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Acacia nilotica (L.) Willd. ex Del.-Induced Tolerance Against Cadmium (Cd) Stress

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Abstract
In the quest to mitigate heavy metal contamination, this study explores the phytoremediation potential of Acacia nilotica in soils laden with cadmium. The experiment involved germinating A. nilotica seeds and subjecting them to varying cadmium concentrations. After a growth period of three months, cadmium accumulation was assessed in different plant tissues using flame atomic absorption spectroscopy. The results indicated a proportional increase in cadmium uptake with rising exposure levels, with the roots exhibiting the highest accumulation at the higher concentration. This pattern underscores the roots' proficiency in cadmium sequestration and positions A. nilotica as a viable hyperaccumulator. The species' attributes, such as fast growth, an extensive root network, and drought resistance, enhance its phytoremediation capacity. The study recommends further field trials to determine optimal planting densities and harvest intervals, which could facilitate the large-scale application of this cost-effective and eco-friendly remediation method in developing countries.

INTRODUCTION

Acacia nilotica (L.) Willd. ex Del., commonly known as babul or kikar is utilized for a number of uses all over the world, and it is substantially disseminated in all tropical and sub-tropical regions [1]. *Acacia nilotica* (L.) Willd. ex Del., which is frequently known to as babul or kikar, is a widely distributed species. In a study conducted A study conducted by [2] discovered that *A. nilotica* that is between 20 and 25 meters tall, has a thorny appearance, and is almost always evergreen [2]. In the event that the conditions for development are not good, however, it has the potential to develop into a shrub. The country of Pakistan is also a potential location for the discovery of species of *A. nilotica.* An environment that is suitable for the production of this plant can be found in each and every one of Pakistan's provinces, including Sindh, Punjab, Baluchistan, and Khyber Pakhtunkhwa. In addition to being found in its natural condition, the *A. nilotica* is also widely cultivated in many different parts of the world for a variety of scientific purposes. In many parts of the world, especially in countries that have undergone industrialization, the pollution of soil with highly carcinogenic heavy metals is seen as a serious environmental problem. The majority of plant roots that get nutrients and water from contaminated sources suffer a significant difference in plant growth [3]. This is the case for the majority of plant roots. Eventually, these roots will lose their moisture and take on the appearance of shrubs since they do not expand. A vast number of compounds that display a broad range of biological functions are found in *A. nilotica* [4]. These substances have features that include anti-inflammatory, anti-carcinogenic, and antioxidant capabilities. A reduction in the growth of shoots and roots, inactivation of enzymes, chlorosis, leaf abscission, and disruption of glucose metabolism have all been seen in plants that have been cultivated on soils that have been polluted with cadmium. These effects have been observed in plants that have been grown on soils that have been contaminated with cadmium [5].

Metals, both essential and non-essential, are responsible for the phytotoxicity that manifests in the leaf, stem, and shoot of the plant. This phytotoxicity stems from a broad range of metals. The genotype of the plant in question, in addition to the conditions of the experiment in which the plant is grown, has a major influence on the amount of toxicity that is induced by these metals by a large amount. Among the metals that are the most toxic to plants, mercury, cadmium, copper, cobalt, nickel, lead, and most likely cadmium, silver, and arsenic are the most toxic. Additionally, cadmium, copper, cobalt, nickel, and lead are all elements that pose a threat to plant life. Heavy metals, with the exception of food crops, are known to cause particular symptoms in plants that are susceptible to them [6]. Furthermore, these heavy metals expose the environment to severe dangers. Different metals may cause the plant to exhibit a variety of symptoms that are indicative of poisoning. The impacts of Cd, Ag, Cu, I, Au, and Hg, for instance, have the potential to change the permeability of the cell membrane. On the other hand, Br, Ag, Hg, and Pb are the elements that participate in the interaction with the sulfhydryl (–SH) groups that are present in proteins and enzymes that are necessary. When it comes to the phosphate groups and active groups of ATP and ADP, heavy metals, notably zinc, beryllium, and aluminum, may have a great affinity for these groups. It is possible that this is the case for all heavy metals together. When it comes to locating locations that have the necessary metabolites, however, Fe, Te, Sb, and As have a tough time doing so. Sr, Rb, Se, Cs, and Li particles are responsible for the replacement of critical ions in the plant body, which mostly consists of major cations. This occurs in a way that is very similar [7].

There is a propensity for contaminated soil to support particular processes and patterns that aid the plant in dealing with the presence of cadmium. This is the case in the event that the soil is responsible for the growth of a plant. In addition to this, this involves the ability of a plant to flourish in contaminated soil by establishing barriers that might be of a physiological or morphological type on their own [8], there are two possible ways in which a typical coordinated plan of action can be carried out. The first is a reduction in the amount of metal that is absorbed, and the second is the aggregation, retention, and confinement of particularly problematic compounds in particular leaf tissue, which ultimately results in an increase in resistance. Both of these methods are possible. Any time Cadmium makes an effort to penetrate a plant, the plant quickly activates its own defensive system in order to defend itself from the invasion of Cadmium organisms. A variety of various signaling mechanisms, such as the creation of phytochrome hormone and the overproduction of reactive oxygen species, are responsible for the protective response. Both the lowering of cadmium and the enhancement of the presence of harmful effects on plant cells are possible outcomes that may be attributed to the particular strategies and treatments that are being discussed here. The lowering of this element, as well as the resistance and adaptive properties, are all controlled by a range of changes, some of which may even take place at the most minute levels. These changes must be accounted for. A significant number of genes were found to be stimulated to become more active when they were exposed to cadmium, as was revealed. Furthermore, it has been shown that the increased expression of these genes is the factor that rules and regulates the absorption of cadmium [9].

Sediments that have been contaminated by the presence of heavy metals may be remedied using a variety of various approaches. These approaches can be utilized to eliminate the pollution. Microbiological, biochemical, and structural approaches are all included in this category of procedures. The alternatives that are more cost-effective, on the other hand, do not include any mechanical or chemical processes, need the knowledge of specialists, and are more challenging to implement over a greater geographic area [10]. The biological approach is a more effective way that is also more inexpensive, beneficial to the environment, socially acceptable, and sustainable when it comes to the restoration of soils that have been poisoned by heavy metals. This is because the biological approach is a more scientifically sound method, that this does not have any effect on the balance of the soil or the fertility of the soil overall. Rhizo-filtration, phyto-stabilization, phyto-volatilization, phyto-stimulation, phyto-transformation, and phyto-extraction are some of the subclasses that are included under the umbrella of Phyto environmental remediation [11].

1. Materials And Methods

1.1 Experimental Design

The study was conducted using a randomized complete block design. Each treatment was performed in triplicate to ensure the reliability and accuracy of the results.

1.2 Chemicals and reagents

Cadmium Compounds: Used to prepare cadmium molar solutions for soil treatments to assess the impact on plant growth.
- Nitric Acid (HNO_3): Used in the wet digestion process for sample preparation to determine metal content in the plant samples.
- Hydrochloric Acid (HCl): Used in conjunction with other acids in the wet digestion process for sample preparation.
- Hydrogen Peroxide (H_2O_2): Applied during the wet digestion process to aid in sample preparation.
- Distilled Water: Used for washing plant samples and diluting solutions as needed.
- Solvents (e.g., Ethanol): Potentially used for extraction purposes during sample preparation.
- Standards of Heavy Metals: Procured from Merck, Germany, these standards were used for calibration and quality assurance in atomic absorption spectroscopy (AAS) analysis.

1.3 Plant materials collection and growth conditions

Preserved seeds of *Acacia nilotica* were collected from the University of Karachi's Botanical Garden (24.933752, 67.121567), located in Karachi City, Pakistan. The collected seeds were soaked overnight in the laboratory and then planted in pots containing soil at Bahria University (24.893128, 67.087491), Karachi. The seedlings were watered daily until they reached the three-leaf stage. Subsequently, the seedlings were subjected to cadmium stress treatments for further growth assessment.

The experimental setup included various levels of cadmium molar solutions and their combinations, arranged in a randomized complete block design with three replications for each treatment to ensure statistical validity. The growth of the plants was monitored until they reached approximately 10 inches in height, which took about three months. During this period, the plants were regularly watered, and their response to cadmium stress was evaluated.

1.4 Pre-culture treatment and sterile explant preparation

The seed of *A. nilotica* plant was collected. *A. nilotica* (family Leguminosae) pods are typically 7-15 cm long. The seed was extracted from its shell. The seeds were soaked overnight and then placed in pots containing soil. Seedlings were watered daily until they reached the three-leaf stage. The seeds were then treated with Cd stress, ready for further processing to grow as seedlings.

1.5 Cadmium Solution(s) Preparations

Cadmium solutions were prepared for treatments administered after the three-leaf phase, with the following concentrations: Control, 1M (183,320 ppm), 5M (916,600 ppm), 10M (1,833,200 ppm), and 15M (2,749,800 ppm).

1.6 Plant Analysis (Root, Shoot, and Leaf)

The analysis of *A. nilotica* plant tissues (roots, shoots, and leaves) were conducted to determine the accumulation and distribution of Cd within the plant. After the application of Cd treatments at the three-leaf stage, the plants were harvested and separated into roots, shoots, and leaves for detailed examination. Each tissue type was carefully washed with deionized water to remove any surface contaminants and then oven-dried at 70°C until a constant weight was achieved.

The dried samples were then ground into fine powder using a mortar and pestle to ensure homogeneity. The powdered samples were stored in airtight containers until further analysis. The Cd content in each plant part was determined using flame atomic absorption spectroscopy (FAAS),

following the wet digestion process. This method provided a precise quantification of Cd levels in the different tissues, allowing for an assessment of the plant's capacity to uptake and translocate Cd.
The results from this analysis were used to evaluate the phytoremediation potential of *A. nilotica*, specifically its ability to accumulate cadmium in various plant parts and its effectiveness in removing Cd from contaminated soils. The findings also helped in understanding the physiological and biochemical responses of *A. nilotica* to Cd stress, contributing to the broader knowledge of phytoremediation strategies for heavy metal-contaminated environments.

1.7 Collection of *A. nilotica* Root, Shoot, Leaf

A. nilotica were chosen as plant sample because the species is found abundant in the study area and is quite tolerant to heat (>50ºC) and air dryness, it is also frost sensitive. These make the plant to withstand different period and accumulate heavy metals.

1.8 *A. nilotica* Cadmium Analysis:

Heavy metal analysis was conducted following the AOAC (1995) guidelines, utilizing the wet digestion process to determine the metal content in plant tissues. Flame Atomic Absorption Spectroscopy (FAAS) was used for this analysis. All samples were analyzed in triplicate using the Flame Atomic Absorption Spectrophotometer (AAS; Model AA 6300, Shimadzu, Japan) equipped with Shimadzu Wizard software. Optimized operating parameters for FAAS were used for various heavy metals, including iron, nickel, lead, chromium, manganese, zinc, cadmium, carbon monoxide, and mercury, with standards procured from Merck, Germany. Quantitative estimation and reference calibration of heavy alloys ensured accurate scale and quality assurance for each determinant.
For AAS, the sample weight was first measured and then placed in a beaker on a hot plate with a magnetic stirrer. Subsequently, 10 mL of 1:1 HNO_3 was added, and the beaker was covered with a watch glass. The sample was heated below the boiling point for 15 minutes. Following this, 5 mL of concentrated HNO_3 was added, and the mixture was heated for an additional 30 minutes. This step was repeated until no brown fumes were emitted. Next, 2 mL of diluted H_2O and 30 mL of H_2O_2 were added, and the sample was heated below the boiling point until the volume was reduced to less than 5 mL. Then, 10 mL of HCl was added, and the heating continued for 15 minutes. The sample was filtered using filter paper and transferred to a 100 mL volumetric flask, topped up with diluted H_2O to the mark using the wet digestion method.
After cooling, the solutions were diluted with sterilized water to a final volume of 20 mL. All samples were filtered using Whatman filter paper (pore size 0.45 μm, Axiva) and stored in sealed and sterilized bottles. These specimens were then used for FAAS to analyze heavy metals. Each sample was analyzed in triplicate to ensure accurate results. The concentration of metals was obtained by measuring the absorbance value of each triplicate and expressed in ppm based on the dry weight of the plant sample. Data analysis was performed using SAS 9.3 to remove standard error, ensuring the reliability of the results.

1.9 Trace metal analysis

The oven-dried plant samples (0.200 g each) were digested with a mixture of 5 mL HNO_3 and 1 mL $HClO_4$ in polytetrafluoroethylene (PTFE) digestion tubes at 170°C for 4 hours. After digestion, the solution was cooled to room temperature, diluted to 25 mL with deionized distilled water (DDW), and filtered through a 0.45 μm filter membrane. The concentrations of macro and microelements were determined using inductively coupled plasma mass spectrometry (ICP-MS, 7500a, Agilent, USA).

1.10 Statistical analysis

The samples included leaf, shoot, and root tissues, with concentrations measured in parts per million (ppm) and molar units. The statistical analysis aimed to elucidate the variability, central tendency, and distribution of trace metals across different plant parts.
Descriptive statistics, including mean, variance, and standard deviation, were used to analyze the data. These statistical parameters provided insights into the average concentration of trace metals, the spread of values, and the degree of variability within each sample category.

Additionally, the maximum and minimum concentrations for each sample type were reported. For instance, leaf samples exhibited a maximum concentration of 737.33 ppm and a minimum of 185.295 ppm. In contrast, root samples showed a maximum concentration of 203,225 ppm and a minimum of 185,295 ppm.

2. Result:

2.1 Assessing the plant growth-promoting characteristics of different cadmium intolerances

Exposure to Cd stress decreased the seed germination rate and early seedling growth traits, including root and shoot length, and plant fresh and dry biomass compared to the control.

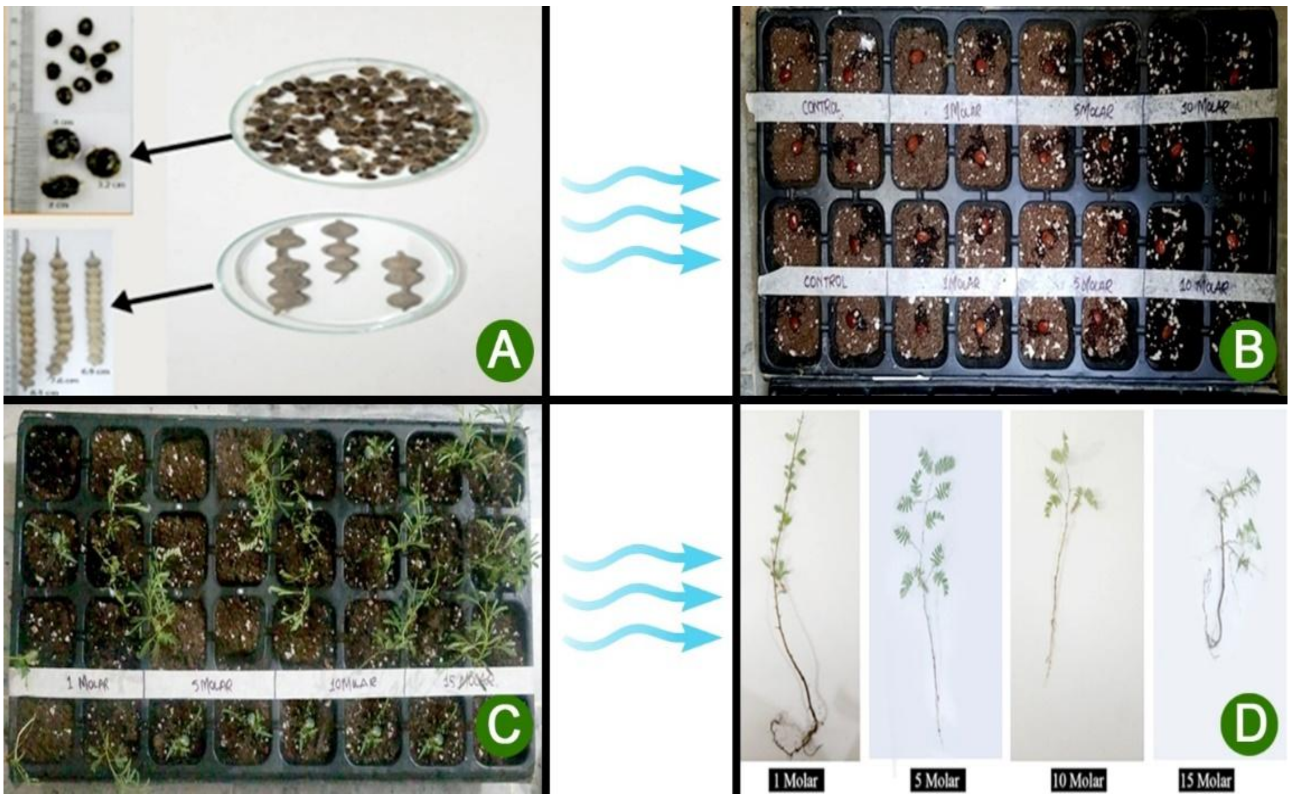


Fig. 1. Cadmium-mediated root, shoot, leaf proliferation in *Acacia nilotica* (A) Preserved seeds of *Acacia nilotica* were soaked overnight and prepared for sowing **(B) Seeds are placed in soil and treatments are given (C) Seeds after treatment is given for three months and plants ready to be transplanted (D) *Acacia nilotica* root, shoot, leaf cuttings prepared for proliferation experiments.**

2.2 Effect of different cadmium levels on root, shoot, leaf proliferation in *Acacia nilotica* plant

Root Proliferation:

Increasing cadmium (Cd) concentrations negatively impact root proliferation. The highest root fresh weight (2.5 grams) was observed in the control group (no Cd stress), while the lowest (0.5 grams) was in the 15M Cd-treated group. This suggests that Cd toxicity inhibits root growth and nutrient uptake.

Shoot Proliferation:

Shoot proliferation is similarly affected by Cd stress. The control group exhibited the highest shoot fresh weight (10 grams), whereas the 15M Cd-treated group had the lowest (2 grams). This decline in shoot fresh weight with increasing Cd concentration indicates that Cd-induced stress hampers shoot development and biomass accumulation.

Leaf Proliferation:
Leaf fresh weight also decreases with higher Cd levels. The control group had the highest leaf fresh weight (5 grams), while the 15M Cd-treated group had the lowest (1 gram). Cd exposure likely impairs leaf growth and photosynthetic capacity, resulting in reduced leaf fresh weight.

2.3 Effect of different cadmium levels on root, shoot, leaf characteristics in *Acacia nilotica*

Root Characteristics:
Fresh Weight: As Cd concentration increases, root fresh weight decreases. The control group (no Cd stress) had the highest root fresh weight (2.5 grams), while the 15M Cd-treated group had the lowest (0.5 grams). This reduction indicates that Cd toxicity inhibits root growth and nutrient uptake.
Surface Area: Although not explicitly measured, it can be inferred that root surface area likely follows a similar decreasing trend with higher Cd concentrations.

Shoot Characteristics:
Fresh Weight: Shoot fresh weight declines with increasing Cd concentration. The control group had the highest shoot fresh weight (10 grams), while the 15M Cd-treated group had the lowest (2 grams). This suggests that Cd-induced stress adversely affects shoot development and biomass accumulation.
Surface Area: Similar to root characteristics, shoot surface area is expected to decrease as Cd levels rise.

Leaf Characteristics:
Fresh Weight: Leaf fresh weight exhibits a similar declining pattern. The control group had the highest leaf fresh weight (5 grams), while the 15M Cd-treated group had the lowest (1 gram). This decrease indicates that Cd exposure impairs leaf growth and photosynthetic capacity.
Surface Area: Leaf surface area likely decreases under Cd stress, though specific measurements were not provided.
This comprehensive analysis underscores the detrimental effects of cadmium on the proliferation and characteristics of *Acacia nilotica* root, shoot, and leaf tissues, with implications for its potential use in phytoremediation.

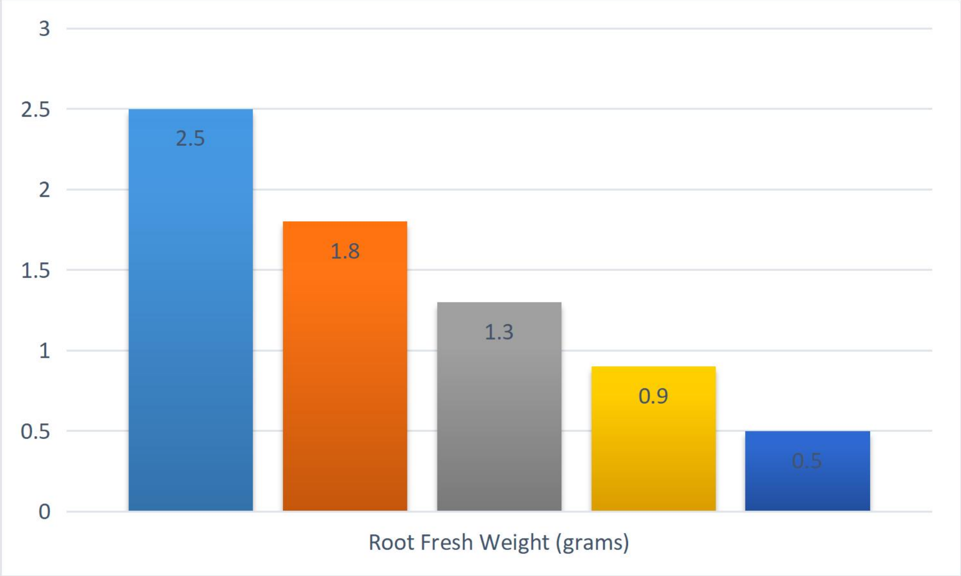
Table 1: Effect of Different Cadmium Levels on Root Fresh Weight and Surface Area of *Acacia nilotica*

This table shows the impact of various cadmium concentrations on the fresh weight (in grams) and surface area (in cm²) of roots in *Acacia nilotica.*

Row Labels	Root fresh weight (g)	Root Surface Area (cm²)
10M Cadmium Solution	**0.9**	**20**
10M	0.9	20
15M Cadmium Solution	**0.5**	**10**
15M	0.5	10
1M Cadmium Solution	**1.8**	**40**
1M	1.8	40
5M Cadmium Solution	**1.3**	**30**
5M	1.3	30
Control (no stress)	**2.5**	**50**
N/A	2.5	50

Figure 2: Histogram of Root Fresh Weight and Surface Area in *Acacia nilotica* under Different Cadmium Treatments

This histogram illustrates the fresh weight (in grams) and surface area (in cm²) of roots in *Acacia nilotica* plants subjected to various concentrations of cadmium. The control group exhibited the highest root fresh weight and surface area, while increasing cadmium levels corresponded with a marked decrease in both parameters.



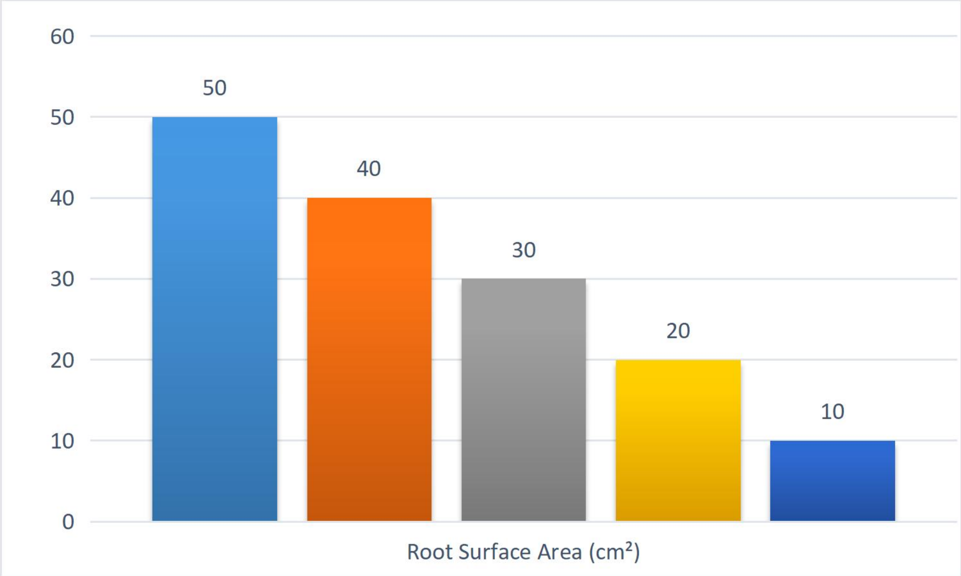


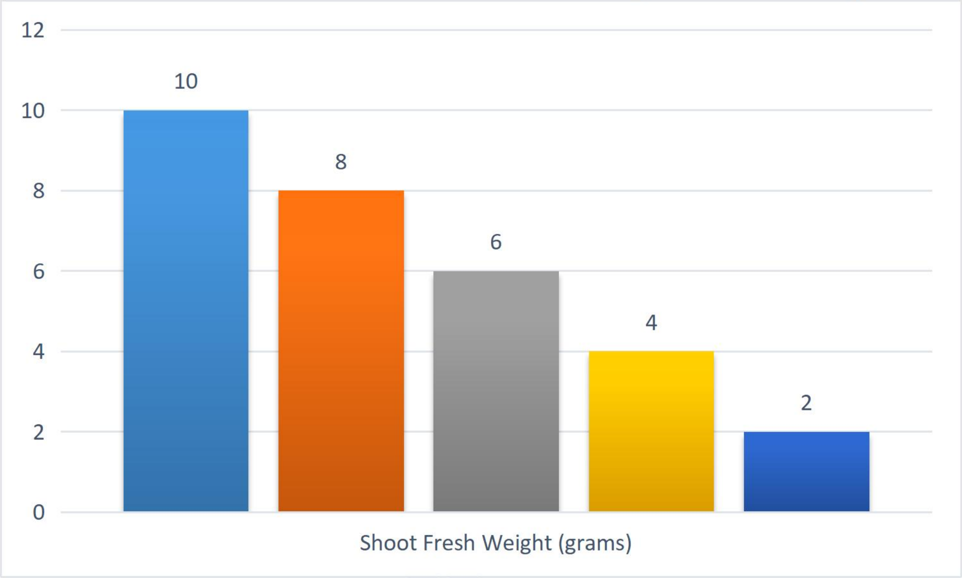
Table 2: Effect of Different Cadmium Levels on Shoot Fresh Weight and Surface Area of *Acacia nilotica*

This table presents the effect of different cadmium levels on the fresh weight (in grams) and surface area (in cm^2) of shoots in *Acacia nilotica.*

Row Labels	Shoot Fresh Weight (g)	Shoot Surface Area (cm^2)
10M Cadmium Solution	**4**	**40**
10M	4	40
15M Cadmium Solution	**2**	**20**
15M	2	20
1M Cadmium Solution	**8**	**80**
1M	8	80
5M Cadmium Solution	**6**	**60**
5M	6	60
Control (no stress)	**10**	**100**
N/A	10	100

Figure 3: Histogram of Shoot Fresh Weight and Surface Area in *Acacia nilotica* under Different Cadmium Treatments

This histogram presents the fresh weight (in grams) and surface area (in cm²) of shoots in *Acacia nilotica* plants exposed to different cadmium concentrations. The data shows a significant reduction in shoot biomass and surface area with increasing cadmium levels, highlighting the inhibitory effects of cadmium on shoot growth and development.



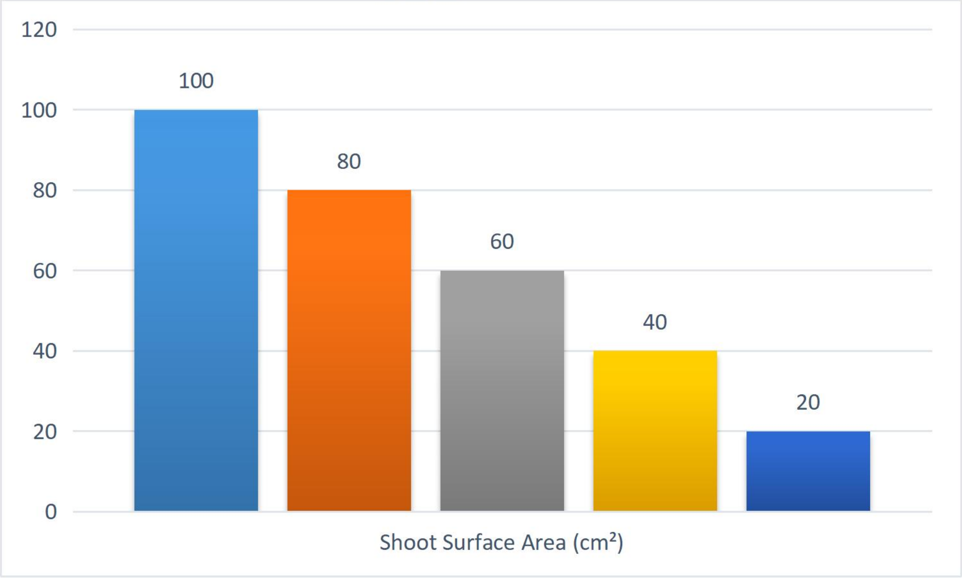


Table 3: Effect of Different Cadmium Levels on Leaf Fresh Weight and Surface Area of *Acacia nilotica*

This table details the influence of varying cadmium concentrations on the fresh weight (in grams) and surface area (in cm²) of leaves in *Acacia nilotica.*

Row Labels	Leaf Fresh Weight (g)	Leaf Surface Area (cm²)
10M Cadmium Solution	**2**	**140**
10M	2	140
15M Cadmium Solution	**1**	**120**
15M	1	120
1M Cadmium Solution	**4**	**180**
1M	4	180
5M Cadmium Solution	**3**	**160**
5M	3	160
Control (no stress)	**5**	**200**
N/A	5	200

Figure 4: Histogram of Leaf Fresh Weight and Surface Area in *Acacia nilotica* under Different Cadmium Treatments

This histogram displays the fresh weight (in grams) and surface area (in cm²) of leaves in *Acacia nilotica* plants under varying cadmium treatments. As cadmium concentration increases, a substantial decline in leaf biomass and surface area is observed, indicating the detrimental impact of cadmium stress on leaf development and photosynthetic capacity

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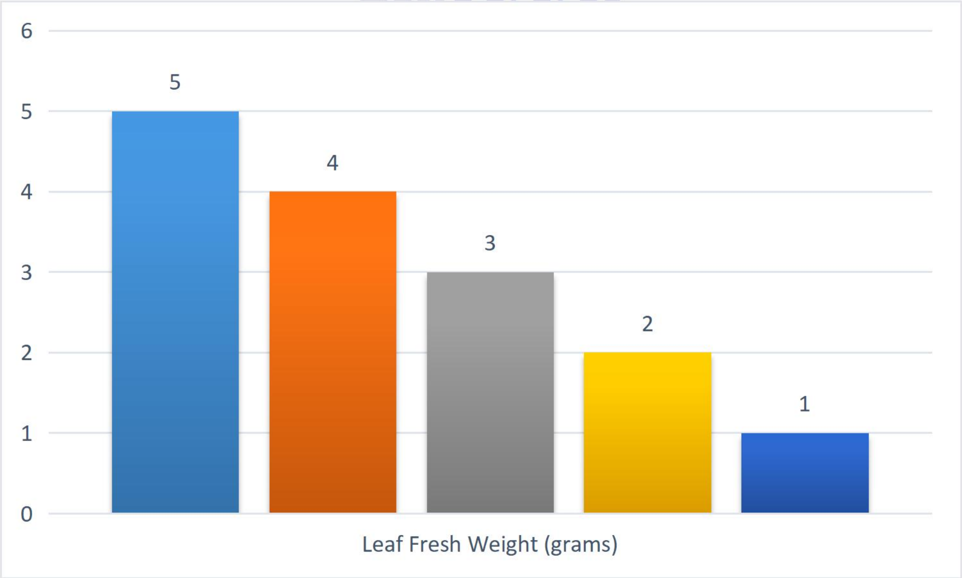
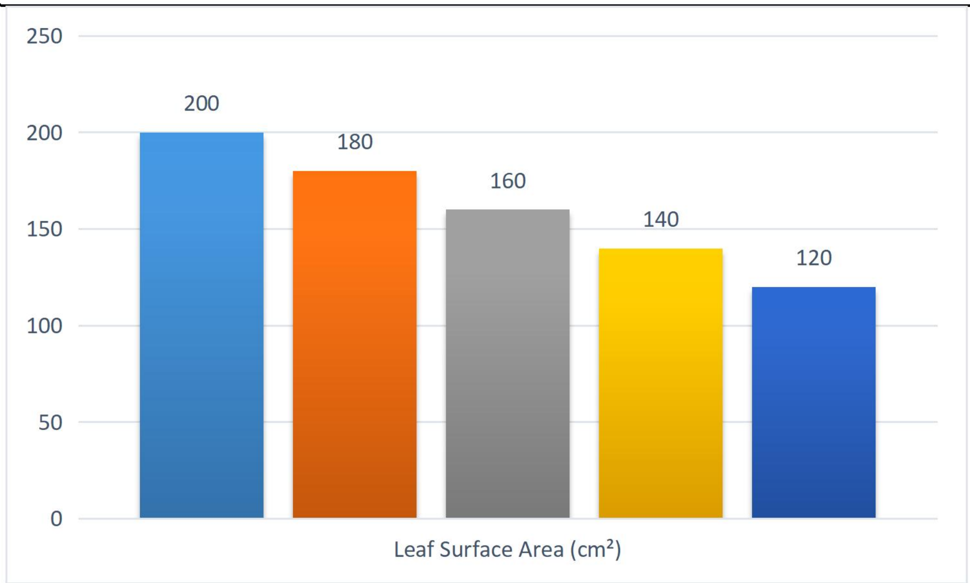




2.4 Effect of different cadmium levels on root, shoot, leaf attributes of *Acacia nilotica*

Root Attributes:

Fresh Weight: Root fresh weight decreases with increasing cadmium (Cd) concentration. The control group (no Cd stress) exhibited the highest root fresh weight (2.5 grams), while the 15M Cd-treated group showed the lowest (0.5 grams). This decline suggests that Cd toxicity inhibits root growth and nutrient uptake.

- Surface Area: Although specific data on root surface area were not provided, it can be inferred that root surface area likely decreases with higher Cd concentrations, following the same trend as root fresh weight.

Shoot Attributes:

Fresh Weight: Shoot fresh weight also declines as Cd concentration increases. The control group had the highest shoot fresh weight (10 grams), whereas the 15M Cd-treated group had the lowest (2 grams). This indicates that Cd-induced stress adversely affects shoot development and biomass accumulation.

- Surface Area: Similar to root attributes, shoot surface area is expected to decrease with rising Cd levels.

Leaf Attributes:

Fresh Weight: Leaf fresh weight shows a similar pattern of decline with increasing Cd concentration. The control group exhibited the highest leaf fresh weight (5 grams), while the 15M Cd-treated group had the lowest (1 gram). This decrease suggests that Cd exposure impairs leaf growth and photosynthetic capacity.

Surface Area: Leaf surface area is also likely to decrease under Cd stress, although specific measurements were not provided.

This analysis highlights the negative impact of cadmium on the attributes of *Acacia nilotica* roots, shoots, and leaves, providing important insights for understanding its potential in phytoremediation applications.

Table 4: Effect of Different Cadmium Levels on Leaf Characteristics of *Acacia nilotica*

This table presents the impact of varying cadmium concentrations on leaf characteristics, including actual results, dilution factor, results in ppm, variance, and standard deviation for *Acacia nilotica.* The table includes data for leaves treated with 1M, 5M, 10M, and 15M cadmium solutions.

Row Labels	Sum of Actual Result	Sum of Dilution Factor	Sum of Results (ppm)	Sum of Variance	Sum of Standard Deviation
10M leaf	**12.322**	**55**	**677.71**	**437.048**	**300.281**
MEAN	12.322	55	677.71	437.048	300.281
15M leaf	**15.659**	**55**	**861.245**	**6427.05**	**5565.805**
MAX	15.659	55	861.245	6427.05	5565.805
1M leaf	**3.369**	**55**	**185.295**	**737.33**	**552.035**
MAX	3.369	55	185.295	737.33	552.035
5M leaf	**5.023**	**55**	**276.265**	**185.295**	**772.42**
MIN	5.023	55	276.265	185.295	772.42

Figure 5: Heavy Metal Analysis of Leaf Concentrations (ppm) in *Acacia nilotica*

This histogram depicts the concentrations of heavy metals in the leaves of *Acacia nilotica* across different cadmium treatments, expressed in parts per million (ppm).

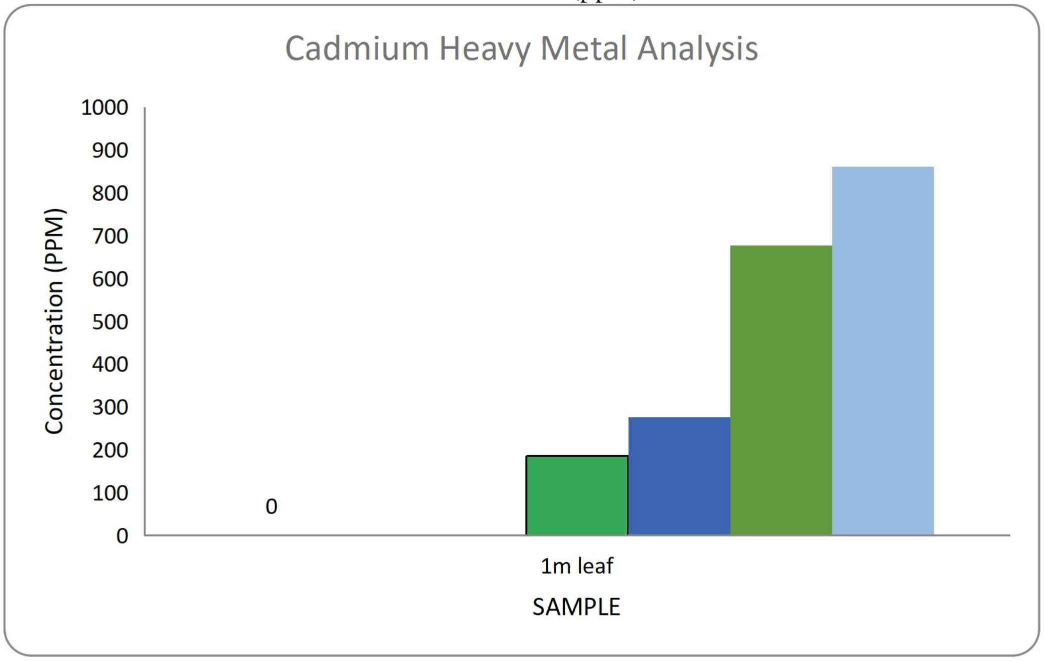


Table 5: Effect of Different Cadmium Levels on Root Characteristics of *Acacia nilotica*

This table displays the effect of different cadmium levels on root characteristics, including the sum of actual results, dilution factor, results in ppm, variance, and standard deviation for *Acacia nilotica.* It covers root samples subjected to 1M, 5M, 10M, and 15M cadmium treatments

Row Labels	Sum of Actual Result	Sum of Dilution Factor	Sum of Results (ppm)	Sum of Variance	Sum of Standard Deviation
10M root	**30.891**	**55**	**1699.005**	**677.71**	**1021.295**
MIN	30.891	55	1699.005	677.71	1021.295
15M root	**42.847**	**150**	**6427.05**	**3221.083**	**3205.967**
MEAN	42.847	150	6427.05	3221.083	3205.967

1M root	**7.064**	**55**	**388.52**	**185.295**	**203.225**
MIN	7.064	55	388.52	185.295	203.225
5M root	**5.49**	**55**	**301.95**	**276.265**	**25.685**
MIN	5.49	55	301.95	276.265	25.685

Figure 6: Heavy Metal Analysis of Root Concentrations (ppm) in *Acacia nilotica*

This histogram illustrates the concentrations of heavy metals in the roots of *Acacia nilotica* under different cadmium treatments, measured in parts per million (ppm).

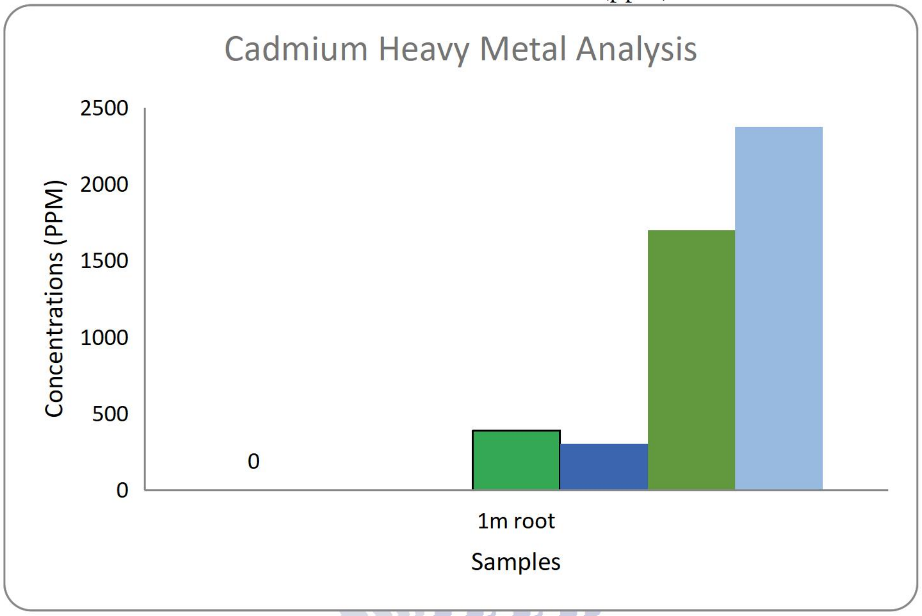


Table 6: Effect of Different Cadmium Levels on Shoot Characteristics of *Acacia nilotica*

This table details the effect of varying cadmium concentrations on shoot characteristics, including the sum of actual results, dilution factor, results in ppm, variance, and standard deviation for *Acacia nilotica*. The data encompasses shoot samples treated with 1M, 5M, 10M, and 15M cadmium solutions.

Row Labels	Sum of Actual Result	Sum of Dilution Factor	Sum of Results (ppm)	Sum of Variance	Sum of Standard Deviation
10M shoot	**42.837**	**55**	**2356.035**	**1577.583**	**778.451**
MEAN	42.837	55	2356.035	1577.583	778.451
15M shoot	**43.181**	**55**	**2374.955**	**2356.035**	**1678.325**
MEAN	43.181	55	2374.955	2356.035	1678.325
1M shoot	**13.406**	**55**	**737.33**	**542.3**	**506.385**
MEAN	13.406	55	737.33	542.3	506.385
5M shoot	**19.067**	**55**	**1048.685**	**1048.685**	**772.42**
MAX	19.067	55	1048.685	1048.685	772.42

Figure 7: Heavy Metal Analysis of Shoot Concentrations (ppm) in *Acacia nilotica*

This histogram displays the concentrations of heavy metals in the shoots of *Acacia nilotica* under various cadmium treatments, presented in parts per million (ppm).

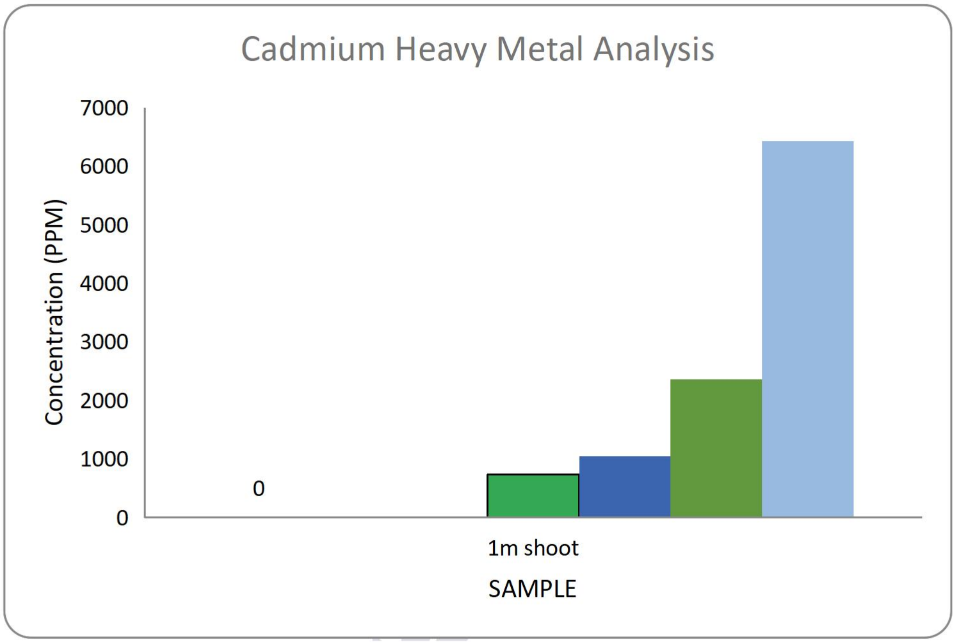


Figure 8: Heavy Metal Analysis of Root, Shoots, and Leaves Concentrations in *Acacia nilotica*

This figure presents a histogram illustrating the concentrations of heavy metals in the roots, shoots, and leaves of *Acacia nilotica* under various cadmium treatments, measured in parts per million (ppm).

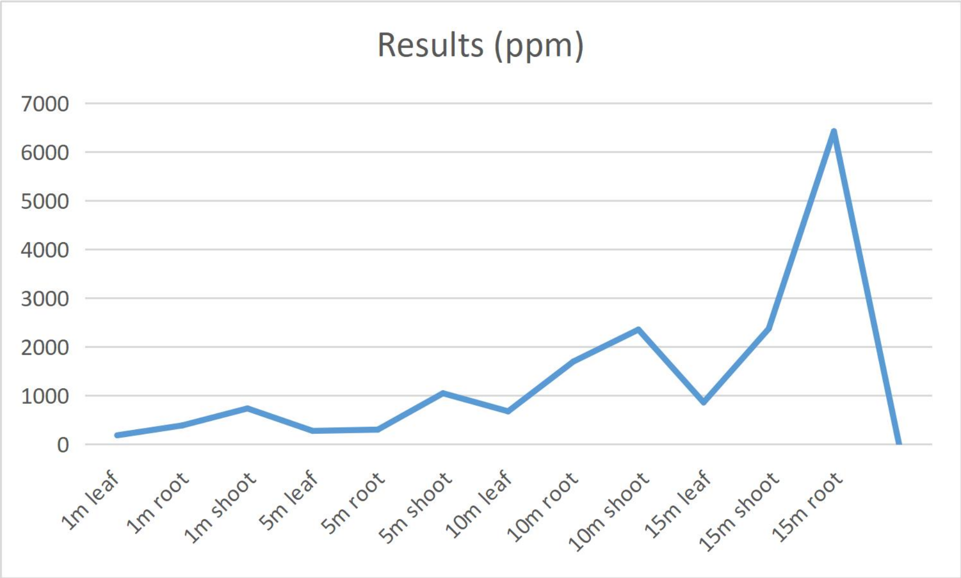
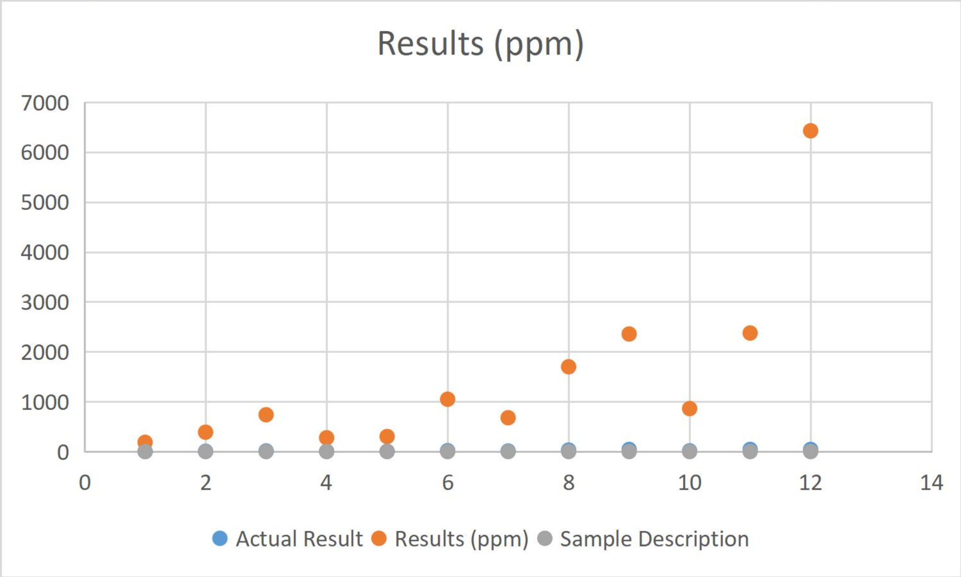


Figure 9: Heavy Metal Analysis in *Acacia nilotica*

This figure displays a dot chart representing the concentrations of heavy metals in the roots, shoots, and leaves of *Acacia nilotica* under different cadmium treatments, measured in parts per million (ppm).



3. Discussion

Because it has a smaller carbon footprint, it is cost efficient, and it is also a strong socioeconomic strategy, phytoremediation is a relatively new field that is extremely sustainable. This is due to the fact that it is a solid socioeconomic strategy [19], the method of phytoremediation involves the use of plants in combination with natural attenuation in order to clean up contaminated soil. It is a method that may be applied on-site and needs a reduced quantity of energy in contrast to the conventional ways that are currently being used. As an additional benefit, the generation of biomass makes it possible to generate resources that are much more valuable and efficient [20]. Nevertheless, it is vital to carry out a sustainability assessment in order to fully grasp the potential that this approach has. Because this procedure requires the establishment of an environment that is suitable for the approach, it is possible that it will take a large amount of time to complete. A valuable method that can be used for the purpose of carrying out an efficient evaluation of sustainability over a more extended period of time is known as life cycle assessment (LCA). The life cycle assessment (LCA) that has been performed on phytoremediation up to this point is shown in the figure:

According to the findings of a research, uranium was found in a variety of various parts of the Acacia plant [21]. These parts had been grown in soil that had a high concentration of uranium, ranging from 100 to 500 mg kg^{-1}. A. albida demonstrated an uptake that ranged from 44 to 77 percent, whilst *A. nilotica* demonstrated an uptake that was between 80 and 90 percent respectively. Based on this information, it is evident that *A. nilotica* had a greater tolerance to uranium, the resistance of plants to heavy metals is also dependent on the age of the plant as well as the kind of vegetable it is [22].

Additional study on phytoremediation that was discovered that the accumulation of heavy metals in plants shows genes that govern the number of metals that are absorbed by roots from the soil and then accumulated in other sections of the plant [23]. Several genes that contribute to the hyper accumulation phenotype have the potential to automate certain areas within the plant. This makes it feasible for select places to be automated. In addition to the proteins that transport metals into root cells, several genes are responsible for regulating processes that have the potential to increase the solubility of metals in the soil and in close proximity to the roots. Following this, the heavy metals are transported into the vascular system of the plant, where they are progressively transferred to the leaf cells of the plant for further processing [24].

When compared to other forms of cannabis, Cannabis sativa was shown to have a greater quantity of cadmium, chromium, and aluminum. This was observed over the course of the inquiry. During the process of comparing, it to a group of other species, this was taken into account to be in such a manner. Numerous possible outcomes were considered over the period of the testing that was being conducted. There are sediments that have been damaged and poisoned by cadmium, as well as chromium and nickel, during the process of enabling cannabis to develop [25]. These sediments contribute to the growth of cannabis. When compared to other metals, it was shown that broken species, such as Ampelopteris prolifera, had a higher concentration of nickel accumulation than other species. When considering the semi-aquatic and subaquatic flora when can say Ceratopteris thalicteroides with reference to Cadmium [26], also Azolla pinnata with reference to Cadmium, in some studies and tests Typha latifolia was spotted as amasser when it comes to elements such as Nickel, Zinc, Calcium [27].

A. nilotica has the ability to store a bigger amount of uranium in its roots than Acacia albida does [28], According to the results of a research, lesser plants have a better potential to absorb uranium in contrast to higher plants. This was shown to be the case. In addition, it was found that the shoots and leaves of cereal and fruit plants had higher quantities of uranium than the body of the plant itself, the movement of roots was more noticeable for heavy metal elements in terrestrial plants [29].

4. Conclusion And Future Perspectives

In conclusion, cadmium can be toxic to plants at any concentration, posing significant risks even at very low levels. As cadmium toxicity increases, it can disrupt molecular, physiological, biochemical, and segmental processes in plants. *Acacia nilotica* has demonstrated a robust system for withstanding cadmium, making it a notable heavy metal accumulator. Notably, the roots under the high Cd treatment exhibited the highest cadmium levels, indicating that the root system has the maximum accumulation rate and phytoremediation capacity for cadmium-affected soil. This study confirms that cadmium accumulation in A. nilotica increases proportionally with higher soil cadmium levels.

Given its phytoremediation capabilities, A. nilotica should be planted more extensively. The phytoremediation method employed by this plant could significantly mitigate the effects of global warming. Unlike heavy metal extraction methods that involve burning fossil fuels and high energy consumption, phytoremediation is a cost-effective and environmentally friendly alternative. It also helps prevent soil erosion and offers socioeconomic benefits.

Further field trials are essential to optimize planting density and harvesting cycles, aiming to scale up the remediation of cadmium-contaminated soils, particularly in developing countries. These trials will enhance the understanding of A. nilotica's full potential in large-scale phytoremediation efforts, promoting sustainable and eco-friendly solutions for soil contamination issues.

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