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RESEARCH ARTICLE

Ecological restoration of coal fly ash–dumped area through bamboo plantation

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Abstract

The present study entails the phytoremediation potential of different bamboo species on 5-year-old FA-dumped site near Koradi thermal power plant of Nagpur, Maharashtra, India. The selected FA-dumped site was treated with farmyard manure, press mud, and bio fertilizer followed by plantation of six promising species of bamboo namely *Bambusa balcooa* Roxb., *Dendrocalamus stocksii* (Munro.) M. Kumar, Remesh and Unnikrishnan, *Bambusa bambos* (L.) Voss, *Bambusa wamin* E.G. Camus, *Bambusa vulgaris* var. *striata* (Lodd. ex Lindl.) Gamble, and *Bambusa vulgaris* var. *vittata* Riviere and Riviere. The experimental results indicated that the organic input in the FA-dumped site nourished the soil by improving its physico-chemical, and biological characteristics. The results revealed the contamination of the site with different trace elements in varied quantity including Cr (89.29 mg kg^{-1}), Zn (84.77 mg kg^{-1}), Ni (28.84 mg kg^{-1}), Cu (22.91 mg kg^{-1}), Li (19.65 mg kg^{-1}), Pb (13.47 mg kg^{-1}), and Cd (2.35 mg kg^{-1}). A drastic reduction in concentration of heavy metals in FA was observed after 1 year of bamboo plantation as compared to the initial condition. The results showed that bamboo species are good excluders of Ba, Co, Cr, Li, Ni, Mn, and Zn, whereas they are good accumulators of Cd, Pb, and Cu. The values of biochemical parameters, such as pH, total chlorophyll, ascorbic acid (AA), and relative water content of all the bamboo leaves ranged from 5.11–5.70, 1.56-6.33 mg g^{-1}, 0.16-0.19 mg g^{-1}, and 60.23–76.68%, respectively. It is thereby concluded that the bamboo plantation with biofertilizers and organic amendments may indicate adaptive response to environmental pollution on FA-dumped site.

Keywords Bamboo · Bioconcentration factor · Translocation factor · Fly ash dumped site · Heavy metals · Phytoremediation · Total chlorophyll · Ascorbic acid

Introduction

Fly ash (FA) as an industrial waste has been completely changed from a “hazardous waste” as useful “Resource Material” (Yadav and Fulekar 2018). This is accomplished due to the technological advancements followed by initiatives and innovations. There are several applications of coal-based FA majorly in construction and related sectors. The utilization of FA has been increasing from 66.6 million tonnes (MTs) in 2008–2009 to 132 MTs in 2017–2018. In the year 2017–2018, the overall utilization of FA in various applications was 67%. Currently in India, 38.67% of FA is utilized in the construction sector for various modes like 25.60% in cement, 9.01% in bricks and tiles, 3.40% in roads and flyovers, and 0.66% in concrete. Apart from this, 10.48% of FA is used in reclamation of low-lying area; 6.9% in ash dyke raising, 6.37% in mines backfilling, 0.66% in concrete, and 0.29% in agriculture (Alam and Akhtar 2011; CEA 2019).

In spite of the utilization of coal FA in different sectors, large quantities of FA remain unutilized and dumped in FA dumping sites. It is likely that 40% of the total FA is unutilized and directly disposed off in landfill that covers about 65,000

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acres of land as a FA dumped site in India (CEA 2019; Rastogi and Paul 2020). These FA-dumped sites are examined for environmental concerns because solid waste depository has the potential to contaminate the existing environment or ecosystem with some metal introducing elements.

FA as a primary waste product along with other coal combustion products, such as carbon dioxide, nitrogen oxides, sulfur oxides, suspended particulate matter, high concentrations of heavy metals (Cr, Mn, Ni, Cu, Zn, Cd), metalloids (Al, Si, As, Se), and organic pollutants, such as polychlorinated Biphenyls (PCB), polyaromatic hydrocarbons (PAH), polychlorinated dibenzofurans (PCDFs), polychlorinated dibenzo-p-dioxins (PCDDs), monomethyl, and dimethyl sulfate are discharged into the air, water, and soil introducing a worldwide danger to the environment and human wellbeing (Chakraborty and Mukherjee 2009; Ribeiro et al. 2014; Verma et al. 2015; Srivastava et al. 2015; Boechat et al. 2016; Munawer 2018). Improper management of FA-dumped sites can affect the soil, agricultural land, ground as well as surface water bodies by percolation of heavy metals affecting the health and livelihood security of the surrounding people (Belyaeva and Haynes 2012; George et al. 2015; Maiti and Prasad 2017; Gajić et al. 2019). People living nearby thermal power plants (TPPs) are more prone to health problems like silicosis, fibrosis of the lung, bronchitis, and pneumonitis due to the long period inhalation of FA particles (Whiteside and Herndon 2018).

Consequently, proper management and disposal of produced FA is of urgent need as it has adverse impact on the ecosystem. Plantation would be a possible alternative to ameliorate all the environmental contaminations emerged by FA dump yards and suitable ecological engineering is required to achieve it (Pandey 2015). Appropriate phyto-remediating plant species can be adopted to restore the FA dumped sites. Restoration through phytoremediation is a plant-based ecofriendly technique to raise the vegetative growth on adulterated land and also utilizes for land recovery and eco-rehabilitation to maintain FA-dumped sites which may help to lessen the harmful impact of the heavy metals (Pandey 2017; Kisku et al. 2018). Numerous literatures have reported that various plant species including shrubs, woody plants, and grasses can uptake the toxic metals and attach the fine ash particles with their root systems, thereby promoting the better soil conditioning (Ram et al. 2008; Juwarkar and Jambhulkar 2008; Jambhulkar and Juwarkar 2009; Kumari et al. 2013; Pandey et al. 2016a, b; Singh et al. 2020b).

Vegetation survey shows that the plants species belonging to the families, such as Asteraceae, Brassicaceae, Chenopodiaceae, Fabaceae, Poaceae, and Rosaceae, spontaneously colonized on the degraded land (Pandey 2015; Pandey et al. 2016a, b). In Poaceae family, bamboo species are one of the fastest-growing woody-stemmed grass and highest yielding renewable natural resource that spread out worldwide with over 1575 species belonging to 111 genera of subfamily Bambusoideae and Gramineae (Ram et al. 2010; Hogarth and Belcher 2013; Sawarkar et al. 2020; Singh et al. 2020a). Bamboo requires minimal maintenance for its cultivation, and it can grow in adverse environmental condition (Nath et al. 2015).

Due to the unique rhizospheric properties, bamboo is considered as one of the fasted growing plants on the earth (Lessard and Chouinard 1980) with the reported growth rates of 250 cm in 1 day (24 h) (Mishra et al. 2014). It is also outlined that bamboos are commonly known to develop in unfertilized or poor soil. So, they are used for restoration of degraded land (Desh 1989). Bamboo requires minimal maintenance for its cultivation, and it can grow in adverse environmental condition (Nath et al. 2015). This special characteristic of bamboo supports as a preliminary point in restoration of degraded land. It is also reported that bamboo has dense foliage which maintains the thick layer of leaf litter, and subsequently this leaf litter is the sources of organic matter which regulate the microclimate and soil moisture, both of which are important towards degraded land restoration (Mishra et al. 2014).

Arunachalam and Arunachalam 2002 has reported that larger root surface of bamboo species shows increased microbial biomass in rhizosphere zone which ultimately helps in increasing the soil fertility. The microbial-assisted remediation of FA-dumped sites are often found to be suitable to restore the hazardous conditions (Tiwari et al. 2008; Babu and Reddy 2011). Venkatesh et al. (2005) conducted a field experiment on plantation of different bamboo species on degraded land and concluded that out of 11 bamboo species, *Dendrocalamus giganteus* Munro, *Dendrocalamus hookeri* Munro, and *Bambusa nutans* Wall. ex Munro, were best for use in improving the fertility of the soil. However, it clearly indicated that the introduction of bamboo on degraded land enhances soil fertility, microbial activities, and also soil enzyme activity (Zhihua et al. 2013).

Roy et al. (2018) investigated that bamboo plantation on FA-dumped site is a good approach for remediation and reclamation of dumped sites. Similarly, Were et al. 2017 investigated phytoremediation of contaminated dumped site using different bamboo species and found species of bamboo, such as *B. vulgaris*, *B. bambos*, *Dendrocalamus asper* (Schult.) Backer, and *B. balcooa* can accumulate chromium (BCF >1, TF >1). Singh et al. (2020b) experimented for development of bamboo diversity on degraded lands/waste lands sites. The study revealed that the restoration of such degraded lands can largely be considered as ecosystem restoration for the re-establishment of the capability of the land to establish its basic structure and function (Singh et al. 2020b). Pandey et al. (2016a, b) studied about the phytoremediation of FA-dumped sites through naturally growing flora, such as *Ipomoea carnea* Jacq., *Solanum surattense* Burm f., and *Lantana camara* Linn.

and concluded that the plants might be used as good phytostabilizers of metal accumulation and as a good approach for FA-dumped site restoration. Different studies also documented specific metal uptake properties of bamboo species which can grow well in toxic environments with minimal maintenance and producing a large amount of biomass (Kigomo 2007; Muraje 2009).

Besides these remediation approaches, bamboo is considered in a list of bioenergy plants because these plants can be used for electricity, heat, or liquid transport fuel production also which may be processed for biodiesel or bioethanol that may create additional sources of energy and also create alternative sources of income, and hence improving socio-economic condition of rural communities (Roy et al. 2018; Azeez and Orege 2018). Due to high growth rate and high biomass production, bamboo species have a good potential for carbon storage as well as carbon sequestration which can be efficiently bound to mitigate and protect the global climate change and also to provide other ecosystem services or functions that help to sustain human livelihoods (Yuen et al. 2017). Biochemical parameters (pH, AA, water, and chlorophyll content) of plant species may be used as a bioindicator of environmental stresses toward plant growth, adaptive capacity, and phytoremediation solution.

However, it is very important to establish plantations due to limiting soil physico-chemical characteristics for the successful growth of plants. Therefore, there is a huge opportunity and an imperative need for stabilization or remediation of the FA dumped sites with suitable reclamation techniques (Yao et al. 2015). Proper soil amendments along with suitable metal resistant plant species, which can grow at adverse environmental conditions, are the actual requirement to successfully rehabilitate the FA-dumped sites (Robinson et al. 2003; Pandey et al. 2016a, b). However, the application of bamboo in ecological restoration of FA dumped sites has acknowledged much attention of ecologists, foresters, and soil Scientists not only for the restoration purposes but also for several other environmental benefits. Hence, the present study was focused on phytoremediation potential, productivity, carbon sequestration capacity, bioaccumulation, translocation factors, and biochemical properties of different bamboo species on the FA-dumped site of Koradi thermal power plants (KTPPs), Nagpur, Maharashtra, India.

Materials and Methods

Study area

The study was conducted in abandoned FA-dumped site of KTPPs Nagpur, Maharashtra, India (Fig. 1). The coordinates of the site are 21.232740° N, 79.084506° E to 21.229927° N, 79.092980° E. The power station is operated by Maharashtra State Power Generation Company Limited (MAHAGENCO) since 1974. This company operates eight units and has an absolute power limit of 1700 MW. The power plant requires 16,000–17,000 t of coal on a daily basis that generates FA which is disposed off approximately around 62 acres of land area (https://www.mahagenco.in/). The initial sampling was carried out in the first week of June 2018 and completed in the last week of July 2019.

Experimental design and sampling

Two-year-old seedlings of bamboo species viz., *Bambusa balcooa* Roxb., *Dendrocalamus stocksii* (Munro.) M. Kumar, Remesh and Unnikrishnan, *Bambusa bambos* (L.) Voss, *Bambusa wamin* E.G. Camus, *Bambusa vulgaris* var. *striata* (Lodd. ex Lindl.) Gamble, and *Bambusa vulgaris* var. *vittata* Riviere and Riviere were collected from CSIR-NEERI, Nagpur, India and relocated in treated pits in study area. These seedlings were planted in FA-dumped site in a pit size of 1 m × 1 m × 1 m amended with farm yard manure (FYM, 30 kg pit^{-1}), vesicular arbuscular mycorrhiza (VAM, 20 nodules pit^{-1}), press mud (PM,10 kg pit^{-1}) in the ratio of 3:0.002:1 and *Azotobacter chroococcum* Beijerinck (1×10^6 CFUg^{-1} pit^{-1}). Proper weeding, irrigation, and replacement of dead seedlings by new were done continuously. Mostly, FA used water from the industry was reused for irrigating plants. Initial growth parameters (height, collar diameter, number of leaves and culm) were evaluated before plantation. All planted bamboo species were regularly monitored at the FA-dumped site during the entire year. After 1 year of plantation, plants samples were collected to estimate the growth parameters, heavy metals content, and carbon sequestration rate. Six plant samples of each bamboo species were randomly taken from different locations of the plantation site.

Determination of physico-chemical and biological characteristics of FA

Physico-chemical characteristics

The moisture content in FA was estimated by the Gravimetric method (Reynolds 1970) and the results were expressed in percentage. Keen-Raczkwski box method (Viji and Prasanna 2012) was followed to estimate bulk density of FA (gm cm^{-3}), porosity (%), and water holding capacity (%).

Acidity and alkalinity of soil was measured using pH meter (hach-intellical phc101, HANNA instruments woonsocket RI USA) with a sample dilution of 1:2.5 (w/v) in distilled water. The electrical conductivity of FA samples was measured using a conductivity meter (Hach HQ14D, HANNA instruments woonsocket RI USA) with the sample dilution of 1:5 (w/v).

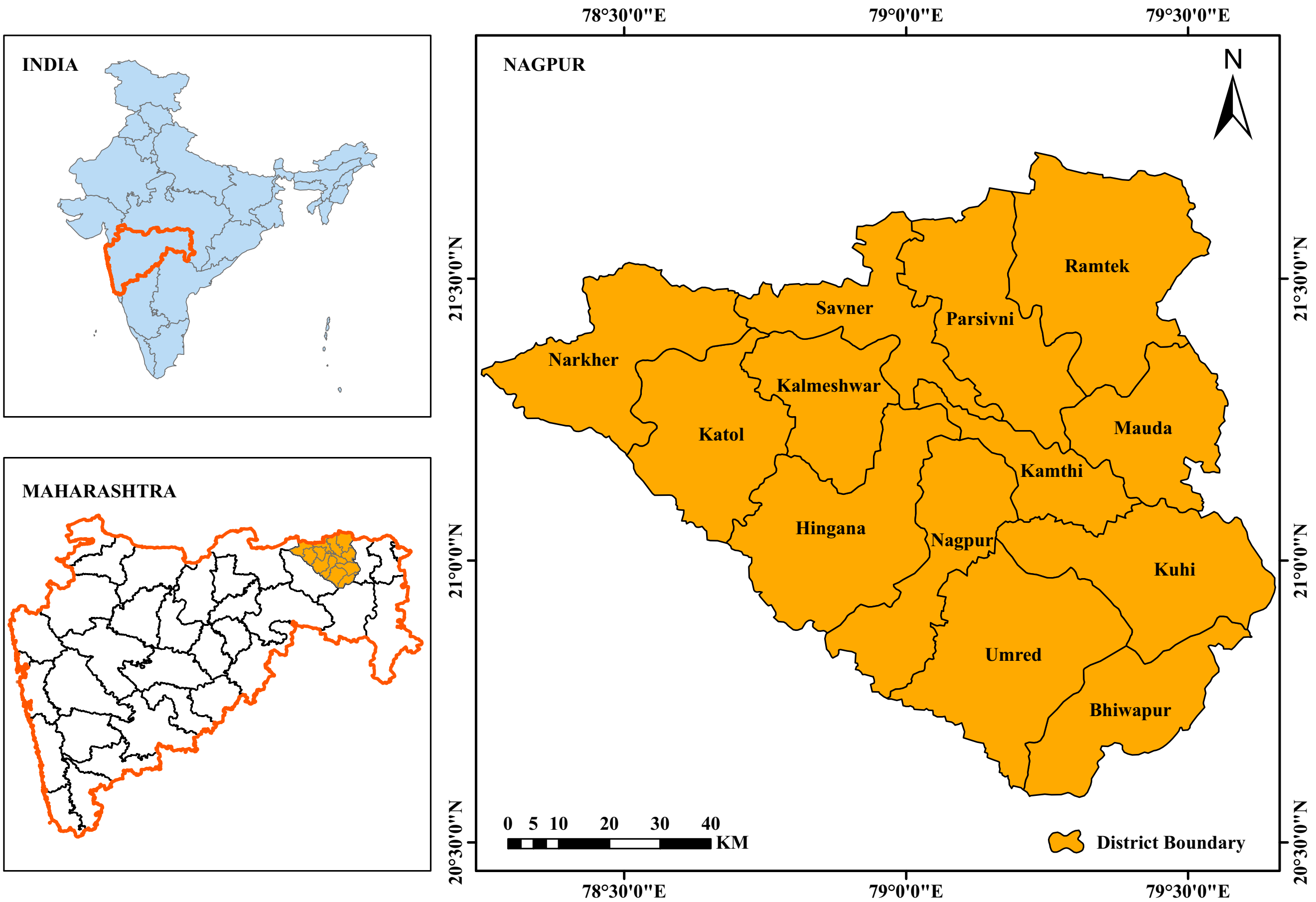

Fig. 1 Phytoremediation of FA-dumped site within KTPPs, Nagpur, India

Total nitrogen was estimated by Kjeldahl's method. One gram sample was taken in digestion tube and 10 ml of the conc. H_2SO_4 with 5 g of catalyst mixture was added. The digestion tube was loaded to the digester and heated up to 420 °C. At the end of the digestion, sample turns to light green in color. After cooling, one side of distillation unit was loaded with digestion tube and the other side was loaded with 20 ml of 4% boric acid with indicator. The distillation unit was auto programmed to add 40 ml of 40% NaOH. The samples were heated by passing steam and generated ammonia was absorbed in boric acid containing conical flask. With the presence of ammonia, the color changes to green. Simultaneously, a blank was maintained without sample throughout the experiment. Available nitrogen was estimated following Subbiah and Asija (1956). Soil sample of 5 g was taken in 1-l round bottom flask. Frothing and bumping of sample was prevented using liquid paraffin. The sample containing flask 100 ml each sodium permanganate and sodium hydroxide solution were added. Samples were distilled in 20 ml of boric acid solution and approximately 150 ml of distillate was collected. With 0.02 N H_2SO_4, the collected distillate was titrated until the color changes to red and flask without soil sample was considered as blank.

Total phosphorous in soil was estimated by Jackson (1967) method. 0.5 mg of sample was mixed with 30 ml acid mixture (HNO_3 and $HClO_4$ at 9:4 ratios) for digestion. After complete digestion, the solution was filtered and an equal volume of vanadomolybdate was added. The absorbance of the mixture was measured at 440 nm using a spectrophotometer. Using a standard calibration curve, the concentration of phosphate was identified in the soil sample.

Available phosphorous was estimated following Olsen's (1954) Method. In a 150-ml conical flask, 2.5 g of soil sample was taken, and a nip of activated charcoal was added. Fifty milliliters of Olsen reagents were added, mixed well, and filtered. In a 25-ml volumetric flask 5 ml of filtrate, 4 ml of freshly prepared ammonium molybdate and ascorbic acid solution was taken. The contents were mixed and incubated for 30 min. The absorbance was measured at 882 nm and the reaction mixture without soil sample was considered as blank. For comparison, the standard calibration curve was prepared by using standard phosphate solution in the range (0–2 mg l^{-1}). The acid digested sample (HNO_3 and $HClO_4$ of 9:4 ratios) was analyzed in a flame photometer (Flame Photometer 128, Systronics, India), to calculate the content of total potassium. One N ammonium acetate was used to measure the available potassium and sodium in soil using flame photometer (Toth and Prince 1949).

Organic carbon was estimated by Walkley and Black method (Singh et al. 1999). One gram of sieved (0.5 mm) soil was taken in a conical flask. Ten milliliters of $K_2Cr_2O_7$ and 20 ml of conc. H_2SO_4 were added and mixed well for a minute and then allowed to incubate for 30 min at room temperature. Then, 200 ml of distilled water, 10 ml of conc. orthophosphoric acid, and 0.2 g sodium fluoride was kept at room temperature for 90 min. Before titration, 1 ml ferroin indicator was added and titrated against 0.5 N ferrous ammonium sulfates until the color changes to brownish red.

For estimation of cation exchange capacity (CEC), 25 g of dried and sieved (0.5 mm) soil sample was mixed with 50 ml of 1 N, NH_4OAc for 60 min and incubated overnight in room temperature. After incubation using Buchner funnel with Whatman No. 42 filter paper, the contents were filtered. The filtrate was leached with NH_4OAc and the leachate was used to estimate the exchangeable cation. A pinch of ammonium chloride salt was added to the leachate and washed with 250 ml of isopropyl alcohol for removal of chloride. The obtained filtrate was tested for chloride with silver nitrate. Ammoniacal nitrogen in leachate was determined by washing with 10% KCl solution (pH 2.5). Collected KCl was made alkaline using 40% NaOH and distilled with Kjeldahl apparatus with few drops of phenolphthalein indicator. Distilled ammonia was collected in 4% boric acid and titrated against 0.02 N, H_2SO_4. Exchangeable cations as Na^+, K^+, Ca^+, Mg^+ were calculated in Meq100g^{-1} following the method given by Jackson 1973 and Robertson et al. 1999.

Biological characteristics

The samples collected from FA dumped site were examined for various microorganisms like fungi, bacteria, Actinomycetes and nitrogen-fixing bacteria (*Azotobacter chroococcum* Beijerinck and *Rhizobium phaseoli strains*) by standard serial dilution methods (Ben-David and Davidson 2014; Singh et al. 2020b). For total bacterial growth, nutrient agar media, rose bengal chloramphenicol agar (RBCA), Kenknight and Munaier's medium, Jensen's medium, and yeast extract mannitol agar medium (YEMA) were used to analyze fungi, Actinomycetes, Azotobacter, and Rhizobium species, respectively (Juwarkar and Jambhulkar 2008). Total microbial species were counted using microbial species (CFU g^{-1}) = (no. of colonies × dilution factor)/weight of sample.

where CFU = colony forming units.

Determination of heavy metals in FA and plants tissues

For heavy metal analysis, air-dried soil and plant samples were ground, sieved and subjected for acid digestion. For soil digestion, nitric acid and perchloric acid (9:4) and for plant parts, nitric acid was used (US Environmental Protection Agency 1996, 1998). After the digestion, filtered samples were subjected in inductive coupled plasma-optical emission spectroscopy (ICP-OES 6000, iCap 6300 DUO, Thermo fisher, England). Metal concentration in samples was expressed in mg kg^{-1} using following equation:

$$\mathrm{mg\ kg^{-1}} = \left(\mathrm{mg\ L^{-1}} \times V/M\right)$$

where V = final volume of sample in volumetric flask (100 ml) and M = dry mass of sample that was digested.

Determination of bioconcentration and translocation factor

To identify metal phytoremediation potential by the plants, BCF and TF were calculated. BAF is the ratio of metal in plant parts with the metal in FA, i.e.:

BCF = metal concentration in plant part/metal concentration in FA

It is the efficiency of plants to accumulate metals in their tissues from FA. On the other hand, TF is the ratio of metal concentration in shoot divided by the metal concentration in the root which shows the ability of the plants for translocation of the metals from root to shoot as given herewith.

TF = metal concentration in shoot/metal concentration in root

For example, TF > 1 indicates increased mobility of the metals from root to stem, leaves, and vice versa (Eid and Shaltout 2016; Pandey et al. 2016a, b). Furthermore, plants exhibiting high BCF and TF values >1 are phytoextractors, while those with BCF and TF values <1 are phytostabilizers (Mendez and Maier 2008).

Determination of plant growth rate and biochemical characteristics of bamboo species after a year

The growth rate of selected plant species was measured (height, diameter, number of culms, leaves, and leaf litter) with the help of measuring tape and vernier caliper (Singh and Soni 2010; Pathak et al. 2017). For estimation of aboveground biomass (AGB), by quadrats method, all the bamboo species within the quadrats of 3 m × 3 m was studied. It was estimated by the allometric equation 1 as given below (Intergovernmental Panel on Climate Change (IPCC) (2003) et al. 2000).

$$\mathrm{AGB\ (kg)} = 0.131 \times \mathrm{DBH}^{2.28} \tag{1}$$

From each experimental quadrat, the height and DBH (diameter at breast height) of all the species were measured and the results were expressed in kg.

Below-ground biomass (BGB) was estimated by measuring the ratio of the shoot to the root. BGB was estimated by using the equation 2 as given below. A default conversion factor of 0.26 of AGB was used to calculate the BGB and results were expressed in kg (Intergovernmental Panel on Climate Change (IPCC) (2003) et al. 2000).

$$\mathrm{BGB\ (kg)} = 0.26 \times \mathrm{AGB} \tag{2}$$

Determination of ascorbic acid concentration from fresh leaf sample of 500 mg was homogenized in 20 ml of extraction media (0.5 gm of oxalic acid and 75 mg EDTA in 100 ml distilled water) (Tiwari 2010). After centrifuging for 15 min, 1.0 ml of the homogenate was blended with 5.0 ml of dichlorophenol indophenols (20 μg ml^{-1}). Subsequent to shaking and its optical density was estimated at 520 nm using a spectrophotometer (Shimadzu, UV-1800, Japan). For the estimation of total chlorophyll content, 500 mg of leaf sample was homogenized in 80% acetone and centrifuged at 3000 rpm for 15 min and the supernatant was collected for analysis. The optical density was measured at 663 and 645 nm with a spectrophotometer (Shimadzu, UV-1800, Japan). The chlorophyll content was expressed as mg gm^{-1} of the sample.

The chlorophyll content was calculated by equation 3 as suggested by Das and Prasad 2010.

$$\begin{aligned}&\text{Total chlorophyll } \left(\mathrm{mg\ gm}^{-1}\right)\\&\quad = (20.2 \times \mathrm{A}645 + 8.02 \times \mathrm{A}663 \times \mathrm{V})/100 \times \mathrm{W}\end{aligned} \tag{3}$$

where A, absorbance at specific wave; V, volume of extract in acetone; W, weight of leaf sample.

For the relative water content (RWC) estimation, collected leaves samples were immersed in distilled water overnight, bolted dry then take the weight to get turgid water (TW). These leaves were dried in oven at temperature of 70 °C and reweighed to obtain dry weight (DW). Thereafter, the relative water content was calculated by using equation 4 suggested by Nwaogwugwu et al. 2017.

$$\mathrm{RWC} = [(\mathrm{FW}-\mathrm{DW})/(\mathrm{TW}-\mathrm{DW})] \times 100 \tag{4}$$

where FW, fresh wt.; DW, dry wt.; TW, turgid water.

Determination of carbon sequestration rate

Carbon sequestration is the process of long-term storage of atmospheric $\mathrm{CO_2}$ by the plants. Carbon sequestered in plants exists in different parts of the plants, such as AGB and BGB. Total carbon stock present in the selected species was estimated by multiplying with the factor of 0.5 to the total biomass (AGB + BGB) (Intergovernmental Panel on Climate Change (IPCC) (2003) et al. 2000; Freibauer 2003). The results were presented as kg of carbon per hectare per year.

Statistical analysis

The changes that occurred on the FA-dumped site before and after rejuvenation were determined using one-way analysis of variance (ANOVA). Statistical analysis was performed using significant results at $p < 0.05$. Standard error was measured as deviation to mean (mean ± standard deviation).

Results

Physico-chemical properties of FA

FA-dumped site was examined before and after rejuvenation to determine the characteristic changes on the bamboo plantations. Table 1 presents the physico-chemical properties of FA dumped site before and after rejuvenation. Moisture content in FA dumpsite increased from 1.52 to 18.42%. Initial bulk density of FA dumped site was found to be 1.8 gm cm^{-3} and after phyto-rejuvenation it was found to be 1.12 gm cm^{-3}. Total porosity and water holding capacity also increased from 62.74 and 40.78% to 74.21 and 50.79%, respectively. Initial pH of FA dumpsite was 7.92 which indicated its highly alkaline nature while that recorded after the plantation increased to 8.11. Similarly, the electrical conductivity also increased from 99.90 to 124.25 μS cm^{-1}. The amount of organic carbon and organic matter of the dumped site before rejuvenation were 0.25% and 0.43%, respectively. The bamboo plantation in dumped site resulted in increased concentration of organic carbon (1.10%) as well as organic matter (1.89%). There is a significant change in overall nutrients in terms of available and total N, P, and K at the initial stage and after rejuvenation in FA-dumped site. The amount of available N, P, and K was very low (1.45, 13.00, 64.73 mg kg^{-1}) before rejuvenation which confirms that the FA-dumped area was not suitable for the growth of plants. However, after the plantation, the condition had significantly changed (30.00, 36.60, 86.69 mg kg^{-1}) just within a span of one year (Table 1).

Biological analysis

Microbial analysis of FA-mixed soil sample collected from rhizospheres of planted bamboo species confirmed that there was a significant increase in microorganisms' population after 1 year of plantation. Initially, the microbial population was negligible or absent in FA-dumped site, however, considerable population of *A. chroococcum*, *R. phaseoli*, and *Actinomycetes* (20×10^3, 20×10^3 and 7×10^3 CFU g^{-1}, respectively) were observed (Table 1).

Table 1 Physico-chemical and biological characterization of FA-dumped area before and after bamboo plantation

Parameters	Before plantation	Press mud + FYM (composition)	After 1 year of plantation
Physical characteristics			
Moisture content (%)	1.52±0.05	60.19±1.93	18.42±0.30**
Bulk density (gm cm^{-3})	1.80±0.03	0.27±0.04	1.12±0.04*
Porosity (%)	62.74±0.01	81.00±2.00	74.21±4.14*
Water holding capacity (%)	40.78±0.11	300.00±4.00	50.37±1.95*
Chemical characteristics			
pH	7.92±0.03	8.20±0.02	8.11±0.09*
EC (μS cm^{-1})	99.90±0.03	3000.00±10.00	124.25±2.65*
Organic carbon (%)	0.25±0.02	34.20±1.60	1.10±0.28*
Organic matter (%)	0.43±0.03	58.83±2.76	1.89±0.48*
Total N (mg kg^{-1})	224±0.51	5400.00±12.18	616±1.20*
Available N (mg kg^{-1})	1.45±0.05	328.00±18.00	30.0±0.05**
Total P (mg kg^{-1})	450±0.05	14,800.00±48.00	2250±0.06**
Available P (mg kg^{-1})	13±0.02	198.00±2.00	36.6±0.07**
Total K (mg kg^{-1})	123.33±5.10	8200.00±3.00	1243.19±3.50**
Available K (mg kg^{-1})	64.73±7.04	195.00±3.00	86.69±7.10*
Exchangeable cations (Meq100 g^{-1})			
Na$^+$	0.85±0.00	3.09±0.04	0.50±0.05
K$^+$	0.28±0.02	6.82±0.06	0.37±0.05
Ca$^+$	3.27±0.06	26.70±1.08	19.66±1.25**
Mg$^+$	0.44±0.02	8.12±1.04	4.90±1.81**
Ca$^+$+Mg$^+$	9.5±2.23	29.22±1.20	24.63±0.80**
CEC	5.22±.04	7.72±0.02	12.88±0.11**
Biological characteristics (CFU g^{-}1)			
Total bacteria	2×10^{2}	19×10^{7}	45×10^{2*}
Total fungi	0	7×10^{6}	3×10^{2*}
A. chroococcum	0	15×10^{5}	20×10^{3*}
R. phaseoli	0	7×10^{6}	20×10^{3*}
Actinomycetes	0	4×10^{6}	7×10^{3*}

The data is represented as mean ± SD of three independent experiments with statistically significant differences at $*p < 0.05$ and, $**p < 0.01$ before and after 1 year of plantation

Heavy metals concentration in FA-dumped site before and after plantation

Metal concentration in FA samples has been presented in Table 2 and compared with before and after 1 year of bamboo plantation. The concentration of different heavy metals in FA-dumped site was found significantly higher than that before the bamboo species were planted. The comparative analysis of heavy metals concentration before and after plantation revealed that the concentrations of all heavy metals were drastically decreased. Among the heavy metals, the concentration of Cr, Li, Pb, Mn, Cd, and Zn decreased 3 times of their initial concentration. The concentration of Co (1776 mg kg^{-1}) was found maximum at initial stage, which decreased metal concentration as follows; Mn (657.94 mg kg^{-1}) > Ba (177.83 mg kg^{-1}) > Cr (89.29 mg kg^{-1}) > Zn (84.77 mg kg^{-1}) > Ni (28.84 mg kg^{-1}) > Cu (22.91 mg kg^{-1}) > Li (19.65 mg kg^{-1}) > Pb (13.47 mg kg^{-1}) > Cd (2.36 mg kg^{-1}). These heavy metals leached into ground water as well as surface water of nearby area and degraded its quality which is a great concern toward environmental prospective. After 1 year of plantation, the concentration of heavy metals decreased compared to the initial stage. The successful development of vegetation cover by bamboo plantation decreased the concentration of different heavy metals from FA-dumped site. The concentration of Co decreased from 1776 to 878.37 mg kg^{-1} followed by Mn 657.94 to 175.89 mg kg^{-1}, Ba 177.83 to 97.29 mg kg^{-1}, Cr 89.29 to 30.14 mg kg^{-1}, Zn 84.77 to 24.52 mg kg^{-1}, Ni 28.84 to 14.17 mg kg^{-1}, Cu 22.91 to 8.82 mg kg^{-1}, Li 19.65 to 6.23 mg kg^{-1}, Pb 13.47 to 4.40 mg kg^{-1}, and Cd decreased from 2.36 to 2.60 mg kg^{-1} (Table 2).

Table 2 Heavy metals concentration in FA dumped area before and after plantation

Metals	Before plantation (mg kg^{-1})	After 1 year of plantation (mg kg^{-1})
Ba	177.83±0.18	97.29±0.30*
Cd	2.35±0.27	1.02±0.33*
Co	1776±0.51	678.37±0.40*
Cr	89.29±0.46	30.14±0.43*
Li	19.65±1.62	6.23±1.60*
Ni	28.84±0.09	14.17±0.51*
Pb	13.47±1.76	4.40±6.00*
Mn	657.94±0.25	175.89±0.60*
Cu	22.91±0.02	8.82±0.81*
Zn	84.77±0.20	24.52±0.53*

The data represented as mean ± SD of three independent experiments with statistically significant differences, *$p < 0.05$ before and after 1 year of plantation

Heavy metals concentration in FA-dumped site before and after plantation

Heavy metals accumulation in various plant parts were measured and presented in Table S1 which clearly indicated the accumulation of heavy metals in root, shoot, and leaf parts of planted bamboo species. Hence, soil of the dumped site showed less heavy metal concentration after plantation of bamboo species. Regarding accumulation within different plant parts, each heavy metals exhibited non-identical responses to the different species of bamboo. Accumulation of Cr was higher in leaf of bamboo species followed by root and stem. *D. stocksii* accumulated greater Cr (37.56 mg kg^{-1}) in its leaves followed by *B. bambos* (30.23 mg kg^{-1}), *B. vulgaris* "Yellow" (28.88 mg kg^{-1}), *B. vulgaris* "Green" (27.53 mg kg^{-1}), *B. balcooa* (24.94 mg kg^{-1}), and *B. wamin* (18.75 mg kg^{-1}). In the case of Zn, stems of bamboo of all the species were found to be effective to accumulate it in higher concentration as compared to root and leaf. Among the six species of bamboo, maximum amount of Zn (135.41 mg kg^{-1}) was accumulated in the stems of *D. stocksii* followed by *B. balcooa* (115.61 mg kg^{-1}), *B. bambos* (83.93 mg kg^{-1}), *B. vulgaris* "Green" (73.14 mg kg^{-1}), *B. vulgaris* "Yellow" (63.54 mg kg^{-1}), *B. wamin* (61.23 mg kg^{-1}). Accumulation of Zn was comparatively very less in leaf of bamboo species. Ni accumulated in various plant parts of bamboo species in the order *B. balcooa* > *B. vulgaris* "Yellow" > *B. wamin* > *B. bambos* > *D. stocksii* > *B. vulgaris* "Green." The stem and leaves of these bamboo species accumulated maximum Ni than roots. Similarly, in the case of Cu, except *D. stocksii* all other bamboo species accumulated it within its stem. *B. balcooa* accumulated higher Cu within its stem (56.85 mg kg^{-1}), root (30.9 mg kg^{-1}), and leaf part (19.43 mg kg^{-1}). Kabata-Pendias (2011) reported normal mean concentration of Cu in plant leaves ranges from 0.5 to 30 mg kg^{-1}. In present study, Cu concentrations in plants leaves were in normal ranged and below the toxic level. The amount of Li accumulated in stem and leaf parts of the bamboo species were nearly similar. Comparatively less amounts of Li were accumulated in root parts of selected bamboo species. *B. vulgaris* "Yellow" was noted to be more effective to store maximum amount of Li in its stem (3.75 mg kg^{-1}), leaf (3.50 mg kg^{-1}), and root (3.59 mg kg^{-1}). However, Pb accumulation was maximum in leaf of bamboo species as compared to stem and roots and followed the order of *B. bambos* (45.9 mg kg^{-1}) > *B. balcooa* > (43.07 mg kg^{-1}) *D. Stocksii* (38.27 mg kg^{-1}) > *B. vulgaris* "Green" (35.45 mg kg^{-1}) > *B. vulgaris* "Yellow" (30.55 mg kg^{-1}) > *B. Wamin* (27.60 mg kg^{-1}). According Kabata-Pendias (2011), the toxic concentration of Pb ranges from 30 to 300 mg kg^{-1} in plants leaves. However, in our study Pb concentration in plants leaves were to some extent in toxic ranges except in the case of *B. Wamin* (27.60 mg kg^{-1}). All the bamboo species were closely similar to accumulate Cd while a little bit increase in accumulation of Cd was observed for *B. wamin* than others. Cd was accumulated in the leaves of *B. wamin* (2.87 mg kg^{-1}) followed by *B. vulgaris* "Yellow" (2.86 mg kg^{-1}), *B. vulgaris* "Green" (2.86 mg kg^{-1}), *B. bambos* (2.85 mg kg^{-1}), *D. stocksii* (2.85 mg kg^{-1}), and *B. balcooa* (2.84 mg kg^{-1}). Kabata-Pendias (2011), reported the toxic and normal concentration of Cd in plants leaves ranges from 5 to 30 mg kg^{-1} and 0.05 to 0.2 mg kg^{-1} respectively. Our finding showed that Cd concentrations in bamboo leaves surpassed the normal range but they are below the toxic levels. Results also depicted that the accumulation of Ni, Li and Cd was comparatively less among all of the heavy metals.

BCF and TF of heavy metals

BCF refers to the biomagnification of heavy metals in plants. In this present study, the BCF value in the case of Cd, Pb and Cu was > 1, which indicated that these metals can be accumulated in greater amount within bamboo species. *D. stocksii* showed highest BCF value toward Pb (13.17) followed by *B. balcooa* (12.09), *B. bambos* (9.95), *B. vulgaris* “Green” (8.18), *B. vulgaris* “Yellow” (7.30), and *B. wamin* (6.71). Higher BCF value towards Cu (5.84) and Cd (3.64) was observed for *B. wamin* followed by other species. The present study showed that except Zn and Co, all other metals (Ba, Cd, Cr, Li, Ni, Pb, Mn, and Cu) have translocated from root to stem or leaf (TF > 1) by the species of *D. stocksii*, *B. wamin*, *B. vulgaris* “Green” and *B. balcooa* (Table 3). In addition, *B. bambos* and *B. vulgaris* “Yellow” showed accumulation of Ba, Co, and Zn in roots (BCF < 1, TF < 1).

Plant growth rate and biochemical characteristics of planted bamboo species after a year

Growth characteristics of bamboo species

After 1 year of bamboo plantation, all the species were studied for their growth parameters like height, diameter, number of culms, and leaf litter. Recorded phenotypic data confirmed that there was a significant increase in height, number of culms of *B. balcooa* and *B. vulgaris* “Yellow” followed by *B. vulgaris* “Green” and *B. bambos* (Fig. 2).

Biochemical characteristics of planted bamboo species

All biochemical contents evaluated from all the bamboo species are presented in Table 4. The pH of all species of bamboo leaves was acidic and it ranges from 5.11 to 5.70. Total chlorophyll content in *B. balcooa* was recorded to be highest (6.33 mg g^{-1}), and the lowest concentration (1.56 mg g^{-1}) was observed in *D. stocksii.* Ascorbic acid in plants provides resistance against stress and other types of hazardous emissions in and around the plant environment (Hasanuzzaman et al. 2012). The findings of the present study also confirmed considerable amount of ascorbic acid in the plants which ranges from 0.16 to 0.19 mg g^{-1}. A high percentage of relative water content was observed in plants which range from 60.23 to 76.68% (Table 4).

Carbon sequestration rate of bamboo species

Estimation of carbon sequestration potential of bamboo species planted on FA-dumped site confirmed that there is a significant increase in carbon content in all the species. The carbon sequestration capacity of the studied bamboo plants ranges from 306.82 to 587.77 kg C ha^{-1} $year^{-1}$. Among all the species, *B. balcooa* contains highest total biomass and carbon content (1175.54 kg ha^{-1} and 587.77 kg C ha^{-1} $year^{-1}$, respectively), whereas lowest was observed in the case of *B. wamin* (613.63 kg ha^{-1} and 306.82 kg C ha^{-1} $year^{-1}$, respectively). These results indicated that bamboo has great potential in sequestering a higher concentration of

Table 3 BCF and TF of bamboo species grown on FA-dumped area

Species		BCF and TF of heavy metals									
		Ba	Cd	Co	Cr	Li	Ni	Pb	Mn	Cu	Zn
B. bambos	BCF	0.08±0.003	3.63±0.12	0.1±0.003	0.6±0.019	0.47±0.015	0.15±0.005	9.95±0.318	0.39±0.012*	3.54±0.113	0.54±0.017
	TF	1.54±0.049+	2.03±0.06	0.55±0.018+	3.39±0.108	2.63±0.084	6.8±0.218	31.36±1.004	5.3±0.170+	1.74±0.056	0.25±0.008
B. vulgaris "Yellow"	BCF	0.17±0.005*	3.6±0.115	0.12±0.004	0.65±0.021	0.55±0.018	0.19±0.006	7.3±0.234	0.23±0.007	3.46±0.11	0.64±0.020
	TF	1.64±0.052+	2.04±0.065	0.26±0.008	2.83±0.091	2.01±0.064	13.61±0.436++	22.24±0.712	1.68±0.054	1.95±0.062	0.18±0.006
D. stocksii	BCF	0.09±0.003	3.51±0.112	0.13±0.004	0.66±0.021	0.43±0.014	0.15±0.005	13.17±0.421*	0.35±0.011	2.93±0.094	0.69±0.022
	TF	0.28±0.009	2±0.064	0.33±0.011	4.15±0.133+	3.94±0.126+	14.77±0.473+	46.94±1.502+	2.85±0.091	1.35±0.043	0.17±0.005
B. wamin	BCF	0.06±0.002	3.64±0.116	0.11±0.004	0.49±0.016	0.5±0.016	0.18±0.006	6.71±0.215	0.21±0.007	5.84±0.187*	0.55±0.018
	TF	0.42±0.013	2±0.064	0.41±0.013	2.17±0.069	2.93±0.094+	15.71±0.503+	55.17±1.765+	1.85±0.059	10.91±0.349++	0.73±0.023+
B. vulgaris "Green"	BCF	0.09±0.003	3.63±0.116	0.1±0.003	0.54±0.017	0.46±0.015	0.13±0.004	8.18±0.262	0.41±0.013*	2.87±0.092	0.52±0.017
	TF	0.3±0.010	1.9±0.061	0.43±0.014	6.99±0.224	2.9±0.093+	30.16±0.965++	67.03±2.145+	5.33±0.171+	4.12±0.132+	0.16±0.005
B. balcooa	BCF	0.11±0.004	3.6±0.115	0.17±0.005*	0.58±0.019	0.43±0.014	0.2±0.006	12.09±0.387*	0.53±0.017*	4.68±0.150*	0.71±0.023
	TF	0.43±0.014	2.04±0.065	0.22±0.007	1.76±0.056	5.9±0.189++	3.35±0.107	38.14±1.220	2.28±0.073	2.46±0.079	0.19±0.006

* The data represented as mean ± SD of three independent experiments. (*) signs indicate statistically significant differences,*$p < 0.05$ and versus BCF of different plantation group and (+) signs indicate statistically significant differences,+$p < 0.05$ and ,++$p < 0.01$

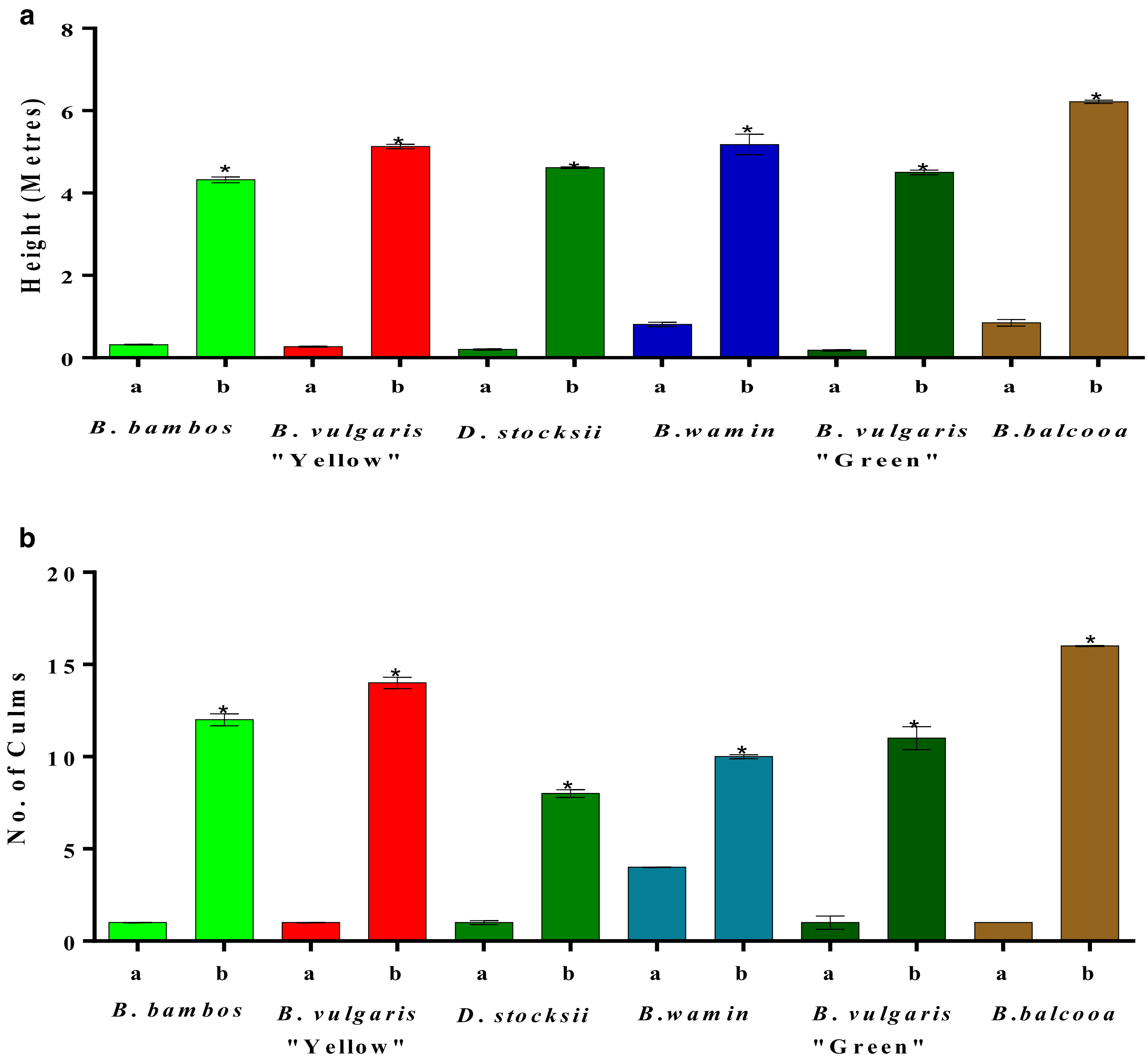

Fig. 2 Growth rate of different species of bamboo plant A height; B number of culms; C culm diameter; and D leaf litter. [(a) Initial plantation data and (b) after 1 year of plantation]. The data represented as mean ± SD of three independent experiments with 12 plant samples and (*) signs indicate statistically significant differences, *$p < 0.05$ versus initial plantation data and after one year of plantation group.

carbon within a short period from atmosphere and store in plant.

Discussion

The initial characteristic of FA-dumped site before and after rejuvenation helps in identification of natural changes occurred (Ram et al. 2010; Saikia and Pandey 2020; Cardoso et al. 2013; Singh et al. 2020a). In the present study, decreased bulk density with increasing moisture content, water holding capacity, and porosity indicated increased availability of plant's nutrients and microbial activities. Low bulk density is the indicator for better root penetration, thereby stabilizing the FA-dumped site (Neuschutz et al. 2006; Ramesh et al. 2008). These observations are corroborated with the findings of the present study. In the present study, after 1-year of plantation, pH slightly increased which signified the favorable growth environment for plants in FA-dumped area. Similar findings were also found in the study performed by Soti et al. (2015). Electrical conductivity (EC) also increased significantly from 99.90 to 122.41 µS cm^{-1} at the beginning. The prepared plantation pits resulted in increase of EC which was supported by the findings of Pandey et al. (2009). Organic

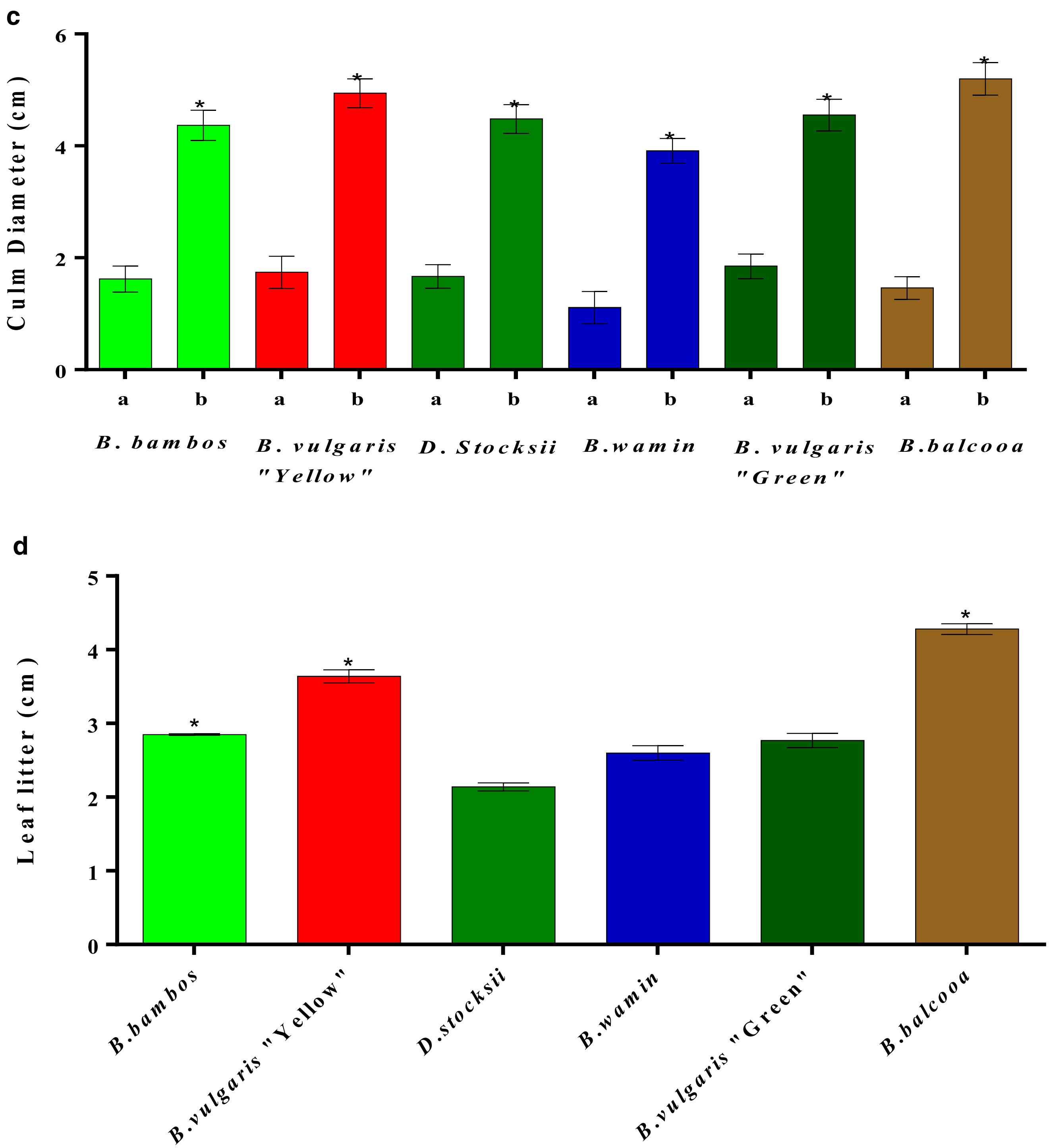

Fig. 2 continued.

carbon (0.25%) and organic matter (0.43%) of the FA-dumped site before rejuvenation was very less due to the absence of organic sources. Within a year, the FA-dumped site with amendments of organics matters and decomposed leaf litter resulted in a significant increase in organic materials as evidenced by Soti et al. (2015). There is a significantly reduced concentration of available N, P, and K in the FA-dumped site, which indicated a lack of biological support material. During the combustion process, nitrogen content in coal gets oxidized and the amount of nitrogen present in FA will not be in the available form for the plants as evidenced from studies conducted by Ram et al. 2008; Pandey et al. 2009; Roy et al. 2018; Maiti and Pandey 2020). Amendment of the dumped site with different types of organic material and

Table 4 Biochemical characteristics of bamboo species planted on FA-dumped area

Species	pH	AA (mg g^{-1})	Total chlorophyll (mg g^{-1})	Relative water content (%)
B. bambos	5.62±0.02	0.18±0.01	4.73±0.11*	67.62±0.49
B. vulgaris "Yellow"	5.70±0.03	0.19±0.01	5.41±0.14*	73.56±0.48
D. stocksii	5.11±0.03	0.18±0.01	1.56±0.14	65.35±0.48
B. wamin	5.66±0.07	0.16±0.02	1.78±0.13	60.23±1.05
B. vulgaris "Green"	5.31±0.03	0.17±0.02	4.16±0.09*	69.55±0.32
B. balcooa	5.24±0.02	0.19±0.02	6.33±0.22*	76.68±0.34*

The data represented as mean ± SD of three independent experiments. (*) signs indicate statistically significant differences in total chlorophyll (*$p < 0.05$ represents significant differences between *B. bambos, B. vulgaris* "Yellow," *B. vulgaris* "Green," and *B. balcooa* versus *D. stocksii* and *B. wamin*) and relative water Content (*$p < 0.05$ represents significant differences between *B. wamin* versus *B. balcooa* group)

manures significantly enhanced its overall nutrient status. From the results, it is confirmed that there is a significant increase in total nitrogen and the available form of nitrogen in FA which increased up to 130 mg kg^{-1}. Similarly, total P and K was found to be 6250 mg kg^{-1} and 2243 mg kg^{-1} and available P and K were found to be 66.6 mg kg^{-1} and 86.69 mg kg^{-1}. All the pits showed more or less similar nutrient content after 1 year of plantation. However, it was a little higher than that of the initial site.

CEC includes all exchangeable cations, such as Na^+, $K^{+,}$ Ca^+, and Mg^+. It referred as the capability of soil to hold positively charged particles or ions present in the soil, which enhances significant soil properties that affect soil stability, availability of nutrient, pH, as well as reaction with soil fertilizer and other ameliorant materials (Singh et al. 2020a; Pandey et al. 2020). From the results, it is confirmed that CEC of FA-dumped site was very low in organic matter (Bakar et al. 2011). After plantation, a significant increase in CEC along with other cations was observed. Due to the supplementation of organic materials during plantation, there is a significant increase in organic matter content that enhances the concentration of CEC.

Biological analysis of rhizosphere from plants in rejuvenated dumped site confirms the significant growth in microbial population. Increased microbial population after plantation on FA-dumped site with FYM, manure, press mud, organic-rich material, as well as bio-fertilizer shows an adequate number of total bacteria, fungi, *A. chroococcum*, *R. phaseoli*, and Actinomycetes (Jambhulkar and Juwarkar 2009). Improvement in the microbial population of rejuvenated dumped site after amendment with different organic materials contributes in stabilizing the site. Decomposed plant litters by microorganisms provide various plant nutrients through the biogeochemical cycle and improve the physico-chemical condition of the fly ash–dumped site.

The study area initially contained numerous trace elements in different quantities among which Cr was the most plentiful followed by Zn, Ni, Cu, Li, Pb, and Cd. Parent material of coal that is utilized in thermal power plants contains different heavy metals which are released and deposited at the FA-dumped site and in FA pond after the combustion process. FA generally consists of 95–99% of oxides of aluminum, silica, iron, and calcium and around 0.5–3.5% contains sodium, potassium, and phosphorous while the remaining part is made up of trace materials (Adriano et al. 1980; Pandey 2017; Pandey et al. 2020). Most of these elements, such as Ba, Cd, Li, Co, and Mn, were found in the toxic range (Kabata-Pendias 2011). A drastic reduction in heavy metals concentration in the FA-dumped site of KTPPs, Nagpur, India was observed after 1 year of bamboo plantation as compared to the initial measurement. Successful development of vegetation cover by bamboo plantation triggered the reduction of heavy metal concentrations in the FA-dumped site.

After 1 year of the plantation, the concentration of heavy metals significantly decreased due to increased root formation and associated rhizomes. Bamboos have the ability to produce greater root biomass and hence stimulating uptake of heavy metals from contaminated soil (Gerhardt et al. 2009). Well-developed roots of bamboo can clean up the contaminated soil through uptake of contaminants and relocating them to other plant parts followed by accumulation and removal through phytovolatilization, phytosorption, and hydraulic pumping systems (Pulford and Watson 2003). Several studies have already reported the phytoremediation potential of different bamboo species like *Gigantochloa atroviolacea* Widjaja, Moso bamboo (*Phyllostachys pubescens* J. Houz.), *B. vulgaris*, *Bambusa merrilliana* (Elmer) Rojo and Roxas, *Bambusa blumeana Schult. f.*, and *D. asper* etc. (Liu et al. 2015; Srivastava and Dwivedi 2016; Bian et al. 2019; Chua et al. 2019). Due to underground microbial activities, heavy metals get solubilized and mobilized to the plants which bioaccumulates in enormous concentration via root system (Banerjee et al. 2015; Khan et al. 2015; Hu et al. 2015; Maiti and Prasad 2017; Maiti and Pandey 2020). A drastic reduction in heavy metal concentrations in the study area was observed after 1 year of bamboo plantation as compared to the initial condition. The results also clearly indicated that the root, shoot, and leaf parts of planted bamboo species were capable to trap the heavy metals. However, each heavy metal exhibited non-identical responses to the different species of bamboo in different parts (Supplementary Table S1).

Higher BCF value towards Cu (5.84) and Cd (3.64) was observed for *B. wamin* followed by other species. These findings showed the capabilities of bamboo species for cleaning up of different sites contaminated with heavy metals especially Cu, Cd, and Pb. Pandey et al. (2015) reported BCF > 1 of heavy metals like Cu, Cr, Pb, and Ni in different parts of *Azolla caroliniana* Willdenow. Singh et al. (2010) reported that if the TF > 1, then metals are accumulated in upper part of a plant whereas TF < 1 indicates the storage of the metals within lower plant parts. In present study, *B. bambos*, thereby showing efficient translocation of Cd (BCF 3.63, TF 2.03), Pb (BCF 9.95, TF 31.36), and Cu (BCF 3.54, TF 1.74) from root to stem or leaves. Similarly, *B. vulgaris* "Yellow" *D. stocksii*, *B. wamin*, *B. vulgaris* "Green," and *B. balcooa* also showing efficient translocation of Cd, Pb, and Cu in upper parts of plants. Therefore, all studied bamboo species were tolerated to Cd, Pb, and Cu pollution and can be utilized efficiently as an accumulator plants (BCF > 1, TF > 1) for phytoremediation of Cd, Pb, and Cu from fly ash dump sites. However, species of *D. stocksii*, *B. wamin*, *B. vulgaris* "Green" and *B. balcooa* act as an excluder plants (BCF < 1, TF < 1) for Ba, Co, and Zn metals which were more concentrated in lower plants parts.

The present study provided similar results of bioaccumulation and translocation as observed in study performed by Pandey et al. (2020).

Due to amendment with FYM and press mud, the moisture availability and organic matter enhanced and favored the plant growth. *B. wamin*, *B. balcooa*, and *B. vulgaris* "Yellow" are more appropriate and productive for FA-dumped areas in Central India among the six planted bamboo species. Bamboo is a cost-effective alternative for FA-dumped mitigation and also a viable policy option for such type of contaminated areas which is supported by the findings of Roy et al. 2018; Pandey et al. 2020.

Also, it is an effective option for local stakeholders and policy option for funding from non-government and government agencies (Pandey et al. 2012). The obtained results of pH were acidic ranging from 5.11 to 5.70 of all bamboo leaves by the emission of acidic air pollutants, such as SOx, NOx, CO_2, or other acidic pollutants from the thermal power plants that affect the pH of leaves (Swami et al. 2004). The pH of plant plays a vital role in defining the plant vulnerability to air pollution. Reduction in the pH of leaves disturbs the biological activities of the plants. Thakar and Mishra (2010) reported that the acidic pH reduces the efficiency of photosynthesis in plants. AA in plants regarded as an antioxidant that increases the resistance level of plants against adverse biotic and abiotic environmental stresses. The considerably high AA content (0.16 to 0.18 mg g^{-1}) in all the selected bamboo species indicates the efficiency to tolerate abiotic stresses such as heavy metals that exerts toxicity (Sinha and Gupta 2005; Alamri et al. 2018). The above findings are also in line with the present study. Chlorophyll content plays a vital role in photosynthesis activity as well as the growth and development of biomass which differs from plant to plant and mainly depends upon the age of leaves and pollution level of the surrounding environment. However, lowering the chlorophyll content slowed down plant growth and development, which would reduce plant phytoremediation efficiency of heavy metals. Photosynthetic activity also decreases when the plants are exposed to a high metal concentration (Emamverdian et al. 2018). Thus, the estimation of chlorophyll content can be important for adaptive plant response to heavy metal stress, air pollution, and selection of phytoremediation technology (Gajić et al. 2018). All these species have high relative water content within plant body which indicates plants maintain physiological balance, even after exposure to air pollution from thermal power plants where transpiration rates are generally high leading to desiccation. According to Rai et al. (2013), higher the RWC in plant, greater the drought tolerance capacity of any plant's species. On the basis of the biochemical properties of the selected bamboo species, it can be concluded that bamboo species have high tolerance capacity to adverse environmental conditions especially including heavy metals in the FA-dumped site.

The biomass production was proportional to the capacity of carbon sequestration. Bamboo culms undergo speedy growth and reach maturity in 3–5 years (Singh et al. 2020b), and hence it is ideal for rejuvenation of FA-dumped sites as it binds soil and stores more carbon dioxide (Korner et al. 2007; Roy et al. 2018; Pandey et al. 2020). Bamboos apparently have relatively low photorespiration (Dura and Hiura 2006), and thus the carbon storage and carbon sequestration rate are high enough as compared to other plants (Marsh and Smith 2007). Carbon sequestration study performed in the present context offers a chance for carbon credits on FA-degraded land. However, bamboo species had high productivity with significant carbon sequestration capacity in the polluted environment and also reduces the total negative impact of global climate change and greenhouse emissions.

Conclusion

In India, restoration using phytoremediation through bamboo plantation seems to be a sustainable solution for FA management apart from generating wealth from waste. Effective management and restoration of FA-dumped sites are essential to maintain environmental sustainability. The present study clearly indicated that the bamboo based phyto-sequestration approach can be a good strategy for ecological restoration as well as rehabilitation of degraded FA-dumped sites. The study pointed out of the selected bamboo species *B. balcooa*, *B. vulgaris* "Yellow" and *B. wamin* was found most appropriate for ecological restoration. In addition, it can be concluded that bamboo species have the potentiality to flourish in an adulterated environment and can remove the toxic heavy metals from soil by accumulating them in different parts of the plants. Moreover, a long-term experimentation schedule is required in restoration activities to continuously monitor the health and quality of FA, presence of trace elements, and their bioavailability along with storage in vegetation, which will provide a strong guideline to manage FA-dumped sites of power plants in the future.

Abbreviations FA, Fly ash; BCF, Bioconcentration factor; TF, Translocation factor; TPPs, Thermal power plants; VAM, Vesicular arbuscular mycorrhiza; AA, Ascorbic acid; TCS, Total carbon sequestration; MTs, Million tonnes

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Declarations

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