3	39.3
Stem	0.00 ± 0.00^{h}	46.38 ± 1.08^{f}	178.75 ± 0.79^{c}	223.94 ± 3.13^{b}	0.00 ± 0.00^{f}	23.2	29.8	22.4
Soil	0.72 ± 0.03^{h}	30.29 ± 0.36^{g}	66.30 ± 1.41^{ef}	234.35 ± 3.66^{b}	0.00 ± 0.00^{f}	15.1	11.1	23.4
Mean	104.82				0.1			
STD	113.31				0.09			

Key; a, b, c, d, e, f, g, and h represent significant differences ($p < 0.001$) between treatments. Same letters indicate no significant difference, while different letters indicate significant differences.

Table 4. Effect of As accumulation and % removal by different parts of *A. barbadensis* and *R. communis* on plants.

As in plant parts	Treatment of *A barbadensis* with As in (mg)				Treatment of *R. communis* with As in (mg)			
	200	600	1000	Control	200	600	1000	Control
Leaf	52.79 ± 0.36^{fg}	166.35 ± 1.12^{d}	289.94 ± 1.69^{c}	0.00 ± 0.00^{h}	22.50 ± 0.91^{g}	86.83 ± 2.58^{e}	135.84 ± 2.53^{d}	0.00 ± 0.00^{h}
Root	122.18 ± 2.12^{e}	386.80 ± 2.44^{b}	606.51 ± 1.88^{a}	0.00 ± 0.00^{h}	95.95 ± 2.62^{ef}	259.96 ± 3.38^{ab}	393.46 ± 3.09^{a}	0.00 ± 0.00^{h}
Stem	-	-	-	-	46.38 ± 1.08^{f}	178.75 ± 0.79^{c}	223.94 ± 3.13^{b}	0.00 ± 0.00^{h}
Soil	21.26 ± 1.47^{g}	41.59 ± 1.70^{fg}	96.61 ± 3.37^{e}	0.83 ± 0.01^{h}	30.29 ± 0.36^{g}	66.30 ± 1.41^{ef}	234.35 ± 3.66^{b}	0.72 ± 0.03^{h}

Key; a, b, c, d, e, f, g, and h represent significant differences ($p < 0.001$) in Arsenic removal between *A. barbadensis* and *R. communis* plants

Fig. 2. (A) Photographs showing 5 week seedlings of *A. barbadensis* and (B) *R. communis* before treatment with varying As concentrations

Fig. 3. A photograph showing *R. communis* after 4 weeks of treatment with different concentrations of As and a control.

Fig. 4. A photograph showing *A. barbadensis* after 4 weeks treatment with varying As concentrations and a control.

Accumulation and Removal As by *R. communis*

The results of arsenic (As) accumulation and removal efficiency for different parts of *R. communis* and the surrounding soil are presented in **Table 3**. Arsenic accumulation increased progressively with treatment concentration across all plant parts. In the leaves, As ranged from 22.50 ± 0.91 mg kg^{-1} at the 200 mg treatment to 135.84 ± 2.53 mg kg^{-1} at the 1000 mg treatment. The roots exhibited the highest accumulation, increasing from 95.95 ± 2.62 mg kg^{-1} at 200 mg to 393.46 ± 3.09 mg kg^{-1} at 1000 mg. The stems displayed intermediate accumulation levels, reaching 223.94 ± 3.13 mg kg^{-1} at the highest treatment. Residual As concentrations in the surrounding soil remained lower than in plant tissues, with 30.29 ± 0.36, 66.30 ± 1.41, and 234.35 ± 3.66 mg kg^{-1} for the 200, 600, and 1000 mg treatments, respectively. The corresponding removal efficiencies were 11.3–13.6% for leaves, 48.0–39.3% for roots, and 23.2–22.4% for stems, indicating that the roots were the principal As sink—residual soil As accounted for 15.1–23.4 % of the initial concentration.

Effect of As accumulation and removal by *A. barbadensis* and *R. communis*

The comparative results of arsenic (As) accumulation and removal efficiency in *A. barbadensis* and *R. communis* after treatment are presented in **Table 4**. Arsenic accumulation increased consistently with treatment concentration across both plant species. In *A. barbadensis*, the roots accumulated the highest As concentrations of 122.18 ± 2.12, 386.80 ± 2.44, and 606.51 ± 1.88 mg kg^{-1} at 200, 600, and 1000 mg treatments, respectively, while leaves recorded 52.79 ± 0.36, 166.35 ± 1.12, and 289.94 ± 1.69 mg kg^{-1}. Similarly, *R. communis* exhibited substantial accumulation in its roots, reaching 95.95 ± 2.62, 259.96 ± 3.38, and 393.46 ± 3.09 mg kg^{-1} at the same respective treatments. The stems showed intermediate values (46.38 ± 1.08, 178.75 ± 0.79, and 223.94 ± 3.13 mg kg^{-1}), while leaves accumulated 22.50 ± 0.91, 86.83 ± 2.58, and 135.84 ± 2.53 mg kg^{-1}.

At the 1000 mg treatment, *A. barbadensis* roots accumulated significantly more As (606.51 ± 1.88 mg kg^{-1}) than *R. communis* roots (393.46 ± 3.09 mg kg^{-1}), demonstrating a higher As absorption capacity ($p < 0.05$). The results show that *A. barbadensis* has a stronger ability for As uptake and phytostabilization compared with *R. communis*. Residual As concentrations in the soil after treatment were lower for *A. barbadensis* (96.61 ± 3.37 mg kg^{-1}) than for *R. communis* (234.35 ± 3.66 mg kg^{-1}) at the 1000 mg treatment, showing that *A. barbadensis* achieved more effective soil As depletion.

DISCUSSION

The increasing contamination with heavy metals has raised environmental concerns due to the substantial damage they cause to humans and ecosystems. Plants are an eco-friendly and cost-effective tool for the remediation of heavy metals [24]. However, their effectiveness in the process depends on the uptake efficiency.

As Availability in Soil before and after Phytoremediation

The increasing trend of As and significant disparity between the pre- and post-treatment levels of *A. barbadensis* and *R. communis* following phytoremediation suggest that the soil was contaminated beforehand. This result is consistent with the finding of Maslin and Maier [20], who reported that the degradation of organic compounds in highly contaminated soil hinders the efficiency of the plant species in the phytoremediation process. Our results also align with the findings of Kuo [15], which comment on the impact of contamination level on bioavailability for rapid phytoremediation. The high mobility of anthropogenic metals observed in the soil, as opposed to pedogenic or lithogenic metals, underscores the need for effective phytoremediation strategies.

As Accumulation by *A. barbadensis* and *R. communis*

A. barbadensis root and leaf demonstrated high tolerance and the ability to grow in soils with varying levels of As. However, the plant failed to transfer a substantial amount of As to the aerial tissues for further evaporation. The remarkable accumulation by the roots compared to other parts is consistent with the findings of Elhag et al. [10] that showed higher accumulation of As, but didn't indicate which part of the plant absorbed the heavy metal. Although higher organic matter, sulphur, and iron concentrations in soil have been reported to influence the reduction of heavy metal uptake ability [17], an increased accumulation of As was also observed in the roots of *Pennisetum purpureum* [18]. Thus, low soil acidity might be linked to the high As accumulation recorded by the roots of these plants in this study. Moreover, the rapid movement of As(III) and As(V) into plant roots, aided by various transporters, has been previously reported in research [16,25]. This suggests that the abundance of nontoxic As species and plant resistance are key to the rapid absorption of As by plant roots from contaminated soil.

Additionally, the rapid absorption of As was enhanced by stress-reducing enzymes and proteins that act on the transporters of plasma cells. These enzymes neutralize acidic As species before they are sequestered into the plant's vacuole where it is undergoes metabolism breakdown [12,17,26]. Similarly, *R. communis* also indicates greater As accumulation in the roots than in the leaves and stem of the plant. The plant has been recognized for its ability to absorb heavy metals, such as DDT, Zn, Pb, and Cd, due to its rapid growth in various polluted environments [1,13,24]. The high accumulation efficiency of the plants in this study could be attributed to their high affinity and selective absorption of arsenic through membrane tissues.

As removal Potential of *A. barbadensis* and *R. communis*

The As removal efficiency observed for *A. barbadensis* in this study is higher than that of *R. communis,* with significant absorption found in the root system. This finding underscores the superior phytoremediation potential of A. *barbadensis* over *R. communis*. These remarkable As discharges by both plants are higher than 0.25%, previously reported for R. *communis* [24], indicating increased efficiency of the plants. This might be linked to the complexity of As species in the two experimental soils and differences in heavy metal tolerance of the plants [27]. Despite the significant accumulation and removal of As demonstrated in this study, the plants did not absorb more than 1,000 mg/kg and remove 1.0% As, which is the standard for hyperaccumulators [23]. The As retained within the root zones led to slow movement

of As to the leaves and stems. The limited translocation suggests phytostabilization of As by the plants [14,21]. The observed slow translocation corroborates the findings of Karle et al. [22], who attributed the increase in tonoplast protein levels to the root vacuole. These proteins reduce the availability of As for transport to the plant's aerial tissues.

CONCLUSION

This study demonstrates the ability of *Aloe barbadensis* and *Ricinus communis* to phytoremediate arsenic-contaminated soils. The results found significant differences in their accumulation capacities. *A. barbadensis* exhibited greater arsenic uptake and retention, particularly in its roots, achieving up to 606.51 mg kg^{-1} accumulation and over 89% total removal efficiency, indicating a dominant phytostabilization mechanism. *R. communis* also accumulated considerable amounts, with maximum root concentrations of 393.46 mg kg^{-1} and total removal efficiencies above 76%. The residual arsenic levels in soils were lower in pots containing *A. barbadensis*, confirming its superior extraction efficiency. Overall, the arsenic removal efficiency decreased slightly at higher contamination levels, suggesting a limitation in uptake under elevated toxicity. These findings highlight *A. barbadensis* as a more effective and sustainable species for phytoremediation of arsenic-contaminated environments, while *R. communis* remains a valuable complementary plant due to its robust growth and tolerance to metal stress.

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