RESEARCH ARTICLE

Evaluation of Phytoremediation Potential of Some Invasive Plant Species Near an Ash Disposal Site

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Abstract

The present study focused on evaluating the heavy metal accumulation potential of invasive plant species growing near an ash disposal site of Talcher thermal power station Odisha, India (20°54′37″N 85°12′24″E). A total number of 8 invasive plant species (weeds) were collected and screened for heavy metal (Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, and Pb) accumulation. Results showed that the fly ash was slightly acidic (pH -6.8) with a high concentration of Fe (10133 mg kg^{-1} dw) while the concentrations of Mn and Cu were 72 and 51 mg kg^{-1}, respectively. The bioaccumulation of heavy metals varied in various plant species. The maximum level of Fe (988 mg kg^{-1}) and Ni (11 mg kg^{-1}) was found in *Solanum nigrum* and *Euphorbia prostrata*, respectively. *Ageratum conyzoides* was the most efficient plant for metal accumulation from FA-contaminated sites among all species. In contrast, the highest translocation factor value was found in *L. camara* for most metals among all plants. In general, the concentration of heavy metals was higher in shoots than in roots for most of the plants, which means that these plant species can be used for phytoextraction of heavy metals, thus helping in the phytoremediation of fly ash-contaminated soil.

Keywords: Invasive plant species, Fly-ash, Heavy metal, Bioaccumulation, Phytoremediation.

Highlights

- The most efficient plants for metal accumulation were *A. paronychioides* and *A. conyzoides*.
- Due to its high TF values*, L. camara* can be utilized as a phytoextractor of metals.
- Invasive plant species may offer a better solution for the remediation and restoration of metal-polluted land.

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Introduction

Millions of tons of fly ash (FA) are generated per annum from thermal power plants (TPPs) after coal burning in TPPs. Due to an increase in the population, the electricity demand is rising resulting in the number of TPPs also increasing. In India, coal-based TPPs are the main source of electricity therefore FA disposal is a major environmental issue. The ash content of Indian coal is high (Dwivedi *et al*., 2008); it causes serious disposal and ecological problems and harms a large number of agricultural and non-agricultural crops. Fly ash dumps may also adversely affect the environment by dispersing fine particles and hazardous constituents contaminating soil, water, air and vegetation (Sikka and Kansal, 1995). FA consists of small glass particles and their deposition on plant leaves prevents proper evaporation and photosynthesis (Gupta *et al*., 2002). Fly ash is a composition of Ferro aluminium silicate minerals containing many essential elements such as sulfur (S), boron (B), calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), zinc (Zn), manganese (Mn) and phosphorus (P), the presence of some desired macro and micronutrients and their porosity make it an excellent soil amendment for plant growth and development (Ahmad *et al*., 2021) but also has some toxic metals such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), and lead (Pb) (Carlson and Adriano, 1993). Mahender *et al.,* (2019) reviewed and reported that the iron content in soil varies depending on the type and depth, ranging from 0.2 to 55% (20,000–550,000 mg kg^{-1}). For example, in Indian soil, the total iron content ranges between 0.4 to 27.3% (40,000–273,000 mg kg^{-1}). Accumulation of iron in plants above 400 mg kg^{-1} is considered toxic. These metals accumulate in crops and affect human health through food consumption. However, in recent times, the utilization rate of FA has increased for various purposes (cement, mine filling, making of bricks and tiles, in roads and flyovers, etc.) (Rastogi and Paul, 2020). The Indian government has also taken new initiatives for FA utilization, e.g., Pradhan Mantri Awas Yojana (Urban) has focused on new construction technologies using FA bricks that are innovative and environmentally friendly (Press Information Bureau, 2023). However, these activities utilize only a limited proportion of FA and the huge amount of FA remains unutilized. Therefore, there is a need to remove heavy metals from this unutilized dumped FA. In this context, phytoremediation is a well-known cost-effective green technology than other physical or chemical processes to remediate FA-polluted areas as well as restore for beneficial purposes (Lone *et al*., 2008). In this technology, plants remove toxic elements from polluted

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sites by accumulating in shoots or immobilizing metals in soil or sediments through root uptake, adsorption onto roots, or precipitation in the rhizosphere. Therefore, the only feasible and environmentally friendly option for managing FA is to employ plants with FA-tolerant vegetation in landfills, which promotes stability and greenery (Rai *et al*., 2004; Pandey *et al*., 2009).

Several different terrestrial heavy metal tolerant plants are reported *Croton bonplandianum*, *Cassia tora*, *Cannabis sativa*, and *Saccharum munja* (Kumari *et al*., 2016). Similarly, the metal-accumulating potential of several aquatic plants - *Hydrilla verticillata*, *Ipomea aquatica, Marsilia quadrifolia*, *Typha latifolia*, and *Azolla pinnata* has been reported (Dwivedi et *al*., 2008; Kumari *et al*., 2016; Pandey *et al*., 2024). Some naturally occurring weeds (*Achyranthus aspera*, *Blumea lacera*, *Borrhevia repens*) and grasses (*Cynodon dactylon* belonging to the Poaceae family) can quickly populate at landfills and have also been proposed to revegetate abandoned FA dumps (Maiti and Nadhani, 2006).

Therefore, the present study focused on evaluating heavy metal contamination levels in vegetation along with the metal accumulation potential of invasive plant species (Weeds) growing in the surroundings of contaminated sites to use them for both phytoremediation and ecological restoration of FA dumps.

Material and methods

Study site

The present study was conducted near Talcher thermal power station in the Talcher, district Angul, Odisha, India (20°54′37″N 85°12′24″E) and the power plant has a total installed capacity of 460 MW. In this power plant, all units are coal-fired; coal for the power station is supplied by Jagannath mines of Mahanadi Coalfields Limited and water for the plant is supplied from the Brahmani River. The power plant produces approximately 1.2 million tons of FA per annum.

Collection and analysis of fly ash sample

The FA-contaminated soil samples were collected from study site (20°56′216″ N 85°08′251″ E), which was about 50 to 80 m away from the ash dyke and samples were homogenized on blotting paper at the study site to make a composite sample. The soil samples were collected in polythene bags and brought to the laboratory. First, the samples were dried at room temperature and then oven-dried at 70°C for 72 hours after that, samples were grounded and sieved for further analysis of pH, electrical conductivity (EC), total organic carbon, and heavy metals. The pH and EC meter measured the pH and EC of fly ash; however, total organic carbon was estimated by Walkley and Black's (1934) method.

Collection of plant samples and their identification

A total number of 8 different types of terrestrial invasive plant species (IPS) belonging to different families were collected from the nearby FA disposal sites (Table 1). Plant samples were kept in plastic bags and brought to the laboratory for heavy metal analysis. A healthy plant set was pressed in a plant press using typical herbarium preparation techniques (Jain & Rao, 1977). After bringing it to the laboratory, the plant specimens were identified using standard taxonomic floras and existing regional monographs/revisions and other authentic specimens deposited at the herbarium of CSIR- National Botanical Research Institute, Lucknow, India.

Preparation and estimation of heavy metals in plant and soil samples

First, plant samples were washed with tap water then double distilled water to remove the sticking fly ash particles. Plant samples were air-dried and then oven-dried at 80ºC for 72 hours and then divided into plant parts (root, stem and leaves). The dried samples of plants are cut into small pieces for digestion, following the protocol (Dwivedi *et al*., 2010), with slight modifications. All samples were acid-digested with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) in the ratio of 3:1, respectively, on a hot plate. While, for the estimation of heavy metals in soil, the analysis was performed after sieving of soil dried samples were taken (0.2 g) digestion was done on the hotplate in HNO_3: HF (3:1), respectively. After the complete digestion, Milli-Q water was added, left overnight, filtered in 10 mL vol, and stored at 4ºC until the estimation. The following heavy metals chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd) and lead (Pb) were estimated through an inductively coupled plasma mass spectrometer (ICP-MS, Model: 7500cx, Agilent). The blank was also run at the time of heavy metal analysis.

Calculation of bioaccumulation and translocation factor

To assess the phytoremediation potential of the metal, we calculated the bioaccumulation factor (BAF) and translocation

Table 1: Invasive plant species belonging to different families and their life cycle collected from fly ash contaminated soil near thermal power plant

S. No.	*Botanical name*	*Family*	*Plant form*	*Life cycle*
1	*Ageratum conyzoides* L.	Asteraceae	Weed	Annual
2	*Alternanthera paronychioides* A. St.-Hil.	Amaranthaceae	Weed	Perennial
3	*Calotropis procera* (Aiton) W.T. Aiton	Apocynaceae	Weed	Perennial
4	*Euphorbia prostrata* Aiton	Euphorbiaceae	Weed	Annual
5	*Lantana camara* L.	Verbenaceae	Weed	Annual or perennial
6	*Solanum nigrum* L.	Solanaceae	Weed	Annual or biennial
7	*Tephrosia purpurea* (L.) Pers.	Fabaceae	Weed	Perennial
8	*Urena lobata* L.	Malvaceae	Weed	Annual

factor (TF) as the transfer factors. The bioaccumulation factor is the ratio of the concentration of a metal in a plant to that in the FA.

Bioaccumulation factor = M_{plant} / M_{FA}

Where M_{plant} and M_{FA} represent the concentration of the metal in plant and FA, respectively.

The translocation factor is the ratio of the metal concentration in the plant shoot to the root, demonstrating the plant's ability to translocate metals. A translocation factor greater than one indicates increased metal mobility to the shoot, while a factor less than one indicates metal storage in roots (Maiti and Pandey, 2021).

Translocation factor = M_{shoot} / M_{root}

Where M_{shoot} and M_{root} represent the concentration of the metal in plant shoot and root respectively.

Statistical analysis

The data were statistically analyzed with the help of SPSS software (version 16.0) and analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT) was used to determine the significant differences between the samples ($p \leq 0.05$). All values are the means (n= 3) ± SD.

Results and Discussion

Physicochemical and heavy metal analysis in fly ash

The results of the physicochemical properties and the heavy metal content of the FA- are given in Table 2 and it showed that the pH of the FA was acidic (pH -6.8). Electrical conductivity was found 225 µs/cm with low total organic carbon content. It may be due to the high content of sulfur present in coal. Coal combustion residues exhibit varying physical and chemical characteristics that are dependent on the type of source coal, ignition or combustion conditions, emission control equipment, and storage and processing methods (Jala and Goyal, 2006). Generally, FA is found to be alkaline in nature because of the low sulfur content in coal and due to the presence of hydroxides and carbonates of calcium and magnesium (Pandey and Singh, 2010), which limits the plant growth but synergetic approach of primary succession like adequate microbial biodiversity, e.g., the activity of *Thiobacillus thioxidane* reduce its alkalinity by depositing sulfur on FA dumps. Among the elements, Fe (10133 mg kg^{-1} dw) content was the highest in fly ash, followed by Mn (72 mg kg^{-1} dw) and Cu (51 mg kg^{-1} dw). Metal content was observed in the order of Fe>Mn> Cu>Zn> Cr> Ni> Co>Pb>As in FA-contaminated soil. Although the analyzed FA samples also contain many elements essential for plant growth, which are beneficial for normal plant growth and contribute to fertile soil, they also contain many toxic heavy metals, making them a problematic solid waste hazard.

Bioaccumulation of metals in plants

A total number of eight terrestrial invasive plant species (weeds) belonging to different families and different life forms (growing locally in FA-affected areas) were selected for heavy metal analysis namely, *Ageratum conyzoides* (Asteraceae), *Alternanthera paronychioides* (Amaranthaceae), *Calotropis procera* (Apocynaceae), *Euphorbia prostrata* (Euphorbiaceae), *Lantana camara* (Verbenaceae), *Solanum nigrum* (Solanaceae), *Tephrosia purpurea* (Fabaceae) and *Urena lobata* (Malvaceae). Khan *et al*., (2023) reported in a review that invasive species are easily spread by wind, water, and insects, occupy a broad range of biological niches and have unique functional characteristics to adapt to climate variation rapidly. Additionally, invasive plants have developed various complicated defense systems to deal with the feeding threat of herbivores (Zhou *et al*., 2023). The comparative total metal accumulation efficiency of different plant species is presented in the graphs (Fig. 1 A-J). Of which some species have been found to accumulate one particular metal e.g., *L. camara* Pb (10 mg kg^{-1} dw) and *A. paronychioides* As (3.7 mg kg^{-1} dw). In general, shoots showed more metal accumulation of metals than the roots. Studied invasive species showed a wide range of metal concentration (mg kg^{-1} dw) for Cr (1.5 to 7.2), Mn (51 to 327), Fe (123 to 988), Co (0.3 to 2.0), Ni (1.2 to 11.4), Cu (6.2 to 37), Zn (16 to 115), As (0.3 to 3.7) Cd (0 to 0.3) and Pb (0 to 10). The results revealed that all weed plant species have shown greater accumulation potential toward metals and better adaptation to fly ash. A previous study reported that plants may have different distributions and dominance in FA-polluted areas depending on the plant species due to their differing metal tolerances and adaptation to FA properties (Kumari *et al*., 2016). The concentration of heavy metals in plant species is influenced by both the pH and type substrate, which determine their accumulation capability (Maiti and Jaiswal, 2008; Pandey, 2012). It has been reported that several transporter proteins have been identified in plant root cells, which aid in the absorption of essential elements (Gall and Rajakaruna, 2013). Results revealed that among the plant species, *A. conyzoides, A. paronychioides* and *S. nigrum* were found to be efficient heavy metal-tolerant plants compared to five other species *C. procera*, *E. prostrata*, *L. camara, T. purpurea* and *Urena lobata* (Fig. 1 A-J). Further, it was also found that some plant species showed more metal accumulation capability for individual metals e.g. *S. nigrum* for Fe (988 mg kg^{-1} dw), *L. camara* for Mn and Pb (327

Table 2: Physico-chemical properties and metal concentration of soil samples near Talcher TPP Odisha. (values are means±S.D.)

Parameters	*Soil*
Physico-chemical properties	
pH	6.80±0.00
EC (µS)	225.67±6.03
TOC (%)	0.40±0.02
Metals (mg kg^{-1}dw)	
Fe	10133± 351
Mn	72.07±6.51
Cu	51.51±5.85
Zn	49.20±4.52
Cr	47.87±2.47
Ni	31.23±4.12
Co	9.96±2.12
Pb	4.77±0.51
As	0.30±0.00

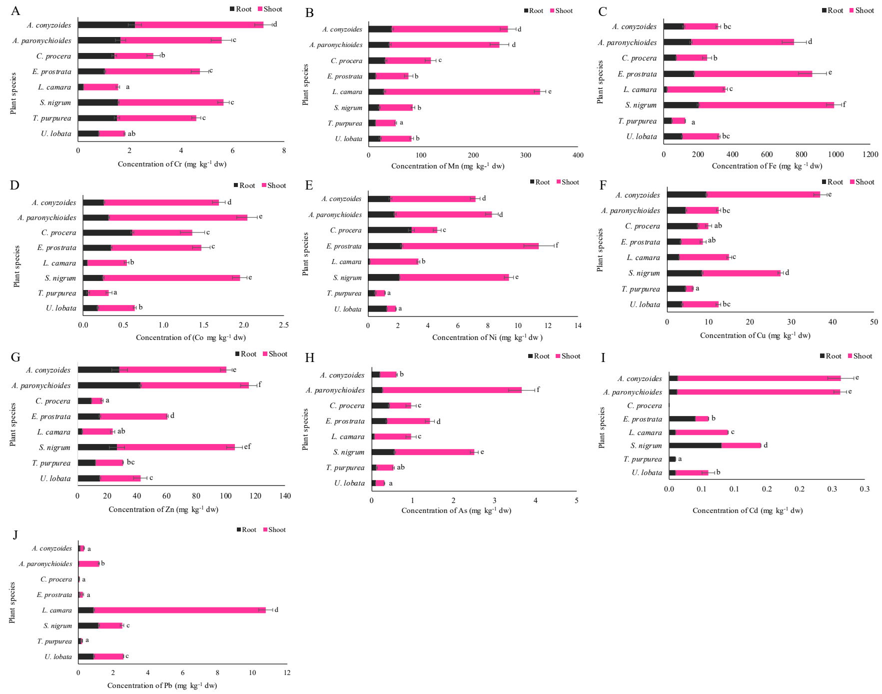

Fig. 1: Accumulation of metals (A) Cr, (B) Mn, (C) Fe, (D) Co, (E) Ni, (F) Cu, (G) Zn, (H) As, (I) Cd and (J) Pb by invasive plant species. Values are means (n= 3) ± SD; ANOVA p <0.05; Different letters denote the significant difference (p <0.05) between means in a bar according to DMRT

Table 3: Bioaccumulation factor of heavy metals in invasive plant species

Plants	*Cr*	*Mn*	*Fe*	*Co*	*Ni*	*Cu*	*Zn*	*As*	*Cd*	*Pb*
A. conyzoides	0.15	3.69	0.03	0.17	0.23	0.72	2.04	2.03	1.75	0.07
A. paronychioides	0.12	3.47	0.07	0.20	0.26	0.24	2.35	12.20	1.75	0.25
C. procera	0.06	1.64	0.02	0.14	0.15	0.19	0.34	3.20	0.00	0.01
E. prostrata	0.10	1.06	0.09	0.15	0.37	0.17	1.23	4.73	0.40	0.06
L. camara	0.03	4.55	0.04	0.05	0.11	0.29	0.48	3.20	0.60	2.29
S. nigrum	0.12	1.17	0.10	0.20	0.30	0.53	2.15	8.33	0.93	0.53
T. purpurea	0.10	0.72	0.01	0.03	0.04	0.12	0.62	1.77	0.07	0.05
U. lobata	0.04	1.14	0.03	0.06	0.06	0.24	0.86	1.03	0.40	0.55

mg kg^{-1} dw and 10 mg kg^{-1} dw, respectively), *A. conyzoides* for Cu and Cr (37 mg kg^{-1} dw and 7 mg kg^{-1} dw, respectively), *A. conyzoides* and *A. paronychioides* for Cd (0.3 mg kg^{-1} dw). Among all species, *A. conyzoides* showed higher concentrations for various heavy metals. The order of accumulation of metals was different between species. In the most dominant species *A. Conyzoides*, it was Fe>Mn> Zn>Cu>Ni=Cr> Co>As>Cd=Pb while the sequence in *A. paronychioides* was found as Fe>Mn>Zn>Cu>Ni>Cr>As>Co>Pb>Cd. *A. conyzoides* belongs to the family Asteraceae and a weed plant, it is one of the most diverse plant families with numerous species that bioaccumulate heavy metals (Patel *et al*., 2021). It is reported that weeds have unique characteristics, such as absorbing more heavy metals and storing them in the vacuole to diminish their harmful effects on plants. (Khan *et al*., 2023). Further, Zhu *et al*., (2018), reported that *A. conyzoides* is a good phytoextractor of metals (Zn, Pb and Cd). Gajaje *et al*., (2021), studied twenty-two plant species for their metal accumulation potential that were growing on FA-contaminated sites and found that *Alternanthera pungens* showed more bioaccumulation and translocation factors for Cr, Cu, and Zn, which support our findings that *Alternanthera* is a good accumulator of metals. Khan *et al*., (2023), reviewed phytoremediation by invasive plant species and reported that another species of *Alternanthera*, *A. philoxeroides* is good for phytoremediation of heavy metals. Another study which was conducted in a lead (Pb) waste pool area, *Euphorbia cheiradenia* was found to be a more efficient accumulator of Pb, Zn, Cu, Ni and Cd (Chehregani and Malayeri, 2007). Gajaje *et al*., (2021), while studying FA dumpsites, showed that *E. hirta* was a good metal accumulator with the highest translocation factor for Zn. These studies support our finding for *E. prostrata*. Further, *Lantana camara* species accumulated metals in the order of

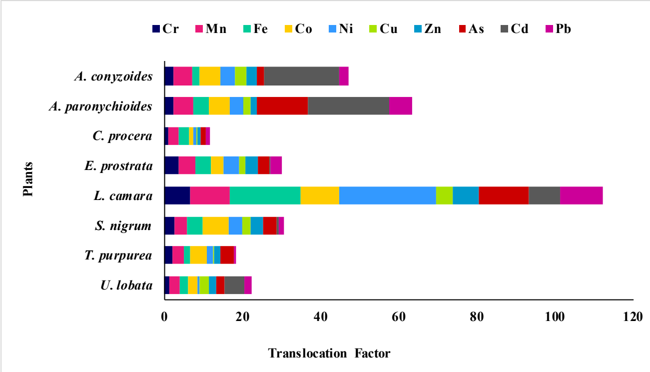

Fig. 2: Translocation factor of plants for different heavy metals

Fe>Mn>Zn>Cu>Pb>Ni>Cr>As>Co>Cd. *L. camara* showed the maximum accumulation for Mn and Pb in comparison to other species. There are reports that *L. camara* can act as a phytoextractor for Cu, Zn, Cr and Mn and shows a good tolerance with different heavy metals such as Cd, Cr, Cu, Mn, Ni, Pb, and Zn (Pandey and Bhattacharya, 2018).

Bioaccumulation and translocation factor of different plants

The potential of plants for remediation can be effectively determined by examining the metal accumulation factors in their various parts (Maiti and Pandey, 2021). Table 3 shows the bioaccumulation factor for different metals in studied plants. The bioaccumulation factor for all metals in all plants varied between 0.01 to 12.20 (Table 3) and most plants showed a bioaccumulation factor of more than one for Mn, As, and Zn. However, the translocation factor for all metals in all plants varied between 0.39 to 24.80. The highest TF value was found for *L. camara* for most metals, followed by *A. paronychioides* and *A. conyzoides* (Fig. 2). All plants showed more than one TF value for most metals, which means these plants have a good ability to transfer metals from root to shoot of the plants. Moreover, *A. conyzoides* and *A. paronychioides* exhibited higher accumulation of most metals compared to the other plants; however, *L. camara* demonstrated the highest translocation factor.

Conclusion

The results of the present study showed that the concentration of heavy metals was higher in the harvestable shoot part than root, which means these invasive species can be used as phytoextractors in FA-contaminated areas. Among the weeds, *A. conyzoides, A. paronychioides, E. prostrata* and *S. nigrum* were found to be the most efficient metal accumulators. Further, the study showed that weeds could be the most effective choice for removing heavy metals because they are fast-growing, have short life spans, and have higher metal translocation ability from root to shoot, which can be harvested. Additionally, their ability to tolerate FA makes them suitable for planting and restoring FA-affected areas.

Author contributions

AP: Conceptualization, Field visit, Investigation, Methodology, Formal analysis, Writing the original draft. SD and SKB: Field visit, Formal analysis. VKS: Review and editing. VP: Conceptualization, Supervision, Writing- review and editing, Fund acquisition, Project administration.

Conflict of Interest

The authors state that they have no conflict of interest.

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