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Impact of Fly Ash Pollution on Quality of Agricultural Soils Around Thermal Power Station

Mahendra G. Thakre[1], Pallavi D. Nasare[2], Sayyed Juned A.[3,*]

Abstract

The coal-fired Khaparkheda Thermal Power Station (KTPS) and its fly ash pond in Nagpur District, Maharashtra, India has been responsible for serious fly ash pollution incidents of agricultural soil. The present study was carried out on the quality of soil samples around the fly ash pond and KTPS. The physicochemical and chemical characteristics of soil samples were observed to be affected due to fly ash pollution. The fertility of soil samples was lower under the impact of fly ash pollution than the unimpacted soil samples. Heavy metal concentrations (lead, cadmium, chromium, and arsenic) were more than the concentrations of trace nutrient metals (copper zinc, nickel, and iron), as the source of trace metals in soil is natural geological while toxic heavy metals is anthropogenic. The statistical analysis indicated anthropogenic source of metal pollution to the soil. The soil samples nearer to fly ash pond and KTPS were more polluted with heavy metals (Pb, Cd, Cr, As, and Cu) and traced nutrient metals (Cu, Zn, Ni, and Fe) than the distant soil samples. Research on the cost-effective phytoremediation measures to mitigate the impacts of fly ash pollution on soil and for eco-restoration of fly ash dumps is presented.

Keywords: Coal-fired power plant, fly ash, agricultural soil, pollution, remedial measures

INTRODUCTION

Electrical energy production is the basis of industrial and community development which is at the cost of deterioration of soil, air and water resources under the impact of pollution. Proper balance is required between industrialization and conservation of resources for sustainable development.

Coal-fired thermal power plants in India are the major sources of energy, contributing a total of 60% of country's total installed capacity and it satisfied 72% of total nation's demand [1]. However, the darker side of thermal power development is the pollution of the environment due to emission of pollutants. Among various pollutants, fly ash pollution is of serious nature. Every year large quantity of fly ash is being produced by the thermal power plants in India. The fly ash generation during 2018–19 was 217.04 million tons [2]. Around 25–30% of it is utilized for production of cement and other useful products; however, 70–75% of fly ash is unscientifically dumped in low lying areas (fly ash ponds) which affect the surrounding soil, water bodies and air quality. Fly ash dumping is responsible for deterioration of soil quality and land use pattern [3].

Fly ash emitted from the stacks of coal-fired power plants has been a major cause of deterioration of public health, crops and

***Author for Correspondence**
Sayyed Juned A.
E-mail: sayyedjuned2009@gmail.com

[1]Associate Professor, Centre for Higher Learning and Research, Department of Environmental Science, Sardar Patel College, Chandrapur (M.S.), Maharashtra, India.
[2]Research Student, Centre for Higher Learning and Research, Department of Environmental Science, Sardar Patel College, Chandrapur (M.S.), Maharashtra, India.
[3]Assistant Professor, Department of Environmental Science, Arts, Commerce and Science College, Onde, Tal. Vikramgad, Palghar (M.S.), Maharashtra, India.

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environment [4]. Fly ash ponds also affect the surrounding environment by polluting the air due to air-borne fly ash and polluting the nearby water bodies and agricultural soil due to fly ash pond breach. Soil pollution due to excess fly ash resulted in accumulation of heavy metals in soil [5–10] leading to reduction in crop growth and yield [11] and reduction in microbial growth and activity [12, 13]. Fly ash amendment in soil at more than 10% had an adverse impact on seed germination of crops [14]. Fly ash more than 20% in soil decreased the yield of crop [15].

The fly ash pond of Khaparkheda thermal Power Station (KTPS) in Nagpur District, Vidarbha Region, India was responsible for farm soil pollution [16, 17]. Serious pollution was also reported from the mega power stations in Vidarbha of Maharashtra including KTPS [18]. These plants were emitting large quantity of fly ash with serious health hazards. The fly ash was seen everywhere on house roofs, gardens, parks, rivers, tanks and wells, fields, vegetables and food stuff, and human beings. In Nagpur district, adjacent Koradi and Khaparkheda thermal power plants caused air and soil pollution in more than 25 villages.

Considering the recurring fly ash pollution incidents in KTPS area, the present investigation was undertaken to study the farmland soil samples around KTPS and its fly ash pond with respect to impacts on physicochemical characteristics, fertility status, and metal pollution as well as research carried out elsewhere on remediation measures for eco-restoration of fly ash dumps and contaminated soils.

MATERIALS AND METHODS

The KTPS and its fly ash pond are situated in Nagpur district, Maharashtra State, India. The study area around the KTPS and its fly ash pond at Waregaon is predominantly having agricultural fields. The soil type was good due to the presence of Kanhan River and many small and large streams in the area. Soil samples from five agricultural farms were collected including two farms around the fly ash dump area, one near KTPS and two from distant areas. In each farm, three representative areas were identified, and soil samples were collected from 15 cm depth, mixed and homogenized and an aliquot (1.5 kg soil) were collected in clean cloth sample bags. This method is in line with IS: 2720. Any foreign detritus or stones were removed from collected soil sample. The soil samples were air dried and sieved with a 2 mm grade sieve. The soil samples were analyzed for physicochemical characteristics following standard methods [19].

STUDY AREA

Topography of the Study Area

Khaparkheda and Koradi thermal power plants are present in Nagpur District (Figures 1 and 2) on the bank of Kanhan River. The tributary of Kanhan River is Kolar River (Figure 3) which flows from Saoner and Patansavangi by the side of flyash dump site/flyash pond of KTPS, receiving its overflow, and then meets Kanhan River at the village Tola. Khaparkheda thermal power station (KTPS) is located near Khaparkheda town in Nagpur District, Maharashtra. The map of Nagpur District shows Khaparkheda and Koradi thermal power plants, Kanhan River, Pench River, etc. (Figures 4 and 5).

LOCATION OF KHAPARKHEDA SUPER THERMAL POWER STATION

Location details of KTPS are the latitude is 210 16’ 57.25 N and longitude is 790 07’ 04.07 E. The area of KTPS is 1.47 km. It is one of the oldest coal-fired power plants of MAHAGENCO in Maharashtra, established in 1989. The installed capacity of KTPS is 1340 MW with 4 units of 210 MW capacity each (installed in March 1989, January 1990, April 2000, January 2001, and August 2011, respectively) and 5th unit of 500 MW capacity. The coal mines of Western Coalfields Ltd., namely Sillewara and Walani open cast coal mines provide coal to KTPS. The coal is transported mainly through railways. Coal India has also opened many coal mines in nearby areas to KTPS and these mines are providing coal to this power plant also. The water resource is obtained from Pench Reservoir through a pond of Koradi Thermal Power Station.

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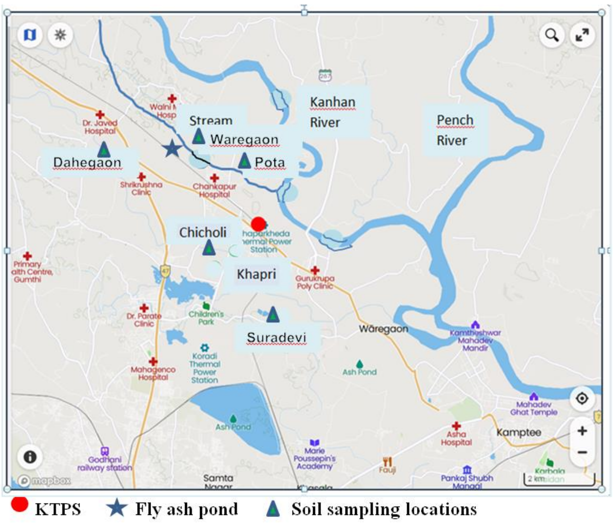

Figure 1. Locations of agricultural soil sampling stations.

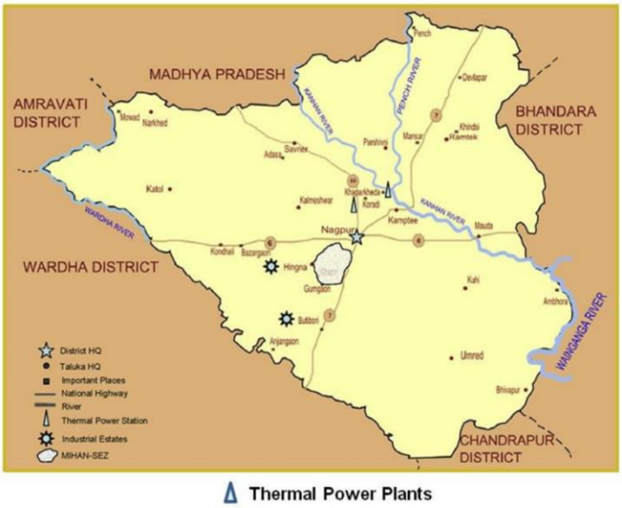

Figure 2. Map of Nagpur showing locations of Koradi and Khaparkheda coal-based thermal power plants.

Figure 3. Kolar river near Khaparkheda Thermal Power Station.

Figure 4. Kanhan river polluted by Flyash from Flyash Pond Breach.

Figure 5. Pench river tributary of Kanhan river.

RESULTS AND DISCUSSION

The land around KTPS is undulating with hillocks and low line areas. The fly ash pond is situated near Waregaon village. Kolar River flows by the side of fly ash pond which meets Kanhan River. The Kolar River receives the overflow containing fly ash from fly ash pond. The fly ash pond breach was also reported to pollute the Kolar and Kanhan River and the agricultural soils around them [20–22].

Table 1. Details of agricultural soil sampling locations.

Sampling Sites	Station Code	Distance (km) w.r.t. Fly Ash Pond	Direction w.r.t. Fly Ash Pond	Distance (km) w.r.t. KTPS	Direction w.r.t. KTPS
Waregaon	S-1	0.5	NE	3.0	NNW
Pota	S-2	2.0 km 1.0 (E)	ESE	2.0	N
Chicholi	S-3	2.5	S	1.2	SW
Suradevi	S-4	5.0	SSE	3.2	S
Dahegaon	S-5	2.5	W	4.0	NW

The locations of the farms from which soil samples were collected are shown in Figure 1 and their distance and direction from proposed site is given in Table 1. The physicochemical characteristics of soil samples are presented in Table 2. The agricultural soils near fly ash pond at Waregaon (S-1) and Pota (S-2) showed soil texture as silt loam with higher content of sand (21–24%) and silt (39–48%).

The bulk density ranged from 1.45 to 1.49. This bulk density is within the ideal bulk density of 1.60 suitable for root growth of crops. The porosity ranged from 55.6 to 66.8%, consequently with higher liquid limit (38–44%) and water holding capacity (55.6–66.8%). These observations indicated the impact of fly ash pollution on the physical structure of S-1 and S-2 soil samples. Higher per cent composition of sand and silt in S-1 and S-2 led to reduction in bulk density as compared to the soils of Chicholi, Suradevi and Dahegaon. Similar observations have been observed by [23] during the study on fly ash fortification to farm soils.

Table 2. Physicochemical properties of soil samples.

S. N.	Parameters		S-1	S-2	S-3	S-4	S-5
	Physical Properties						
1.	**Soil Texture**		**Silt Loam**	**Silt Loam**	**Silt Loam**	**Clay Loam**	**Clay Loam**
2.	Grain size distribution (%)	Gravel	20	17	21	12	11
		Sand	34	21	24	34	32
		Silt	39	48	43	37	39
		Clay	7	14	12	17	18
3.	Bulk density, g/cc		1.45	1.49	1.75	1.78	1.85
4.	Liquid limit, % moisture		38	44	34	25	22
5.	Porosity, %		66.8	55.6	36.8	33.8	32.4
6.	Water holding capacity, %		45.1	64.7	35.1	36.1	31.5
	Chemical properties						
1.	pH		8.53	8.55	7.87	7.53	7.66
2.	Electrical conductivity, μS/cm		456	488	92	56	89
3.	Calcium as Ca^{++}, mg/kg		732	954	1132	1365	1380
4.	Magnesium as Mg^{++}, mg/kg		223.4	254.7	323.4	623.4	789.1
5.	Chlorides as Cl, mg/kg		33.8	31.8	33.8	33.8	35.8
6.	Sulphates as SO_4, mg/kg		64.0	52.0	64.0	61.0	68
7.	Organic matter, %		0.334	0.83	0.67	0.934	0.87
8.	Total nitrogen as N, kg/ha		109.0	118.0	273.0	298	277
9.	Total phosphorous as P, kg/ha		7.6	5.5	47.6	37.6	45.8
10.	Total potassium as K kg/ha		278.3	206.8	178.3	164.3	190.9
11.	Lead (Pb), mg/kg		41.62	45.69	21.34	6.24	3.37
12.	Cadmium (Cd), mg/kg		2.56	3.17	2.62	0.26	0.18
13.	Chromium (Cr), mg/kg		5.78	7.42	2.27	4.88	3.58
14.	Arsenic (As), mg/kg		5.37	6.94	2.66	0.26	0.21
15.	Copper (Cu), mg/kg		12.24	15.67	10.41	9.74	7.73
16.	Zinc (Zn), mg/kg		42.84	45.71	39.48	32.84	35.71
17.	Nickel (Ni), mg/kg		28.56	34.47	21.15	18.45	15.58
18.	Iron (Fe), mg/kg		15.43	18.95	13.74	10.42	9.83

The soil sample from Chicholi (S-3), away from fly ash pond, showed silt loam texture with higher content of silt. The soil samples from Suradevi (S-4) and Daheaon (S-5) which are away from KTPS and fly ash pond, showed clay loam soil texture with more clay content (17–18%) and comparatively low content of silt (37–39%) and sand (32–34%). The bulk density of Chicholi, Suradevi and Dahegaon soil samples ranged from 1.75 to 1.85, being above the ideal bulk density of 1.60 suitable for root growth of plants.

The pH of S-1 and S-2 soils i.e. 8.53 & 8.55 are slightly higher than pH of S-3 to S-5 soil samples i.e. 7.53–7.87. Electrical conductivity (μS/cm) was more in S-1 and S-2 soil sample as 456 and 488 μS/cm respectively, while it was low in S-3, S-4, and S-5 soil samples being 92, 56, and 89 μS/cm, respectively. Fly ash is known to increase the salt content of the soil as it is rich in cations. Improvement in the EC of soil was also observed during application of modified fly ash as soil conditioner in wheat farms [24]. The soil samples S-3, S-4 and S-5 were non-saline soils with very low levels of soluble salts, while soil samples S-1 and S-2 were slightly saline soils and suitable for seedlings and salt sensitive plants.

The chlorides and sulphates did not do very much in all the soil samples. Chlorides ranged from 31.8 to 35.8 mg/kg and sulphates ranged from 52 to 68 mg/kg. Rainwater, irrigation, fertilization, dust, and air pollution add chlorides in soil and is an essential nutrient to higher plants [25]. The minimum requirement of chlorides for crop growth is 1 g/kg dry weight [26, 27]. So, chlorides concentration is very low. The safe limit for sulphate in soil is given as 0.2 percent by weight (2000 mg/kg) according to Texas Department of Transportation (TxDOT) [28]. Thus, the sulphate concentration of soil is very low and does not pose the problem of acidity in soils.

Calcium and magnesium are important in maintaining fertility of soil. They are adsorbed on soil surface (exchangeable cations) and exchange with cations in soil solution. Calcium concentration of most sandy soil is below 400-500 mg/kg while in clayey soils are above 2500 mg/kg (Espinoza et al., 2021). The S-1 and S-2 soil samples have low clay content and have calcium concentration of 732 to 954 mg/kg. On the contrary, the soils S-3, S-4, and S-5 have calcium concentration ranging from 1132 to 1680 mg/kg of soil. The fertility of soil was also found to be improving from S-1 to S-5 soil samples.

Table 3. Soil status with respect to phosphorus, potassium, and magnesium.

Scales of interpretation, results as mg/kg	**SAC Status**	**Exchangeable Phosphorus**	**Exchangeable Potassium**	**Exchangeable Magnesium**
	VL	0–1.7	0–39	0–19
	L	1.8–4.4	40–75	20–60
	M-	4.5–9.4	76–140	61–200
	M+	9.50–13.4	141–200	61–200
	H	13.5–30.0	201–400	201–1000
	VH	>30.0	>400	>1000

The scales of interpretation for exchangeable phosphorus, exchangeable potassium and exchangeable magnesium are given Table 3 for comparing observed data (Hazelton and Murphy, 2007). The phosphorus concentration was 5.5–7.6 mg/kg in S-1 and S-2 soils (medium low, M-) and 37.6–47.6 mg/kg in S-3, S-4, and S-5 soil samples (very high) suitable for the growth of crops. The potassium in S-1 and S-2 soil samples ranged from 206.8 to 278.3 mg/kg which was high concentration and in S-3, S-4, and S-5 soil samples from 164.3 to 190.9 mg/kg which was medium high (M+) suitable for plant and crops (Table 3). The magnesium concentration in all the soil samples ranged from 223.4 to 789.1 mg/kg which is very high and suitable for plant growth (Table 3). These observations are supported by the analysis of fly ash from dumping sites and directly from Bhatinda Thermal Power Plant showing that the exchange complex is dominated by the cation Ca followed by Mg, Na, and K [29–32].

Fly ash in soil at low concentrations improves physical, chemical, and biological properties of soil and enhances available macro- and micro-nutrients for plants as seen in case of S-3 soil sample near KTPS. However, the application of unweathered fly ash at high concentration to soil shows a tendency of accumulating elements like B, Mo, Se, and Al at toxic levels responsible for reduction in crop yields and consequently influence animal and human life [33] as observed in case of S-1 and S-2 soil samples.

The total nitrogen varied from 109 to 118 kg/ha in S-1 and S-2 soil samples, while it was higher ranging from 273 to 298 mg/ha in S-3, S-4, and S-5 soil samples. The total phosphorus also showed similar trend, being 5.5–7.6 kg/ha in S-1 and S-2 soil samples, while it was 37.6–47.6 kg/ha in S-3, S-4, and S-5 soil samples. This is obvious due to the toxicity of excess fly ash in S-1 and S-2 soils to the vegetation, resulting in less cycling of nutrients resulting in low levels of total nitrogen and total phosphorus. However, a reverse trend was observed in the case of total potassium. Higher total potassium (206.8–278.3 kg/ha) in S-1 and S-2 soil samples as compared to 164.3–190.9 kg/ha in S-3, S-4, and S-5 soil samples.

Table 4. Soil fertility classification followed in Maharashtra & some other states.

Soil Fertility Level (Status Code)	Organic Carbon (%)	Available N (kg/ha)	Available P_2O_5 (kg/ha)	Available K_2O (kg/ha)
Very high (6)	>1.00	>700	>80.0	>360
High (5)	0.81–1.00	561–700	64–80	301–360
Medium (4)	0.61–0.80	421–560	48–64	241–300
Medium Low (3)	0.41–0.60	281–420	32–48	181–240
Low (2)	0.21–0.40	141–280	16–32	121–180
Very low (1)	<0.20	<140	<16.0	<120

Source: Modified after Tandon (2005).

The fertility of the soil samples was assessed by referring the values of major nutrients like total available nitrogen, total available phosphorus and total available potassium with the standard rating limits for soil test values used in India (Table 4). Final assessment of the fertility of the soil samples are given in Table 5. The S-1 soil sample nearest to the fly ash pond showed low soil fertility mainly due to very low levels of available N and available P_2O_5. Another S-2 soil sample, again nearest to fly ash pond, has medium low soil fertility which was improved due to high organic carbon due to growth of weeds observed in stagnant portions of the farm. Soil sample (S-3), nearest to KTPS, showed slight improvement to medium low fertility due to improvement of organic carbon and available P_2O_5. S-4 and S-5 soil samples showed further improvement and showed medium fertility [34, 35]. This indicates that the excess fly ash pollution might have accumulated toxic metals in highly toxic concentration, leading to reduction in soil microbial activity responsible for maintaining soil fertility.

Table 5. Assessment of fertility of soil samples.

Parameters	Soil Samples				
	S-1	S-2	S-3	S-4	S-5
Organic carbon	Low (2)	High (5)	Medium (4)	High (5)	High (5)
Available N	Very low (1)	Very low (1)	Low (2)	Medium low (3)	Low (2)
Available P_2O_5	Very low (1)	Very low (1)	Medium low (3)	Medium low (3)	Medium low (3)
Available K_2O	Medium (4)	Medium low (3)	Low (2)	Low (2)	Medium low (3)
Final assessment	Low (2)	Medium low (2.5)	Medium low (2.75)	Medium (3.25)	Medium (3.25)

The N:P ratios in soil are good indicators of the status of soil nutrients. The global soil N:P ratio is estimated at 13:1 [36]. The N:P ratios in S-1 and S-2 soils were 23:7 and 21:5, indicating limiting phosphorus concentration, while the lower values in S-3, S-4 and S-5 soil samples viz. 5.73, 7.9, and 6.1, respectively indicating limiting Nitrogen concentration in the soils. Similar observations on the nutrient status of the soils were reported from nearby area of Hingna Taluka of Nagpur district [37]. The fertility status analysis is important in studying the agricultural and nonagricultural soils [38].

Fly ash is formed during the high temperature coal combustion in power plants. Fly ash consists of very fine spherical particles with diameter from a few μ to 100 μ. Fly ash has all the nutrients required for the growth of plants. Available carbon and nitrogen are present in small amounts; available potassium (K) is medium, and available phosphorus (P) is high. Chemically it is amorphous ferro-alumino silicate mineral with major elements like Si, Al, Fe along with rich amount of Ca, Mg, K, P, S, and Ni. The trace nutrient metals, heavy metals and radionuclides are present in traces. The micronutrients present in fly ash are Cu, Zn, Mn, Fe, B, Mo, and trace heavy metals Se, Cr, Pb, Co, Cd, As, Hg [39–41].

Fly ash is responsible for enriching the soil with trace elements as well as is responsible for addition and storage of heavy metals in the soil. The trace nutrient metals are naturally present in the soil while toxic metals are mostly added to soil due to anthropogenic activity. The concentrations of trace metals are regulated by the biological activity of plants over the soil. On the contrary, heavy metals are extremely persistent and non-biodegradable in nature so they are prone to accumulate in soil and biomagnify in the food crops and may affect public health. In the area of coal-gangue fired-thermal power plant in China, one researcher [17] recorded high levels of Cr, Cu, Mn, Ni, Pb, Sb, V, and Zn in soil samples with high ecological risks and in a kernel of sweet corn exceeding Chinese food safety standards.

Table 6. Rating of micronutrients in soil [30].

Micronutrient	**Rating in Soil***			**Concentration in Soils**	
	Low (ppm)	**Medium (ppm)**	**High (ppm)**	**S-1, S-2 & S-3**	**S-4 & S-5**
Zinc	<0.5	0.5–1.0	>1.0	39.48–45.71 (High)	32.84–35.71 (High)
Iron	<5	5–10	>10	13.74–18.95 (High)	9.83–10.42 (Mostly Medium)
Manganese	<5	5–10	>10	–	–
Copper	<0.2	0.2–0.4	>0.4	10.41–15.67 (High)	7.73–9.74 (High)
Nickel	<20	20–30	>30	21.15–34.47 (Medium)	15.58–18.45 (Low)

The concentrations of heavy metals in the soil samples are shown in Figure 2. All the toxic metals and trace nutrient metals are present at higher concentration in S-1 and S-2 soil samples and at comparatively lower concentration in S-3, S-4, and S-5 soil samples. The village Chicholi soil sample also showed higher concentrations of toxic metals and trace metals. This may be due to the fact that this area is very near to KTPS and get fly ash through the stack emissions. These observations indicate the impact of fly ash on soil with respect to increase in the metal concentration in soils. Similar observations have been observed in case of power plants of the Kostalac and Gaeco coal basins in Serbia [31], and in case of thermal power plant at Farakka, West Bengal [33] and Jamshoro thermal power plant in Pakistan [30].

The micronutrients in soil are zinc, iron, manganese and copper. The rating of micronutrients in soils and their requirements for plant growth are given in Table 6. The micronutrient concentration in soils (S-1 & S-2) around the fly ash pond and KTPS (S-3) were higher than the respective High Ratings in soil, mostly due to fly ash pollution. Micronutrient concentrations in distant soil samples (S-4 & S-5) were slightly lower than S-1–S-3 soils, but higher than High Rating in case of zinc and copper and within the High Rating in case of iron and Nickel. This observation is supported by the finding that rich micronutrients namely DTPA-Zn (0.62–1.14 mg/kg) and DTPA-Cu (2.68–3.86 mg/kg) were responsible for optimum production of Nagpur mandarin oranges (22.0–28.3 tons/ha) in Vidarbha Region of Maharashtra [37–39].

The addition of fly ash at low level (0.5–10%) has many beneficial impacts on soil, such as enhancing organic carbon content [8], reduction of bulk density, increase in salt content, and increase in available water content [35]. However, soil pollution with fly ash led to decrease in crop productivity due to B toxicity, and P and Zn deficiency [1, 5]. Fly ash has a cementing effect that may impede the root development of crops resulting in poor growth and productivity. In soil, the decrease in total number of bacteria, actinomycetes, fungal counts and enzyme activity, such as soil phosphatases, sulphatases, dehydrogenase, and invertase was observed with increase in fly ash [27]. Thus, high rates of fly ash to soil may be detrimental to enzymatic activities of soil and nutrient cycling process.

Remediation of fly ash dumps is the priority as it is the main source of air, water and soil pollution. Phytoremediation is environmentally friendly and cost-effective method of remediation of fly ash dumps. However, the adverse factors in phytoremediation are unfavorable mechanical instability, high content of salts, deficient nitrogen and phosphorus nutrients, toxic levels of As, Cd, Cr, Cu, Hg, Mn, Mo, Ni, Pb, and Se, negligible level of microorganisms for soil related activities and almost absence of mycorrhizae [11, 19–20].

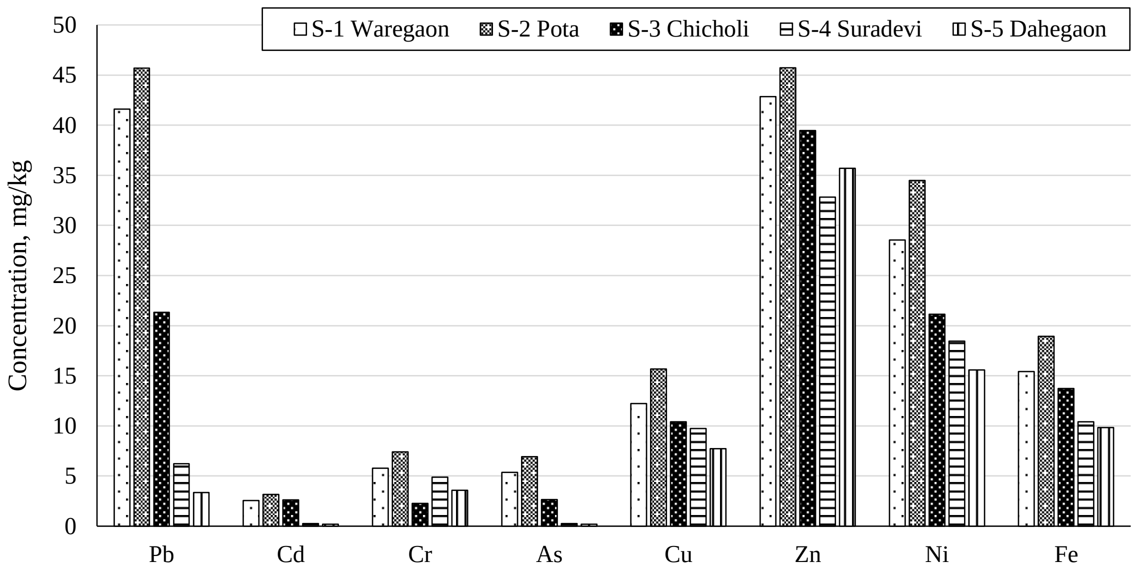

Figure 2. Distribution of metals in the soil samples.

Some researchers found out the solution to fly ash dump remediation. A comprehensive review [12] of ecological potential of plants for phytoremediation and eco-restoration of fly ash deposits are available. The dumped fly ash may be renovated by using bitumen and water spray and subsequent compaction and growing vegetation over it [12]. Remediation of fly ash polluted sandy and sandy loam soils by the same technology increases the water availability for plants [13]. Similarly, the amendment of polluted soil with sewage sludge also helped to restore the soil activities [28]. Eco-restoration of fly ash dumps is achieved by developing self-sustaining vegetation cover of the mix of grasses and legumes, and planting shrubs and trees in succession [14–15, 18–19, 23, 26]. The suitable choices of plants for phytoremediation are Chloris, Pennisetum, Vetiveria, Paspalum, Cynodon (grasses); Leucaena, Acacia, and Sesbania (legumes) and Prosopis, Eucaliptus, and Ricinus (trees) [29].

CONCLUSIONS

Pollution of soils surrounding the fly ash dumps and coal-fired thermal power plants with toxic heavy metals has been observed to be of concern, as it may lead to biomagnification in agricultural products and impacts on public health due to consumption of contaminated food. The reduction in soil fertility due to toxic metal pollution may affect agricultural productivity. The toxic metals recorded were Pb, Cd, Cr, As, and Cu. apart from trace nutrient metals at higher concentrations. The toxic metals Pb, Cd, As, and Cr showed strong positive correlation with each other indicating their common origin from fly ash. Environmentally friendly and cost-effective remedial measures, such as phytoremediation are given to remediate the fly ash polluted soils and fly ash dumps.

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