



Comparative assessment of soil properties and heavy metals indices at rehabilitated and non-rehabilitated sites in coal mine spoils

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Abstract

Rehabilitation of open-cast coal mines is a critical intervention for bringing back productive surface soil and sustaining ecosystem functioning. Mining activities not only disturb the key soil properties, but also cause heavy metal contamination. Significantly, 32,000 acres of land in Odisha have been affected by coal mine. In this study, two representative mine areas, Talcher and Jharsuguda in Odisha were selected for our study. The soil physicochemical, available soil nutrient, microbial biomass carbon, soil enzymatic activities and heavy metal contents were estimated in the three sites (rehabilitated, non-rehabilitated and paddy fields) and two soil depth (0–15 and 15–30 cm) of both Talcher and Jharsuguda. The soil pH was higher in rehabilitated sites (5.55 to 8.42) as compared to the paddy fields (5.38 to 5.85) and non-rehabilitated sites (4.16 to 4.57). The average available nitrogen and phosphorus contents were lower in non-rehabilitated sites than the rehabilitated sites and paddy fields. Labile carbon pools (readily mineralizable carbon and microbial biomass carbon), soil enzymatic activities (dehydrogenase and fluorescein di-acetate) were negatively affected by mining activities and it was higher in paddy soil than the rehabilitated and non-rehabilitated sites. Further, the heavy metals (cobalt, copper, iron, and lead) were relatively higher at non-rehabilitated and rehabilitated sites. Heavy metal-based geo-accumulation, integrated pollution and pollution load indices were indicated the possible pollution risk in the rehabilitated study site also. Therefore, we recommend a better technical effort should be made in the top-soil management of coal mine spoil areas during rehabilitation to sustain the productive ecosystem functioning.

Keywords Coal mine spoils · Rehabilitation · Pollution load index · Heavy metals · Paddy

Introduction

Coal mining plays a pivotal role in the economic development in India and many other countries as it is an integral part of the commercial energy production and mostly utilized for the generation of electricity. Although, coal plays a strategic role in energy development, but the long-term environmental impacts caused by coal mining cannot be ignored (Chaulya 2003; Jie et al. 2021). Coal mining results in generation of a large amount of overburden that releases

toxic contaminants to soil biota, which in turn affects the soil health (Swaine and Goodarzi 1995; Milder et al. 2013; Ghosh and Maiti 2020). Open cast mining activities have been found to cause distortion of soil physicochemical properties and land degradation in many ways that includes heaping of the fragmented rock during mining and the removal of the fertile top soil. A mixture of coal, coarse rocks, sands, dusts, shale, pebbles and other toxic wastes are frequently found in the mine spoil (Sheoran et al. 2010; Choudhury et al. 2021). Due to lack of fertility and biological rich top-soil, the mine spoils become infertile and hinder the pedogenesis and restoration of vegetation (Maharana and Patel 2013).

The coal mining processes result in the deposition of large amount of spoils and waste materials having high metal content. More so, natural weathering and leaching from the spoil heaps also releases toxic elements into the soil (Pietrzykowski et al. 2013; Bhuiyan et al. 2021). In coal mining locations, metal contamination is a key limiting factor for

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soil quality and health. Furthermore, during the restoration phase, mine wastes may be mixed with surface soil. These irreversible and persistent metals might build up in reclaimed soils. Additionally, heavy metal deposition above the threshold level may cause soil contamination and deterioration of soil quality, affecting agricultural productivity and posing a danger to human and animal health via the food chain (Tang et al. 2018). Therefore, it is necessary to assess the rehabilitated areas to check the metal accumulation in the reclaimed sites.

Odisha is a coal-rich state located in the eastern part of India. Odisha has two Gondwana coalfields, situated in the western part of the state namely Talcher and Ib valley that caters to both open-cast as well as underground mining (Palatasingh and Satapathy 2021). Anugul (12 mining leases; 9,590 ha) is the major coal mining district followed by Jharsuguda (1 mining leases; 7,656.55 ha), Sambalpur (1 mining lease; 170.305 ha) and Sundargarh (1 mining lease; 140.84 ha). A total of 79,295 million tonnes of coal reserves has been estimated in Odisha which constitutes about 25% of the total reserves of the country as of 2018 (Ministry of Coal, Govt of India 2021). The production of coal was 140.36 million tons in Odisha, during 2019–2020 (Mahanadi Coalfields Limited (MCL)).

Coal is an important natural resource and fossil fuel that is abundant in Odisha. A stream of advantages from coal mining in Odisha, including revenue from export profits, industrialization, and employment generation. Coal mining benefits the society while also causing several problems. Mining-induced pollution, relocation, natural resource depletion or deterioration are the key environmental problems confronting the coal sector in Odisha. It has an impact on rural populations' long-term livelihoods. However, the detrimental effects of coal mining on people's health, land, water, air, plants and animals, and livelihoods might be mitigated with good planning. It is critical to strike a balance between coal mine development and environmental rehabilitation in order to sustain livelihoods of local people (Singh and Chaudhury 2019).

Soil is a limited and valuable natural resource, and maintaining its quality is utmost concern. Moreover, soil quality is connected to a variety of factors such as the environment, social, economic, and human health (Brevik et al. 2015; Hou et al. 2020). Both surface vegetation and soil quality are affected by mining activities. Slow rate of mine spoil rehabilitation is major concern for microbial growth and vegetation.

Rehabilitating degraded lands (by anthropogenic or natural methods) involves restoring their productivity and biotic functions to a desired level. Soil physico-chemical parameters, which are long-term markers of soil quality/health in mine waste rehabilitation regions, must be restored (Esposito et al. 2010; Worlanyo and Jiangfeng 2021). Rehabilitation strategies should be inclusive of the betterment of soil physical as well as biological and chemical processes with reduction of heavy metal loads. The topsoil management including enriching of microbial populations, nutrient cycling, increasing resilience of the soil system are necessary to make the system self-sustaining.

Thereby, in this study, we focused on the three sites in the coalmining areas (rehabilitated, non-rehabilitated mine sites, and adjacent paddy fields) and judged the physiochemical and biological parameters to see the soil quality status which is necessary for the sustainable crop productivity. Considering these issues, the objectives of the study was to compare the physio-chemical and biological characteristics of the soil as well as heavy metal pollution indices in three different land uses; rehabilitated, non-rehabilitated mine sites, and adjacent paddy fields in Talcher and Jharsuguda of the state Odisha, India.

Materials and methods

Study sites

Two coal mine areas were selected at Talcher and Jharsuguda (Odisha), India. The study areas are located in eastern India at latitudes 20°59' N, 85°08' E (Talcher), and 21°85' N, 84°00' E (Jharsuguda), respectively. The coal mines are in sub-tropical climate (1421 mm annual rainfall; average annual temperature 32 °C; average relative humidity 78.6%) that experiences periods of rabi and kharif seasons for rice cultivation. In both Talcher and Jharsuguda, the mining was started more than 10 years before. However, the rehabilitation of the mining sites was started before 5 to 6 years of the sample collection in both Talcher and Jharsuguda.

Soil sampling

Soil samples were collected from the 'coal mine spoil' area at Talcher and Jharsuguda. Study areas were divided

into 3 sites with distinct land-uses, viz., (i) cultivated paddy field; (ii) rehabilitated site after coal mining; and (iii) non-rehabilitated site after mining. The sites were selected within a radius of 2 km. Three replicated samples (each sample composited by eight representing zig-zag points) were collected randomly from each site at two soil depths of 0–15 cm (topsoil) and 15–30 cm (subsoil). The samples were homogenized properly, transported to laboratory with due care and stored at 4 °C for further microbial and biochemical analyses. For soil organic carbon, pH, electrical conductivity (EC) and heavy metal analyses the air-dried samples (sieved through 2.0 mm sieve) were used.

Soil physico-chemical properties

A digital pH/EC meter (Model: Systronics, MKVI) was used to measure the soil pH (1:2.5 ratio of soil: water). Soil organic carbon (SOC) content was estimated by the wet-oxidation method (Walkley and Black 1934). Kjeldahl technique was used to measure the available nitrogen content (Subbiah and Asija 1956). The Olsen (0.5 M NaHCO₃) extractable phosphorous content of the soil was estimated by using stannous chloride reduction following the blue-colour method (Olsen 1954).

Soil biological properties

The readily mineralizable carbon (RMC) content of the soil was estimated after extraction with 0.5 M K₂SO₄ followed by wet digestion of the extract with dichromate (Witt et al. 2000). Microbial biomass carbon (MBC) was determined using the chloroform fumigation extraction method (Vance et al. 1987). Dehydrogenase activity of soil was measured by Spectrophotometric method (Casida et al. 1964). In this method the 2, 3, 5-triphenylotetrazolium chloride (TTC), (as an artificial electron acceptor) is reduced to red-coloured triphenyl formazon (TPF); followed by measuring the concentration of TPF spectrophotometrically (Casida et al. 1964). Fluorescein diacetate (FDA) hydrolysis activity was assayed by the method given by Schnurer and Rosswall (1982), and as modified later by Adam and Duncan (2001).

Heavy metal concentration in soil

Modified nitric-perchloric acid digestion procedure as recommended by the AOAC (1990) was followed

for determination of heavy metals iron (Fe), manganese (Mn), cobalt (Co), lead (Pb) concentration. The 1 g of sieved oven dried soil sample was digested by using 5 mL of HNO₃, 15 mL of concentrated H₂SO₄ and 0.3 mL of HClO₄ using a dropping pipette. The mixture was digested in a fume cupboard with continuous heating until a dense white fume appeared. The mixture was cooled and diluted with distilled water and filtered through acid-washed Whatman No. 44 filter paper into a 50 mL volumetric flask. The filtrates were then estimated in atomic absorption spectrophotometer (AAS) (Model: Analyst 100, Perkin-Elmer, USA).

Heavy metal-based indices

Three metal-based indices were calculated based on the metal content of the soil and is generally used to assess the extent of soil degradation in terms of metal contamination.

(i) Geo-accumulation index, I_{geo} (Rodriguez-Seijo et al. 2016):

$$I_{geo} = \log_2 \left(\frac{C_n}{1 : 5B_n} \right) \quad (1)$$

where, C_n refers to the total metal concentration measured in each soil, and the corresponding control value (background value) is expressed as B_n. Possible lithogenic related background variations are compensated by using a constant (1.5).

Table 1 Defined classes of Geo-accumulation index (I_{geo}), Integrated pollution index (IPI) and Pollution load index (PLI) for identifying the contamination levels in analyzed soil samples

Igeo class	Igeo values	Contamination level
0	Igeo ≤ 0	Uncontaminated
1	0 < Igeo ≤ 1	Uncontaminated/moderately contaminated
2	1 < Igeo ≤ 2	Moderately contaminated
3	2 < Igeo ≤ 3	Moderately/heavily contaminated
4	3 < Igeo ≤ 4	Heavily contaminated
5	4 < Igeo ≤ 5	Heavily/extremely contaminated
6	Igeo ≥ 5	Extremely contaminated
IPI class	IPI values	
	IPI ≤ 1	Low
	1 < IPI ≤ 2	Medium
	IPI > 2	High
PLI class	PLI values	
	< 50	Drastic rectification measures are not needed
	≥ 50 to < 100	More detailed study is needed to monitor the site
	≥ 100	An immediate intervention to ameliorate pollution to maintain soil quality



Table 2 Physicochemical properties of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha

Sites	Depth (cm)	Jharsuguda										
		Talcher					Jharsuguda					
		Physicochemical properties		Soil Organic Carbon (g kg ⁻¹)		Available nutrients (kg ha ⁻¹)		Physicochemical properties		Soil Organic Carbon (g kg ⁻¹)		Available nutrients (kg ha ⁻¹)
pH	EC (dS m ⁻¹)	Soil Organic Carbon (g kg ⁻¹)	Soil Organic Carbon (g kg ⁻¹)	N	P	pH	EC (dS m ⁻¹)	Soil Organic Carbon (g kg ⁻¹)	Soil Organic Carbon (g kg ⁻¹)	N	P	
Paddy field	0–15	5.55 ± 0.10	0.17 ± 0.04	5.6 ± 0.04	5.6 ± 0.04	181.0 ± 1.0	26.9 ± 2.3	5.85 ± 0.04	0.21 ± 0.07	6.1 ± 0.09	162.0 ± 0.04	12.0 ± 1.00
	15–30	5.51 ± 0.05	0.18 ± 0.02	4.4 ± 0.04	4.4 ± 0.04	194.8 ± 0.4	19.4 ± 0.6	5.38 ± 0.1	0.17 ± 0.02	4.9 ± 0.07	117.0 ± 0.2	12.2 ± 0.23
Rehabilitated	0–15	7.35 ± 0.1	0.18 ± 0.02	6.7 ± 0.02	6.7 ± 0.02	17.0 ± 0.01	25.4 ± 0.2	5.55 ± 0.2	0.04 ± 0.01	3.9 ± 0.2	60.2 ± 0.05	8.4 ± 0.6
	15–30	8.42 ± 0.2	0.12 ± 0.02	4.2 ± 0.09	4.2 ± 0.09	32.6 ± 1.2	10.7 ± 0.2	5.75 ± 0.4	0.02 ± 0.01	2.8 ± 0.1	59.6 ± 2.0	15.9 ± 0.8
Non-rehabilitated	0–15	4.53 ± 0.4	0.84 ± 0.06	2.6 ± 0.06	2.6 ± 0.06	17.0 ± 0.1	6.1 ± 0.06	4.38 ± 0.09	0.91 ± 0.1	1.8 ± 0.06	53.3 ± 0.04	16.2 ± 0.13
	15–30	4.57 ± 0.6	0.85 ± 0.05	1.8 ± 0.02	1.8 ± 0.02	31.6 ± 0.4	6.0 ± 0.4	4.16 ± 0.1	0.93 ± 0.08	1.1 ± 0.02	43.9 ± 1.2	18.8 ± 0.2

ANOVA statistics (<i>p</i> ≤ 0.05)													
CD values	Factors	A			S			A × S			D		
		A	S	A × S	S	A × S	A × S	D	A × D	S × D	A × S × D		
pH		0.178	0.218	0.308	0.218	0.308	0.308	NS	0.252	0.308	NS		
EC		NS	0.047	0.066	0.047	0.066	0.066	NS	0.054	NS	NS		
SOC		0.054	0.066	0.094	0.066	0.094	0.094	0.054	NS	NS	NS		
Avl N		0.580	0.710	1.004	0.710	1.004	1.004	0.580	0.820	1.004	1.420		
Avl P		NS	12.353	17.471	12.353	17.471	17.471	NS	14.264	NS	NS		

EC: electrical conductivity; N: nitrogen; P= phosphorous

A = area (Talcher and Jharsuguda), S = site (paddy field, rehabilitated and non-rehabilitated) and D = depth (0–15 and 15–30 cm); NS = non-significant; ± Number represents the standard deviation (SD)

This index represents the extent of contamination in terms of seven enrichment classes (Table 1).

(ii) Pollution indices (PI and IPI) (Rodriguez-Seijo et al. 2016):

$$PI_i = \frac{C_n}{B_n} \tag{2}$$

The IPI was calculated as the mean of respective PI values of metal (PI = 1, 2, ... i) (Table 2).

(iii) Pollution load index (PLI) (Ali et al. 2016):

$$PLI = \sqrt[n]{PI_1 \times PI_2 \times PI_3 \dots PI_n} \tag{3}$$

Here, subscript 1, 2, 3 ..., n of PI denotes the pollution indices of n number of metals (1, 2 ... n). (Classification of PLI values as mentioned in Table 1).

Statistical analysis

The OPSTAT was used for the analysis of variance (ANOVA) and the least significant difference at $p \leq 0.05$ levels and the interaction effects of three factors i.e., (i) area (A) (Talcher and Jharsuguda), (ii) sites (S) (paddy field, rehabilitated and non-rehabilitated) and (iii) soil depth (D) (0–15 and 15–30 cm) were estimated for each parameter.

Results and discussion

Physicochemical properties of soil

The average soil pH of paddy fields in both the areas (Talcher and Jharsuguda) was found to be slightly acidic

and ranged from 5.38 to 5.85 (Table 2). In contrast, soil belonging to the non-rehabilitated sites after mining was in an extremely acidic range, which varied from 4.53 to 4.57 and 4.16 to 4.38 in Talcher and Jharsuguda, respectively. Rehabilitated sites after mining showed a relatively higher pH as compared to the paddy fields and non-rehabilitated sites and varied from 5.55 to 8.42 (Table 2). The factor area (A) and sites (S), and their interaction effect (A × S, A × D and S × D) had a significant effect on soil pH except soil-depth (D) and A × S × D (Table 2). The average electrical conductivity (EC) was higher in non-rehabilitated sites (ranged from 0.84 to 0.93 dS m⁻¹) followed by paddy fields (0.17 to 0.21 dS m⁻¹) and rehabilitated sites (0.02 to 0.18 dS m⁻¹) in both Talcher and Jharsuguda (Table 2). Among all the factors, S, A × S and A × D had significant effects on the EC.

Soil chemical properties

The higher soil organic carbon (SOC) contents were obtained at the topsoil (0–15) than subsoil (15–30) at all the sites (Table 2). The SOC content was in the range of 4.4 to 6.1 g kg⁻¹, 2.8 to 6.7 g kg⁻¹ and 1.1 to 2.6 g kg⁻¹ in paddy fields, rehabilitated and non-rehabilitated sites of Talcher and Jharsuguda, respectively. However, comparing the three sites, the average SOC contents were significantly higher in paddy fields (5.3 g kg⁻¹) as compared to rehabilitated (4.4 g kg⁻¹) and non-rehabilitated (1.8 g kg⁻¹) sites. The higher soil available nitrogen (N) content was recorded in paddy fields (ranged from 117.0 to 194.8 kg ha⁻¹) as compared to rehabilitated sites (17.0 to 60.2 kg ha⁻¹) and non-rehabilitated sites (17.0 to 53.3 kg ha⁻¹) in both Talcher and Jharsuguda. The three factors (A, S and D) and their interaction effects (A × S, A × D, S × D and A × S × D) had a significant effect on soil available N contents (Table 2).

Fig. 1 Readily mineralizable carbon (RMC) contents of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha

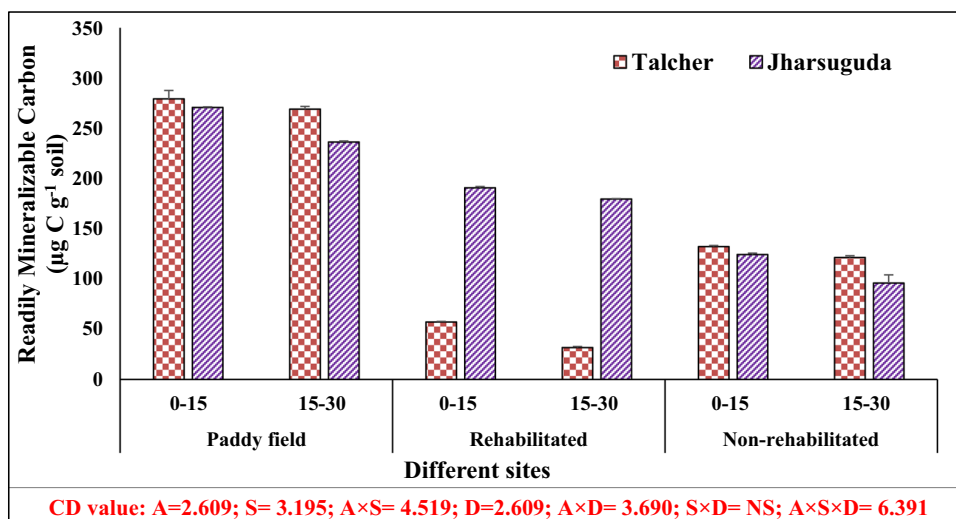


Fig. 2 Microbial biomass carbon (MBC) contents of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha

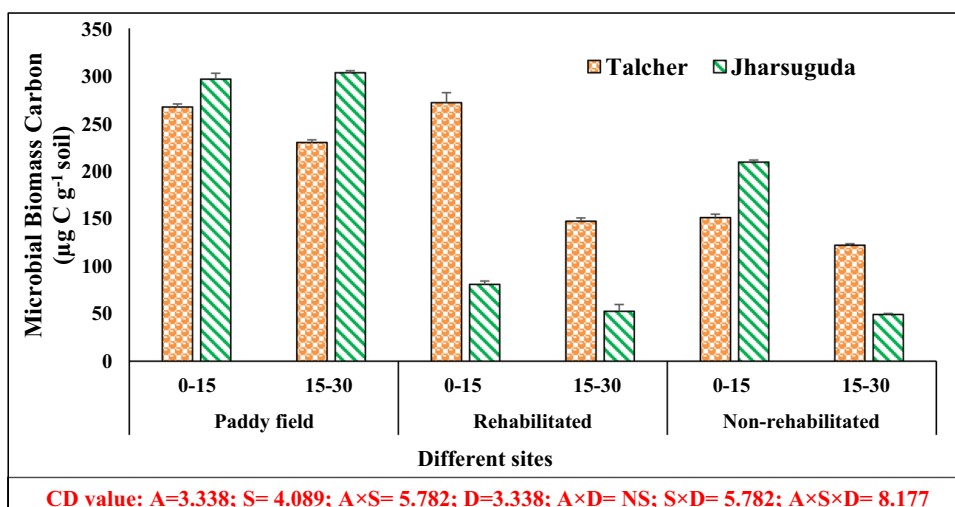
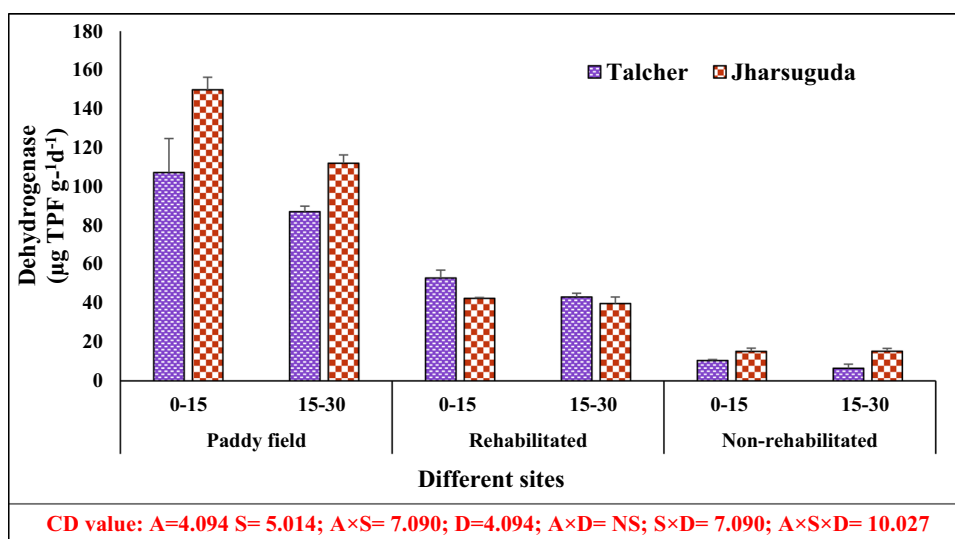


Fig. 3 Dehydrogenase (DHA) activity of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha



Variation in Olsen's extractable phosphorus (P) was observed in the two different locations, which ranged from 6.0 to 26.9 kg P ha⁻¹ at Talcher and 8.4 to 18.8 kg P ha⁻¹ at Jharsuguda (Table 2). The average available P was higher in paddy fields (17.6 kg ha⁻¹) as compared to rehabilitated sites (15.1 kg ha⁻¹) and non-rehabilitated sites (11.8 kg ha⁻¹) in both Talcher and Jharsuguda. Among all the factors, S, A×S and A×D had significant effects on soil available P content (Table 2).

Soil biological properties

Considerable variation in readily mineralizable carbon (RMC) was found at different sites. The RMC contents were ranged from 236.2 to 279.1, 31.8 to 190.9 and 96.1

to 132.4 µg C g⁻¹ soil, in paddy fields, rehabilitated and non-rehabilitated sites, respectively in both Talcher and Jharsuguda (Figure 1). In both the areas (Talcher and Jharsuguda), the average MBC contents were higher in paddy fields (274.3 µg C g⁻¹ soil) followed by rehabilitated (138.2 µg C g⁻¹ soil) and non-rehabilitated (132.8 µg C g⁻¹ soil) sites (Figure 2). The three factors (area, sites and soil-depths) had significant effects on the RMC and MBC contents (Figs. 2 and 3).

The higher soil dehydrogenase activities (DHA) were observed in paddy fields (ranged from 87.1 to 149.7 µg TPF g⁻¹ day⁻¹) in both the location (Talcher and Jharsuguda), due to the presence of higher soil organic matter that supports higher microbial activities (Figure 3). However, lower DHA activities were observed in non-rehabilitated (6.5 to

Fig. 4 Fluorescein-diacetate hydrolyzing (FDA) activity of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha

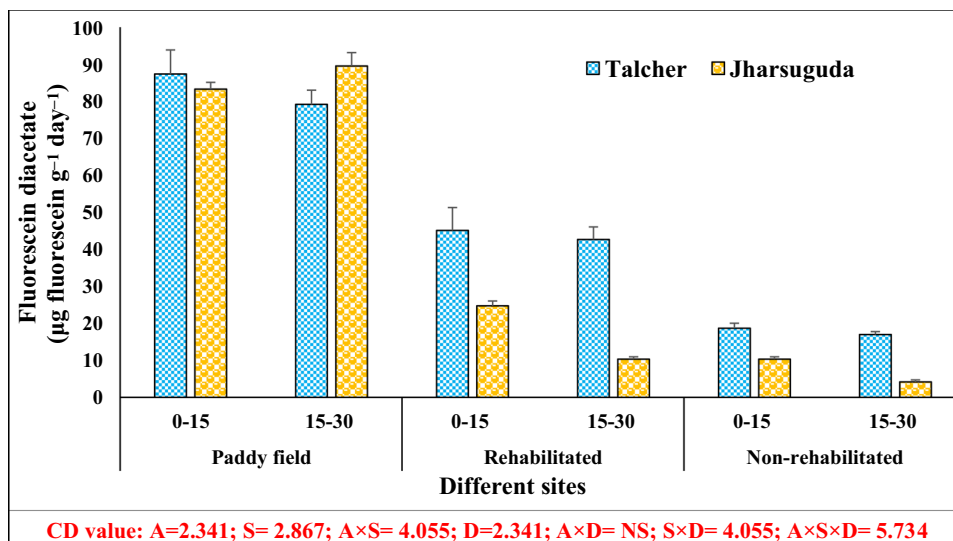


Table 3 Micronutrients and heavy metal concentrations (mg kg⁻¹ of soil) of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha

Sites	Depth (cm)	Talcher				Jharsuguda			
		Co (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Co (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Pb (mg kg ⁻¹)
Paddy field	0–15	0.55 ± 0.1	55.32 ± 1.6	24.80 ± 2.9	4.10 ± 0.6	0.38 ± 0.02	54.82 ± 2.5	19.73 ± 2.3	8.76 ± 0.9
	15–30	0.75 ± 0.02	87.18 ± 2.0	30.52 ± 1.1	7.33 ± 0.1	0.40 ± 0.08	89.38 ± 2.0	30.75 ± 1.9	10.93 ± 0.5
Rehabilitated	0–15	2.15 ± 0.2	101.17 ± 3.0	40.90 ± 2.2	12.15 ± 2.0	0.55 ± 0.06	76.68 ± 1.3	31.33 ± 2.1	18.60 ± 0.3
	15–30	1.98 ± 0.08	109.03 ± 5.5	47.63 ± 4.9	11.80 ± 1.6	1.75 ± 0.05	107.17 ± 6.6	46.55 ± 2.6	20.37 ± 0.8
Non-rehabilitated	0–15	3.23 ± 0.04	108.83 ± 4.6	98.28 ± 5.6	43.10 ± 1.0	5.53 ± 0.01	140.67 ± 4.0	63.00 ± 2.2	67.77 ± 1.9
	15–30	2.40 ± 0.04	115.83 ± 5.1	51.32 ± 2.0	19.43 ± 1.9	4.40 ± 0.14	105.07 ± 1.0	31.67 ± 1.6	15.50 ± 1.0

*Threshold limit Co- 50 (mg kg⁻¹); Fe-5000 (mg kg⁻¹); Mn- 2000 (mg kg⁻¹); Pb- 100 (mg kg⁻¹)

ANOVA statistics ($p \leq 0.05$)

CD Values	Factors	A	S	A×S	D	A×D	S×D	A×S×D
	Co	0.060	0.074	0.104	0.060	0.085	0.104	0.147
	Fe	NS	3.075	4.349	2.511	3.551	4.349	6.150
	Mn	2.051	2.511	3.552	2.051	2.900	3.552	NS
	Pb	0.864	1.058	1.496	0.864	1.222	1.496	2.116

*The maximum allowable limits of metals in soils by World Health Organization (WHO)

A=area (Talcher and Jharsuguda), S=site (paddy field, rehabilitated and non-rehabilitated) and D=depth (0–15 and 15–30 cm); NS=non-significant; ± Number represents the standard deviation (SD)

15.3 µg TPF g⁻¹ day⁻¹) and rehabilitated (39.9 to 52.9 µg TPF g⁻¹ day⁻¹) sites of Talcher and Jharsuguda (Figure 3). The soil FDA activities showed a similar trend like DHA among the sites in both the locations (Talcher and Jharsuguda). The average FDA activities were higher in paddy fields (84.8 µg fluorescein g⁻¹ day⁻¹) followed by rehabilitated (30.7 µg fluorescein g⁻¹ day⁻¹) and non-rehabilitated

(12.6 µg fluorescein g⁻¹ day⁻¹) sites of both the areas and two soil depths (Figure 4). The three factors and their interaction effect had a significant effect on soil DHA and FDA activities.

Table 4 Geo-accumulation indices of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha

Area	Sites	Depth	Geo-accumulation indices			
			I _{geo} (Co)	I _{geo} (Pb)	I _{geo} (Fe)	I _{geo} (Mn)
Talcher	Paddy field	0–15	0.008	0.051	0.0003	0.006
		15–30	0.011	0.091	0.0005	0.008
	Rehabilitated	0–15	0.033	0.152	0.0006	0.010
		15–30	0.03	0.148	0.0006	0.012
	Non-rehabilitated	0–15	0.049	0.540	0.0006	0.026
		15–30	0.037	0.243	0.0006	0.013
Jharsuguda	Paddy field	0–15	0.005	0.109	0.0003	0.005
		15–30	0.006	0.137	0.0005	0.008
	Rehabilitated	0–15	0.008	0.233	0.0004	0.008
		15–30	0.027	0.255	0.0006	0.012
	Non-rehabilitated	0–15	0.085	0.849	0.0008	0.016
		15–30	0.067	0.194	0.0006	0.008

Heavy metals in soils

In the three contrasting sites of two different area revealed that metal contents were higher on non-rehabilitated sites over, rehabilitated and paddy soil (Table 3). The mean concentration of cobalt (Co), iron (Fe), manganese (Mn) and lead (Pb) in soils of non-rehabilitated sites were in the range between 4.4–5.53, 105.07–140.67, 31.67–63.00 and 15.50–67.77 mg kg⁻¹, respectively in Jharsuguda. Whereas, in Talcher, the mean concentration of Co, Fe, Mn and Pb in soils of non-rehabilitated sites was 2.40–3.23, 108.38–113.38, 51.52–98.28 and 19.43–43.10 mg kg⁻¹, respectively. Results also showed that even after rehabilitation of mining areas, significant amounts of metal were accumulated at the reclaimed sites. However, the abundance of metals was lower at top soil (0–15 cm) as compared to the lower depth (15–30 cm) in the paddy field and rehabilitated sites. However, in the non-rehabilitated sites, the top soil showed higher metal contents than that of lower soil depth (Table 3).

Metal-based indices

Based on the results of chemical analyses, three different metal indices were estimated to observe whether mining and further rehabilitation work in Jharsuguda and Talcher have been contaminated the nearby lands. Results were compared between three different sites i.e., paddy field, rehabilitated and non-rehabilitated sites. The geo-accumulation indices (I_{geo}) of all the four metals (Co, Fe, Mn and Pb) showed the highest values at non-rehabilitated

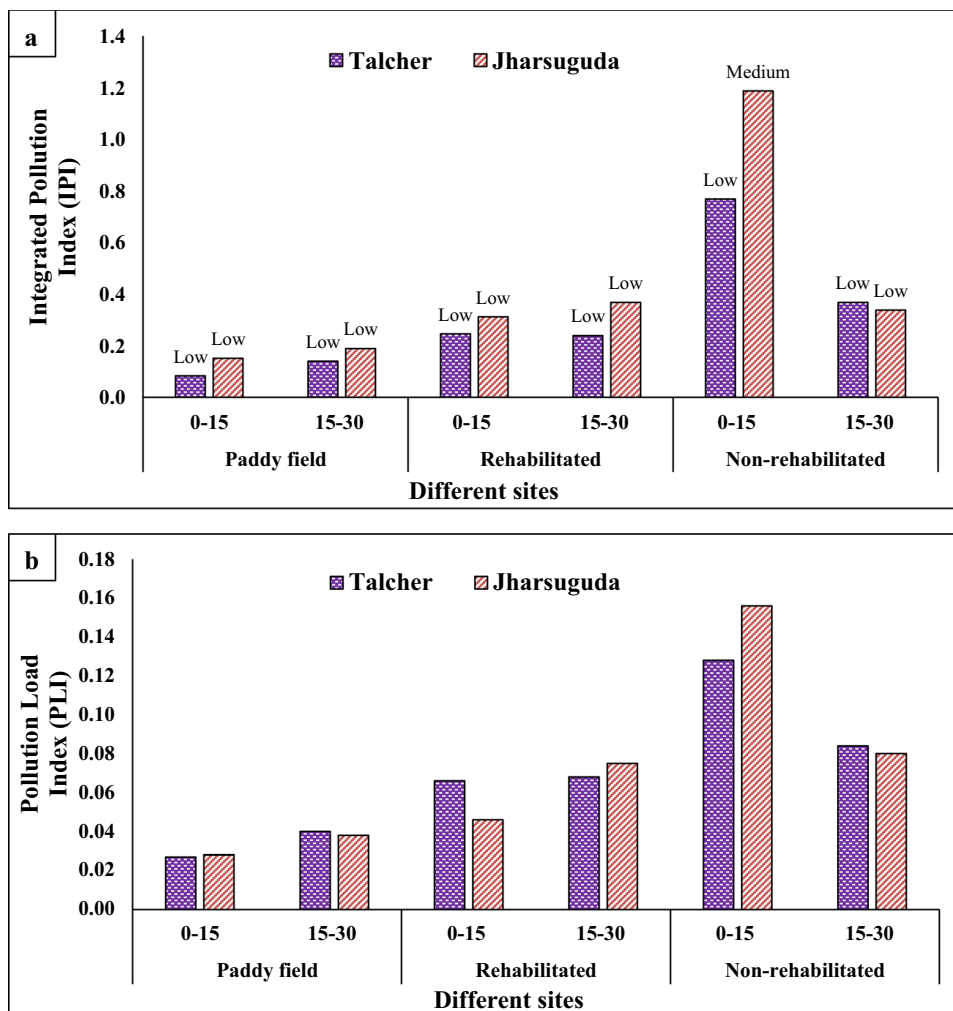
soil, whereas paddy soils showed the lowest I_{geo} values (Table 4). Further, among the metals, the I_{geo} of iron (Fe) showed the least variation among the sites, as well as in two locations. Non-rehabilitated sites at Jharsuguda (I_{geo}: 0.085 (Co) and 0.85 (Pb)) revealed a higher range of I_{geo} values at both the soil depths over that of Talcher (I_{geo}: 0.05 (Co) and 0.54 (Pb)), which apparently indicated the former location is exposed to more risks of metal contamination due to mining. Though rehabilitation has moderated the scenario, and paddy field of nearby locations seemed to be less affected. As per the I_{geo} classification (Table 1), the I_{geo} values of our experimental sites fall in the class 1, which denotes uncontaminated or moderately contaminated zones.

The Integrated pollution index (IPI) values of Jharsuguda also showed a higher range at non-rehabilitated sites (1.19), which comes in 'Middle' class of soil contamination. The IPI of other sites was observed to have < 1 value, hence those sites have low risk of contamination (Fig. 5a). Pollution load index (PLI) values showed that in all sites of Talcher and Jharsuguda falls in the class < 50, indicated drastic rectification measures are not needed at this stage (Fig. 5b).

Soil biogeochemical properties: changing scenario due to rehabilitation of mine soil

The pH plays a major role in biodiversity maintenance by regulating soil reaction, buffering and plant nutrient availability. Severe soil disturbing activities like mining unavoidably causes changes in soil pH. In general, the pH at non-rehabilitated sites is acidic in nature. This might be due

Fig. 5 Variation in values of metal indices; Integrated Pollution Index (IPI) and Pollution Load Index (PLI) of three sites (paddy soil, rehabilitated and non-rehabilitated sites after coal mining) at two different soil depths (0–15 and 15–30 cm) in Talcher and Jharsuguda districts of Odisha



to the leaching of basic cations from the top soils. Under such acidic conditions, toxicities of hydrogen ion (H^+), iron (Fe) and manganese (Mn) and other heavy metal ions could be possible (Singh et al. 2020). Acidification of mine spoil from number of mineral deposits has also been reported (Taha et al. 2017). Nevertheless, earlier research (Dutta and Agarwal 2002) suggests that natural succession or a suitable planting strategy can increase soil pH on coal mine spoil in both passive and active reclamation modes. This can be explained by the mixing of subsurface layers with top soils during reclamation (Shi et al. 2021), or it might be due to the activity of root exudates from tree species planted on rehabilitated soil causing the variance in soil EC (Mukhopadhyay and Masto 2016).

Soil organic carbon (SOC) is an important indicator of long-term soil health. We observed that SOC rose by 117 and 158% respectively, in top soil and at lower depth at

restored sites in Talcher and Jharsuguda mine-spoils locations. Even at the Talcher site, the SOC content of rehabilitated soil was found to be similar to that of paddy soil. Plantation of tree species, specifically increasing the soil carbon content through the input of litter from vegetation through time, might be used to improve SOC and restore coal mine waste (Jha and Singh 1991; Pena et al. 2015; Mukhopadhyay and Masto 2016). There are some obvious events associated with the mining activity (stripping, stockpiling, and reinstatement) causing physical disturbances to the top soil, which further lead to substantial nutrient loss (Sheoran et al. 2010). Nitrogen and phosphorus, two major plant nutrients, are usually found to be deficient in the mining areas. We also found significantly lower concentrations of available N and P content in the non-rehabilitated and rehabilitated sites as compared to paddy soils. The deficiency of nutrients was directly related to the reduction in soil microbial activity

and excessive leaching. Several reasons might have contributed to the depletion of nutritional status in mine soils. Changes in biological properties of soils, such as a decrease in microbial biomass carbon, a decrease in organic matter as a substrate for soil urease (Kizilkaya and Bayrakli 2005), and a decrease in urease enzyme synthesis due to a decrease in microbial population (Bandick and Dick 1999), may be the cause of less N availability in mining areas. Bendfeldt et al. (2001) and Urraa et al. (2020) discovered that organic additions (saw dust and sewage sludge) boosted mineralizable soil N and extractable soil-P, resulting in improved nutrient availability and mine soil quality. Thus, appropriate top soil reclamation is critical to minimizing N and other nutrient losses. The release of soluble P from P-bearing minerals during mining operations might explain why non-rehabilitated sites had a greater concentration of accessible P in the study sites. On the other hand, the addition of basal phosphatic fertilizers is likely to have contributed to the accumulation of P in the paddy fields under investigation. Soil biological activities are inextricably related with ecosystem processes and are essential indicators in determining soil quality. Microbial biomass carbon (MBC) is frequently used as an indicator to assess how soil microbiota respond to management approaches, environmental changes, site disturbance, and soil pollutants. Non-rehabilitated sites had lower MBC and RMC than rehabilitated and paddy soil. Soil enzymatic activity are also valuable indicators for detecting changes in certain biological processes in mine soils (Lemanowicz 2019). Furthermore, it aids in assessing the changing nutrient dynamics in soil. Unmined paddy soils had the highest microbial activity, followed by rehabilitated sites and non-rehabilitated mine spoil sites. Researchers also discovered reduced MBC levels in mine spoil soil, as well as an excess of heavy metals and their detrimental impacts on soil microorganisms. Non-rehabilitated sites had lower MBC, RMC, and enzymatic activity, followed by rehabilitated and paddy soil. The active center and structure of soil enzymes are changed due to the presence of heavy metals, which resulted in a decrease in the concentrations of the enzymes amylase and invertase, which respectively impede the breakdown of starch and sucrose (Guo et al. 2019). Furthermore, the interaction of heavy metals prevents microbial growth (Zhu sin et al. 2006), which lowers enzyme synthesis and secretion and leads to a reduction in the soil microbial biomass carbon. The effective and suitable plantation could improve the MBC and other soil microbial parameters in mine areas, particularly in rhizosphere soil (Sinha et al. 2009; Mukhopadhyay et al. 2016).

Dehydrogenase is a sensitive indicator of microbial activity (electron transport system), and metabolic status of soil microorganisms (Su et al. 2019). The present study also discovered an increase in dehydrogenase activity at rehabilitated sites, which may be related to the soil's higher SOC content compared to non-rehabilitated sites. In a related study, pH, EC, organic carbon and P content, and dehydrogenase activities were identified as key indicators of soil quality in a reclaimed coal mine spoil in Dhanbad, India (Mukhopadhyay and Masto 2016b). Higher FDA values were noticed in paddy soils compared to non-rehabilitated sites in our study. Depleted SOM and increased heavy metals levels may be the cause of decreased FDA activity in mine spoil regions (Martnez-Toledo et al. 2017), which is relevant to the current study.

Heavy metal pollution, rehabilitation procedure and approach towards sustainable soil health

Mining activity serves as an ample source of metal contamination in ecosystems. This activity might affect relatively localized areas, but has a crucial impact on the on-site and surrounding environment. We investigate the metal pollution of the soil in the coal mined areas. The overburden spoils and coal gangue were the main sources of heavy metal pollution in coal mining areas. Improperly managed overburden spoils and coal gangue have the potential to transmit harmful compounds to reclaimed soil, resulting in significant soil contamination in reclaimed regions (Sun et al. 2014; Zhou et al. 2014). In our study, we found that as compared to the paddy fields the concentration of Co, Fe, Mn and Pb in the top soil of rehabilitated site were higher by 1.45–1.82, 1.41–1.81, 1.59–1.64 and 2.1–2.96 factor, respectively in both the areas (Talcher and Jharsuguda). It indicates the mixing of over burden soils and coal gangue during the rehabilitation process. According to Ghose and Kundu (2004), the concentration of Fe and Mn in overburden soil grew with time and eventually exceeded the concentration in unmined soil. Similarly, heavy metal concentration was greater in reclaimed soils at the Heidaigou opencast coal mine region than in nearby unmined areas. As a corollary, Tang et al. (2018) discovered, elevated concentrations of Cu, Zn, and Pb in reclaimed areas in Xinzhuangzi, China, which were greater by factors of 1.51, 2.05, and 1.48, respectively, than agricultural soil near a coal mine. The metal concentration in certain locations might be caused by effluents produced during mining and leaching from coal gangue (Zhou et al. 2014). In this study, the metal concentrations in non-rehabilitated sites from both the areas were found to be several

orders of magnitude higher than the paddy fields and rehabilitated sites. However, the concentrations of these metals were lower than the WHO/FAO threshold levels (as shown in Table 3). (Chiroma et al. 2014). The comparison of the paddy field, rehabilitated site, and non-rehabilitated site revealed that the soils of the study area were contaminated with metals even after the reclamation procedure. Besides, metals are non-biodegradable due to significant absorption on humus and clay colloids in soils (Bakircioglu et al. 2011; Liu et al. 2013; Sun et al. 2014), enabling them to persist for a longer period of time in reclaimed areas after coal mining. Thus, excess metals existing in the reclaimed site might migrate to agricultural crops cultivated in similar locations in later years, potentially contaminating the food chain and posing a risk to human health. So far, the information of pollution indices like I_{geo} , IPI, PLI has been used in a limited number of studies to assess the degree of metal pollution as well as land degradation (Ololade 2014; Rodriguez-Seijo et al. 2016; Zhou et al. 2015; Golui et al. 2019). In this study, we have attempted to explore the possibility of using these indices for rehabilitated and non-rehabilitated mine soil along with paddy field soil of vicinity at two different soil depths. As a result, a comparative account for these indices can be created, which may be relevant in future courses of action in the comparable study agenda for Indian circumstances and elsewhere.

Mining activities remove surface soil, resulting in nutrient loss and disruption of biological activity (Singh and Singh 2006; Tate 2020). Although restoring ecological integrity is a fundamental goal of surface mine reclamation in disturbed regions, stockpiling of top soil in mounds during mineral excavation has been discovered to have an impact on the physical, chemical, and biological aspects of soil (Goswami et al. 2014). Furthermore, preserving top soil and soil quality appears challenging owing to significant rainfall throughout the rainy season in nations with tropical climates. Even after rehabilitation, non-scientific storage of top soil might result in a decline in organic matter and a poor nutritional content of the soil. Moreover, the time delay between initial removal and final placement of top soil deteriorates the properties of stockpiled soil, eventually rendering it biologically inactive (Schwartz 2021). Stockpiling top soil not only reduces microbial activity but also disrupts soil structure. Also, during restoration, subsurface is dumped on the surface and fertile surface soil is covered. Thus, even after rehabilitation, soil physiochemical and microbiological parameters are not suitable for possible crop development, as we discovered at our study location. We also discovered heavy metal enrichment in non-rehabilitated sites, followed by rehabilitated

sites for any of the management reasons. The derived metal indices of both locations were not in the high alert category, and pollution load index (PLI) values imply that significant rectification procedures are not required at this point. So, there is a possibility to improve the quality of rehabilitated soil as well as non-rehabilitated soil of selected sites by plantation of some suitable tree species like *Azadirachta*, *Eugenia*, *Butea*, *Moringa*, *Bauhinia*, *Aegle* etc. (Sinha et al. 2009). Root exudates of the tree species can favourably alter soil pH, EC, CEC, nutrient cycling and carbon-accumulation in rhizosphere soil (Mukhopadhyay et al. 2016). Other alternatives include phytostabilization using Mediterranean shrubs and liming (Moreno-Jiménez et al. 2012; Roy 2021; Trippe et al. 2021). Additional feasible strategies for restoring mine soil quality include sewage sludge composting, sawdust composting, and green waste composting (Rossini-Oliva et al. 2017; Bendfeldt et al. 2001; Penido et al. 2019).

Conclusion

Soil physio-chemical and biological properties were measured in both coal mining sites (non-rehabilitated and rehabilitated areas) and adjacent paddy soil. The nutrient status, particularly available nitrogen, phosphorous and soil organic carbon content were drastically reduced in the non-rehabilitated and rehabilitated sites as compared to the paddy fields. Further, other indicators of soil biological parameters like microbial biomass carbon, readily mineralizable carbon and enzymatic activities were low in rehabilitated and non-rehabilitated sites. Metal pollution indices showed a risk of soil pollution in non-rehabilitated and rehabilitated areas. Therefore, it can be postulated that the restoration process after mining activity is not yet complete and there is a further chance of reclamation. Quality and productivity of such soils can also be increased by the addition of various low-cost and local organic amendments (wood chips and residues, saw dust, sewage sludge, animal manures, hay, bark mulch) because of their ability to promote the microbial activities (bacteria and mycorrhiza), which provides the nutrients (N, P and micronutrients) and enrich organic carbon stock to the soil. In present condition, the rice cultivation can slowly be initiated in rehabilitated areas but a sufficient amount of organic matter (20–30 tones ha^{-1}) must be added in the initial 2–3 years for better yield and sustainability of the soil. Green manure could be another option to enrich the soil fertility in the rehabilitated areas. The quality of soil should be periodically checked by the chosen soil indicators.



Moreover, heavy metals content in harvested grains must be monitored from time to time so that higher metal concentrations in soil should not hamper the grain quality.

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Author contributions SLS and RK had jointly done the laboratory analyses while SLS collected all the soil samples from distant locations. PB conceptualized the study, finalized the methodology, analyzed the data. DB calculated the metal-based indices. PB and DB outlined and drafted the manuscript. AKN did the required editing. PKD and SRP supported in laboratory analysis and statistical analysis of data.

Data availability All research data are available with authors.

Declarations

Conflict of interest The authors declare that they have no competing interest to the work reported in this paper.

Ethical approval Not applicable.

Consent to Participate All authors informed consent to participate in this paper.

Consent to Publish All authors informed consent to publish this paper.

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