Journal of Soils and Sediments (2025) 25:3439–3459
https://doi.org/10.1007/s11368-025-04170-z

SOIL DEGRADATION CONTROL, REMEDIATION AND RECLAMATION

Recovery of damaged mine spoil: an ecological & geotechnical perspective

Nimisha Tripathi[1] · Raj S. Singh[2] · Swades K. Chaulya[2] · Colin D. Hills[1]

Received: 12 June 2025 / Accepted: 22 October 2025 / Published online: 13 November 2025

Abstract

Purpose Surface coal mining operations generate large quantities of mine-waste that are disposed in land-raised 'mine-waste dumps', which are generally unstable, nutrient deficient and unsuitable for creating ecological structure and functions. The natural recovery of disturbed ecosystems is a long-term process extending to decades. The purpose of the present work is to explore the restoration opportunities using a scientific revegetation approach for re-establishment of ecological services and mine dump stabilisation in selected Indian mining wasteland.

Methods A 18 year re-vegetation study was undertaken into the Indian coalmine spoils to understand the process of ecosystem development, with an ecological and geotechnical perspective. This long-term investigation examined (i) the physico-chemical properties of soil/mine spoil following standard methods; (ii) screened suitable plant species for restoration; (iii) assessed the impact of revegetation on mine dump slope stability by measuring the dump geometry using an electron distance meter (EDM), numerical simulations and in-situ shear jack test; and (iv) basic ecological services that were achieved in two different spoil heaps located in Jharia, formerly comprising native grassland and forest, some 20 km apart.

Results The results clearly indicated that leguminous plants significantly enhanced spoil stability from 4 to 18 years after re-vegetation. Following, considerable quantities of organic carbon were stored in the mine spoil, with increases of 125–250% and by 82–282% being recorded at 6 and 18 years, respectively. Similarly, C in below ground biomass (BGB) increased by 380–945%, and 300–993%; C in plant biomass by 194–345% and 392–695% and 214–429% and 73–662%; and C in soil microbial biomass (MBC) by 157–372 kg ha^{-1} and 121–292 kg ha^{-1}. The factor of safety (FOS) was significantly enhanced from 1.4 to 1.6 and 1.9 after 6 and 18 years of plantation on dump slope, respectively. Further, the ecological services were considerably enhanced by increased soil carbon stock, soil nutrient, microbial biomass, reduced soil runoff and wildlife movement.

Conclusion Long-term monitoring following a scientific re-vegetation approach can assess ecosystem recovery and the re-establishment of ecological services in damaged ecosystems from mining. The physico-chemical and biological properties of re-vegetated mine spoils helps to assess the critical indicators for mine spoil dump stabilisation and ecosystem recovery. These indicators can be used to elucidate the geotechnical and ecological engineering processes pertinent for mine spoil and degraded ecosystem management.

Keywords Coal mine spoil · Revegetation · Carbon content · Slope stability

Communicated by Remigio Paradelo Núñez

✉ Nimisha Tripathi
n.tripathi@gre.ac.uk

✉ Raj S. Singh
rajcimfr@gmail.com

1 Indo-UK Centre of Environment Research and Innovation (IU-CERI), University of Greenwich, Chatham Maritime, London ME4 4TB, UK

2 Indo-UK Centre of Environment Research and Innovation (IU-CERI), CSIR-Central Institute of Mining and Fuel Research, Barwa Road., Dhanbad, Jharkhand 826015, India

1 Introduction

In India, as much 0.44 million ha of land is subject to operational coal mines and thermal power plants, with >78% being available with coal mines. Apart from this, vast land is available as derelict land, due to ca. 297 abandoned and discontinued mines (Singh and Banerjee 2024). The eastern India has the most significant share of land (>50% of India's total) available with coal mines. The coal mining in India is largely dominated by surface mining with the share of underground mining declining to 6% during last decade (Ministry of Coal 2021). During surface mining, the overburden is removed and deposited in mine-waste dumps which can be physically unstable and difficult to re-vegetate (Tripathi et al., 2014).

These mine dumps are unconsolidated deposits of significant high (e.g. x10's of meters) and can be steeper than their prescribed safety limits resulting from limited land and high spoil volumes (Gupta and Singh 2018). If not stabilised, these mine spoil dumps can be unstable and an on-going safety concern for the mining industry, environmental agencies and the public.

From an ecological perspective, mine spoil is damaged ecosystem unsuited to soil healthy microbial activity and plant growth, due to its unfavorable chemistry and poorly developed soil structure (Nayak and Mishra 2024; Tripathi and Singh 2011). The recent unprecedented increase in Indian mine waste dumps and their effect on ecosystems is of great concern, as the natural recovery (colonisation) of plant and faunal species with stabilisation of dump slope is a long-term process (Tripathi et al. 2016; Ranjan et al. 2015; Park et al. 2021; Kumar et al. 2023; Thakur et al. 2024). Further, mine dump failure and the associated with loss of life has increased in recent years. A re-vegetation strategy employing targeted planting of specific species can assist the recovery of mine spoil and the ecosystem that has been degraded, damaged, or destroyed (Tripathi et al. 2016).

Soil degradation can result in the loss of or alteration of many soil properties and functions. The physical, chemical, and biological properties of soil are basic indicators of quality (Doran and Parkin 1994; Larson and Pierce 1994), and these can be used to assess mine spoil for potential re-vegetation. Otherwise, mine working generally contains factors that limit ecosystem development over the short term in the absence of reclamation practices (Bradshaw 1997).

Re-vegetation has a catalytic effect upon soil restoration potential, by changing soil microclimatic conditions, thereby increasing vegetation-structural complexity, and the development of litter and organic matter, which can develop during the early years following plantation (Zhang et al. 2024; Singh et al. 2002). We hypothesised that long-term re-vegetation could improve biomass and productivity which results in (i) improvement in carbon storage from litter fall and fine root mortality (ii) nitrogen fixation by leguminous plant in the root zone enhances soil fertility, (iii) recovery of nutrient cycling by soil microbial biomass, (iv) stabilisation of mine spoil through root proliferation, (v) developing ecological services. Effective monitoring of these elements on revegetated ecosystem helps in adaptive management activities to achieve the restoration goals (Bhaduri et al. 2022; Collen and Nicholson 2014).

The objective of the present paper is to evince the long-term study of 18 years to observe the changes in plant growth performance, soil nutrient recovery through microbial biomass, slope stability and carbon sequestration and improvement in ecological services in two Indian mine-spoil dump after re-vegetation.

The primary research contributions of this paper are outlined as follows:

- Stabilisation of overburden dump slopes through physical reclamation and bio-stabilisation facilitated by tree roots.
- The selection of suitable plant species aimed at achieving effective revegetation of overburden, which in turn, minimises soil erosion, improves soil fertility, and accelerates the recovery of the ecosystem.
- Evaluation of long-term plant growth performance and the physico-chemical and mechanical characteristics of overburden dumps, assessed continuously over an extended period of 18 years post-plantation, encompassing soil structural and functional attributes, as well as dump soil stability (including shear strength factor of safety of the dump material through numerical modeling techniques).

It should be noted that the generation of mine spoil is not confined to India. Substantial extractive industries exist in China, North America, Africa, Australia and elsewhere. Although mine dumps are well managed in many countries, e.g. Australia, in others, especially the developing countries where environmental standards are evolving, improved low-cost strategies for managing these dumps are required. Furthermore, the engineered slopes of mine spoil heaps can deteriorate over time (Goh et al. 2007) due to significant variability (Masoudian et al. 2019), and so an economic and efficient restorative approach that can be applied to different types of mine spoil dumps in different parts of the world will offer obvious advantages.

2 Materials and methods

2.1 Study sites

The two overburden dumps chosen and an adjacent wasteland, sit amongst the rolling landscapes of the Jharia coalfields in Jharkhand (Bharat Coking Coal Limited), and Raniganj, West Bengal (Eastern Coalfields Limited). These two sites were located at 23º 47'43.3" N longitudes 86º19'40.54" E latitudes, and 23º 45' 11.2" N longitudes and 86º45'399" E latitudes (Fig. 1). Approximately 20 km from each location were two control sites, comprising a grassland and a native forest habitat. At each of the four sites to be examined, 3 sub-sites of 1 ha were investigated by regular examination/sampling. Therefore, 12 individual sites were examined in this study.

The large-scale coal mining in Jharia started in 1894 (Saxena, 1991). Currently, approximately 1887 sq. km are considered as 'wastelands' because of coal mining activities (BCCL, 2017). There are 23 large underground and 9 large open cast mines being worked in Jharia (Pal et al. 2016).

The Raniganj Coalfields was the site of first Indian coal mine, opened in 1774. Approximately 7.5 km^2 of land is subject to severe subsidence, abandonment and spoil tipping. At present, there are 107 operating mines of which 89 are underground and the remaining 18 are opencast. Total coal reserves to 600 m depth are estimated at 23 billion tonnes (Mohalik et al. 2019).

The selected coal mine spoil dumps are 20–30 m in height and had slope angles of $<35°$. Each dump was re-vegetated 5 years after tipping operations ceased. The selection of native and introduced plant species was based on the work of Singh et al. (2006), with the best performing tree species (primarily leguminous species) being planted after amendment of soil with farmyard manure at a ratio of 5:1 kg per pit of size $30 \times 30 \times 45$ cm. Tree saplings were transplanted on dumps before the onset of seasonal rain during May-June 1993. Figure 2 displays the view of the plantation on the flat area of the overburden dump top after 6 months and 1 year of planting. Figure 3 shows the view of the plantation on the slope of the overburden dump after 1 year and 18 years of planting.

The adjacent grassland site contained only perennial grasses with a few scattered trees were present in patches. The dominant grasses were *Heteropogon contortus* and co-dominant grass was *Saccharum spontaneom* with *Cynodon dactylon*, *Cyprus rotundus*, *Chrysopon fulvus and Chrysopogon acciculatus* species. The native forest 'control' area comprised mixed dry deciduous trees dominated by the tree species *Shorea robusta*, *Terminalia tomentosa*, *Butea monosperma*, *Dalbergia sisoo*, *Madhuca indica*, *Terminalia arjuna*, *Pongamia pinnata* and *Azadirachta indica*.

The plant species chosen for revegation of the mine spoil sites included leguminous trees: *Dalbergia sisoo*, *Albizzia lebbeck*, *Acacia nilotica*, *Leucena leucocephala;* non-leguminous: *Azadirachta indica* and *Delonix regia*, the bushes: *Lantana camara*, *Eupatorium odoratum* and *Leonotis neptifolia*; and the herbaceous species: *Xanthium strumarium*, *Saccharum spontaneum*, *Tridex procumbence* and *Evolvulus* spp.

2.2 Soil sampling

Using a randomised-block design, five soil samples were collected from the upper 10 cm layer from 3 replicate plots at each of the two control sites (forest and grassland) and the two mine spoil dumps. The samples from each plot were combined into one representative sample. This sample was then sub-divided into two-sub samples, with one (in its field-moist condition) used for determining moisture, plant available nutrients (N, P & K), and microbial biomass C, and the other being air-dried for physical/chemical characterisation (following the procedure outlined by Rowell, 1994).

2.3 Soil characterisation

The soil/spoil samples were characterised for their physical and chemical properties, including pH, electrical conductivity (EC), moisture, bulk density, water holding capacity, organic carbon, available and total nutrients including N (total and mineral), P, K, Fe, Cu, Mn and Zn (following Mehta, 1954; Rowell, 1994; Brady 1985 and Piper, 1994).

The soil mineral-N is very crucial to predict microbial activities, N mineralisation and the root turnover processes, but is largely dormant immediately after planting. Mineral N (nitrate + ammonia-N) was determined immediately after sample collection, following Jackson (1958) and Wetzel and Likens (1979).

Microbial biomass C in soil/mine spoil samples was determined using the chloroform ($CHCl_3$) fumigation-incubation method of Jenkinson and Powlson (1976), except that liquid $CHCl_3$ was used instead of vapour and CO_2-C evolved from fumigated soil for 10–20 days was taken as control (Tripathi and Singh, 2012a). Microbial biomass C was calculated following Jenkinson and Ladd (1981), Singh et al. (1991a) and Jenkinson and Ladd (1981).

2.4 Plant morpho-metric analysis

Morphometric data was collected at regular age intervals (at 2-yearly intervals to 12 years, and then again at 18 years).

For determination of below-ground biomass (live + dead roots) five replicate monolithic samples of $25 \times 25 \times 10$ cm were taken at 0–10 cm, 10–20 cm and 20–30 cm depth. The

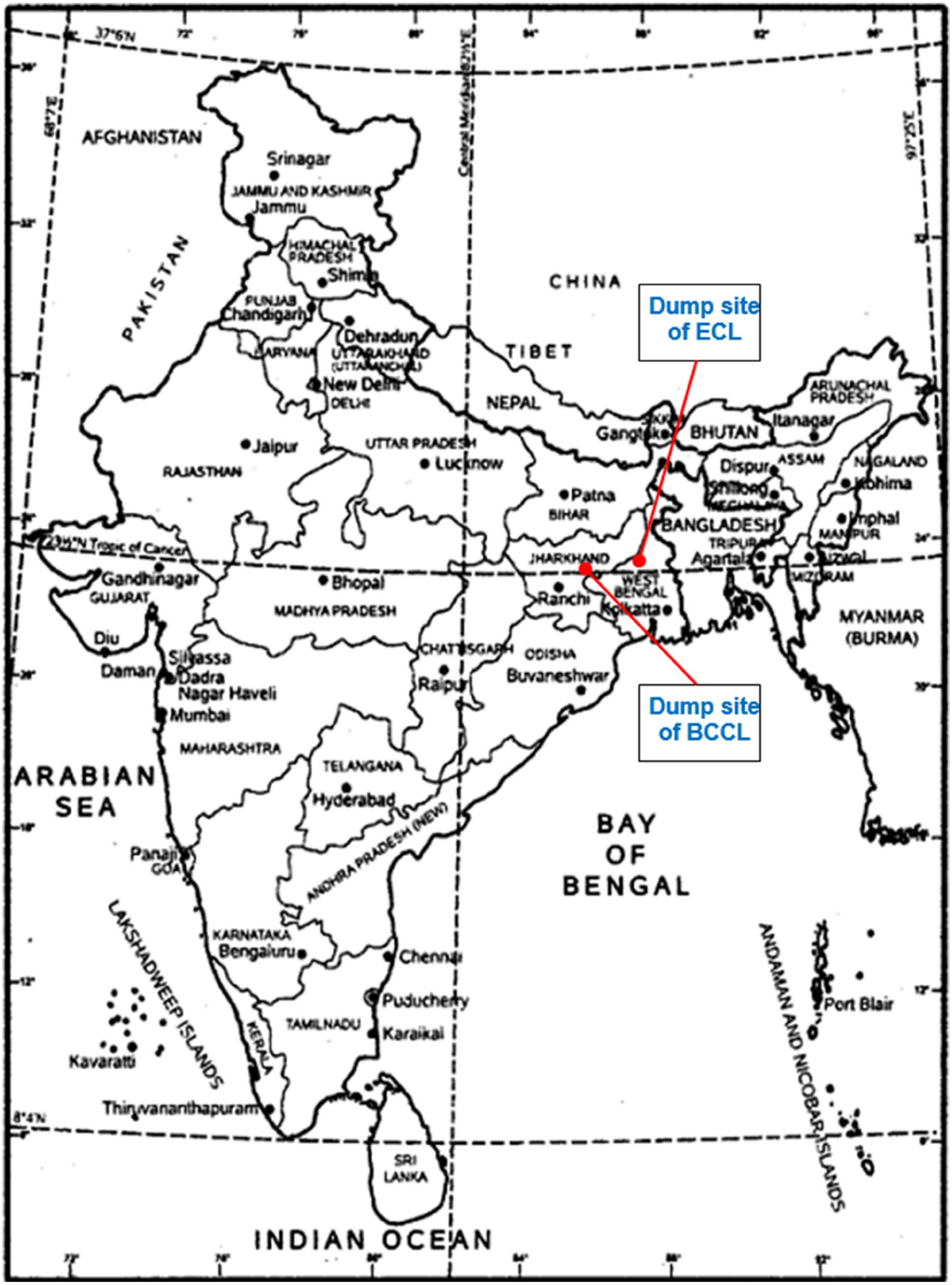

Fig. 1 Location map of two dump plantation sites in India

Fig. 2 View of plantation on overburden dump top, (**a**) after 6 months, and (**b**) after 1 year of plantation

monoliths were washed, and the below-ground biomass was collected following Tripathi et al. (2009).

2.5 Dump stability

The dump stability analysis, as summarised in Fig. 4 following Tripathi et al., (2012b), included the measurement of dump geometry using an electron distance meter (EDM). A digital terrain model (3-D view) was used to delineate the boundary of dump (Fig. 5). Further, the dump geometry, boundary conditions and physical properties were used for numerical simulation models to assess the degree of stabilisation and factor of safety (FOS) of revegetated mine spoil dumps.

2.5.1 Numerical modeling

Numerical simulations for leguminous and non-leguminous species were conducted by the Finite Difference Method (FDM) after dividing the whole domain into two different two-dimensional zones (elements) interconnected with their grid points or nodes, as described in Tripathi et al. (2012b).

Five models were used to simulate the field conditions before and after re-vegetation with leguminous plants at 3, 6, 12 and 18 years. No external load was applied in the numerical model. The calculated nodal displacement due to gravitational loading in each zone was used to assess the strain and sheer stresses over the dump. The Mohr-Coulomb

Fig. 3 View of plantation on overburden dump slope, (**a**) after 1 year and (**b**) after 18 years of plantation

constitutive relation was used to calculate the FOS and behavior of mine spoil dump.

The dump selected for numerical modelling was 26–30 m high with a slope angle of 35° and base length of 90 m. The elements selected near slope (area of interest) were smaller (0.5 × 0.5 m), while those for the remaining dump area were larger (0.5 × 2 m). The creation of boundary conditions included (i) displacement in the vertical direction keeping the horizontal direction fixed (i.e. the roller boundary) along the rear of the dump, and (ii) the fixed boundary with no displacement in horizontal and vertical directions along the base, as shown in Fig. 6.

The numerical modelling approach is described below:

(i) The whole domain was assigned with same properties (fixed boundary conditions) as measured in the field to

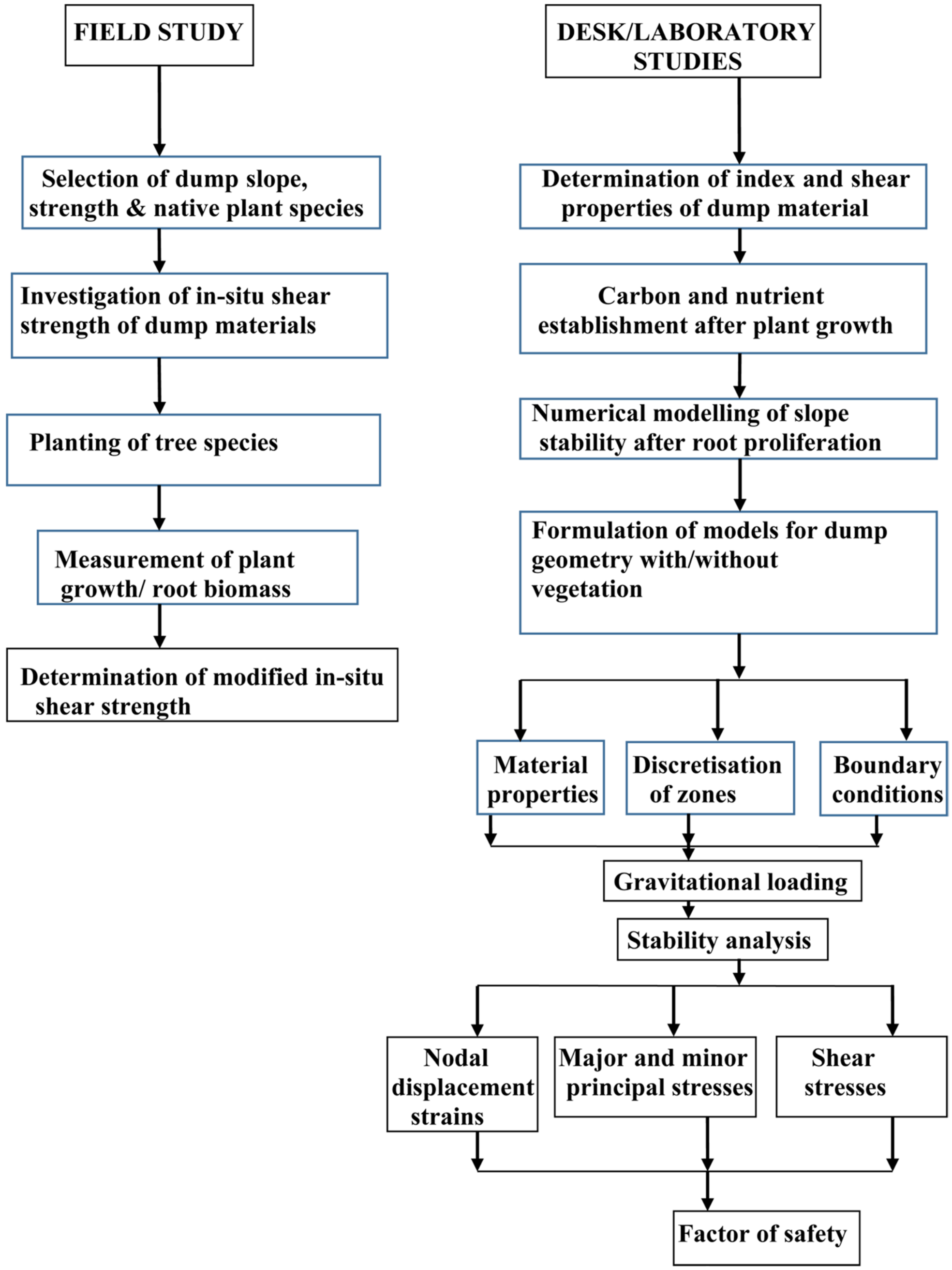

Fig. 4 The methodology for investigating mine dump stability

simulate the natural dump material before plantation (Fig. 6).

(ii) A modified layer was assigned that included the cohesion (c) and friction (φ) values measured on dump slopes after planting with leguminous plants at 3, 6, 12 and 18 years (Fig. 7).

2.5.2 Shear strength properties

Shear strength properties of dump material play a vital role in the dump stability. Determination of reliable shear strength values is a critical part of any dump slope design and small variation in it can result in significant change in the dump slope stability. A failure relationship, following Mohr Coulomb failure law (Lambe and Whitman 1979) was drawn and is shown in Fig. 8.

2.5.3 In-situ Jack shear test

In-situ shear strength properties of the dump material (before biological reclamation and after 3, 6, 12 and 18 years of plantation) have been carried out by in-situ jack sear test as described by Hribar et al. (1986) and Chaulya (1997). The biostability method including the in-situ

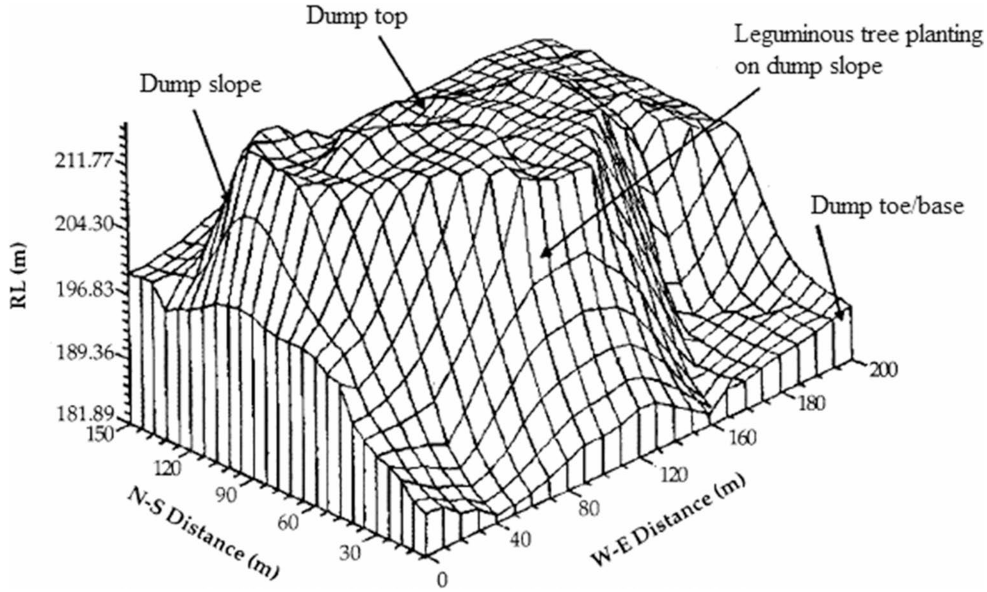

Fig. 5 A 3-D view of dump slope and boundary

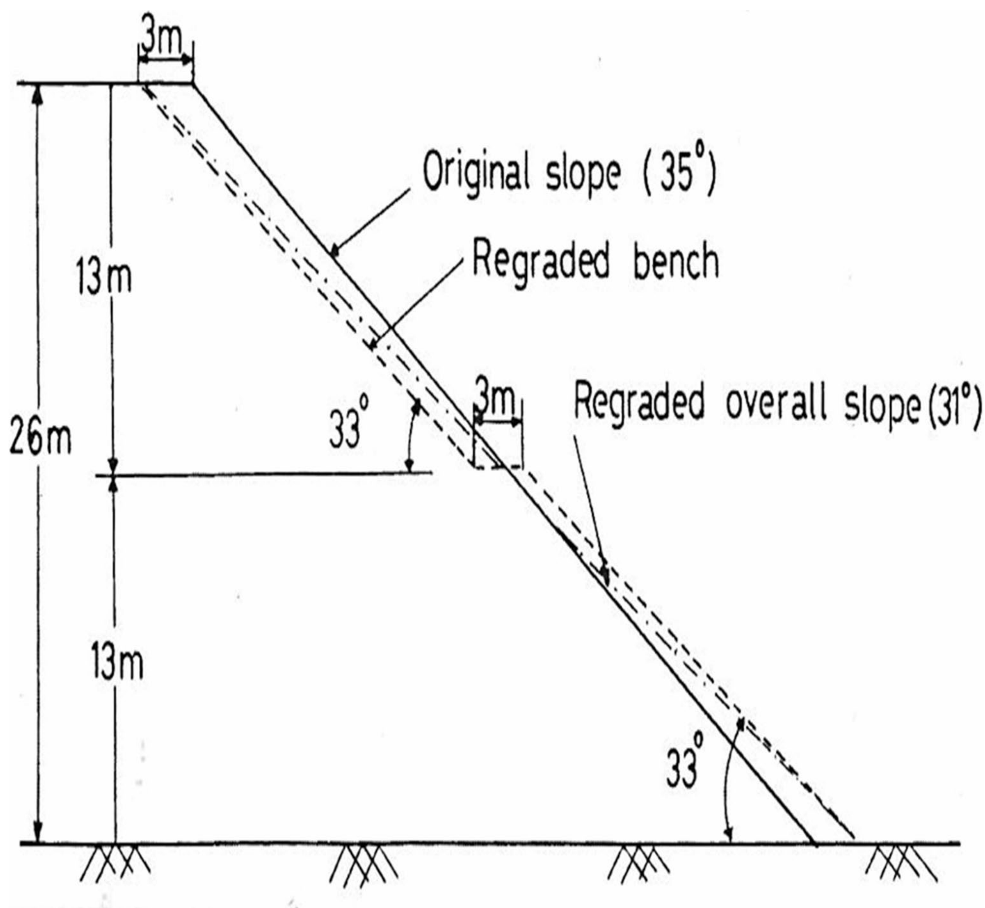

Fig. 6 Geometry of dump used for numerical modeling

jack shear test diagram is also described by Tripathi et al. (2012b). These tests have been repeated five times for both barren dump and reclaimed dump (separately for dump material with grass roots). A block of known dimension (40 cm height, 80 cm width and 100 cm length) is made and pushed gradually to fail by a fixed reaction face

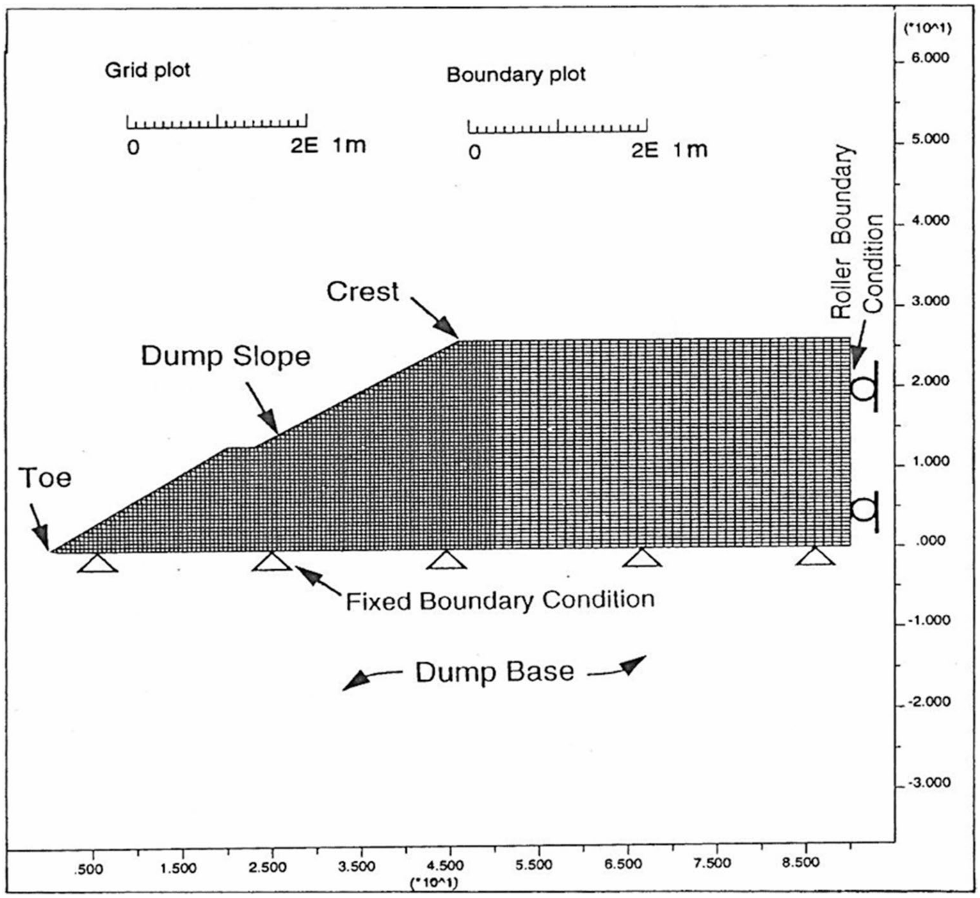

Fig. 7 Area of interest with different dump material properties

(Fig. 9). The observation is recorded at various stages of failure. The loading face of the block is kept at a distance equal to the total length of the equipment assembly. The sides of the test block are separated from the main soil mass by a narrow cut of 15 to 20 cm width to the full depth and loosely backfilled by the excavated soil (Fig. 9). Both reaction face of the pit and the test block must be vertical so that the load applied is horizontal.

The shear jack assembly is lowered in the pit and put into the testing position. The load is applied in increments of 0.5 t. It is maintained for a period of 10 to 15 min after which the load is increased to the next stage. It can be noticed that after loading, the block of soil starts moving up along a sliding plane. This causes cracks and heaving of the failed material. The application of load is continued until the test block moves horizontally by 10 cm. The load at the start of movement (P_{max}) and at the time when block moves by 10 cm (P_{min}) are recorded. After the test, the assembly is taken out from the pit. The true shape of the sliding surface is determined by removing the soil which shears off along the sliding plane. After the removal of failed soil, the depth of the failure surface is measured at three locations along the width of the block and at every 10 cm intervals along the length of the block. The average value of the depth (h) which is measured at three locations is used to determine the shear strength parameters.

The shear strength parameters, cohesion (c) and angle of internal friction (φ), have been determined as discussed below.

A cross section as shown in Fig. 9 has been drawn for all the pits tested by making use of the average depth of the sliding surface. It has been further subdivided into suitable number of slices. The weight of each slice (w) and length (l) along the sliding plane have been determined. Further, the weight of the whole sliding mass (W) has been determined from the following equations:

$$w = \gamma h_m x b \quad (1)$$

$$W = \sum_i^n w_n \quad (2)$$

Where,

h_m = mid height of the slice (m); γ=unit weight (t m^{-3}); x=width of the slice (m); b=the width of the test block (i.e. 0.8 m); and n=the number of slices.

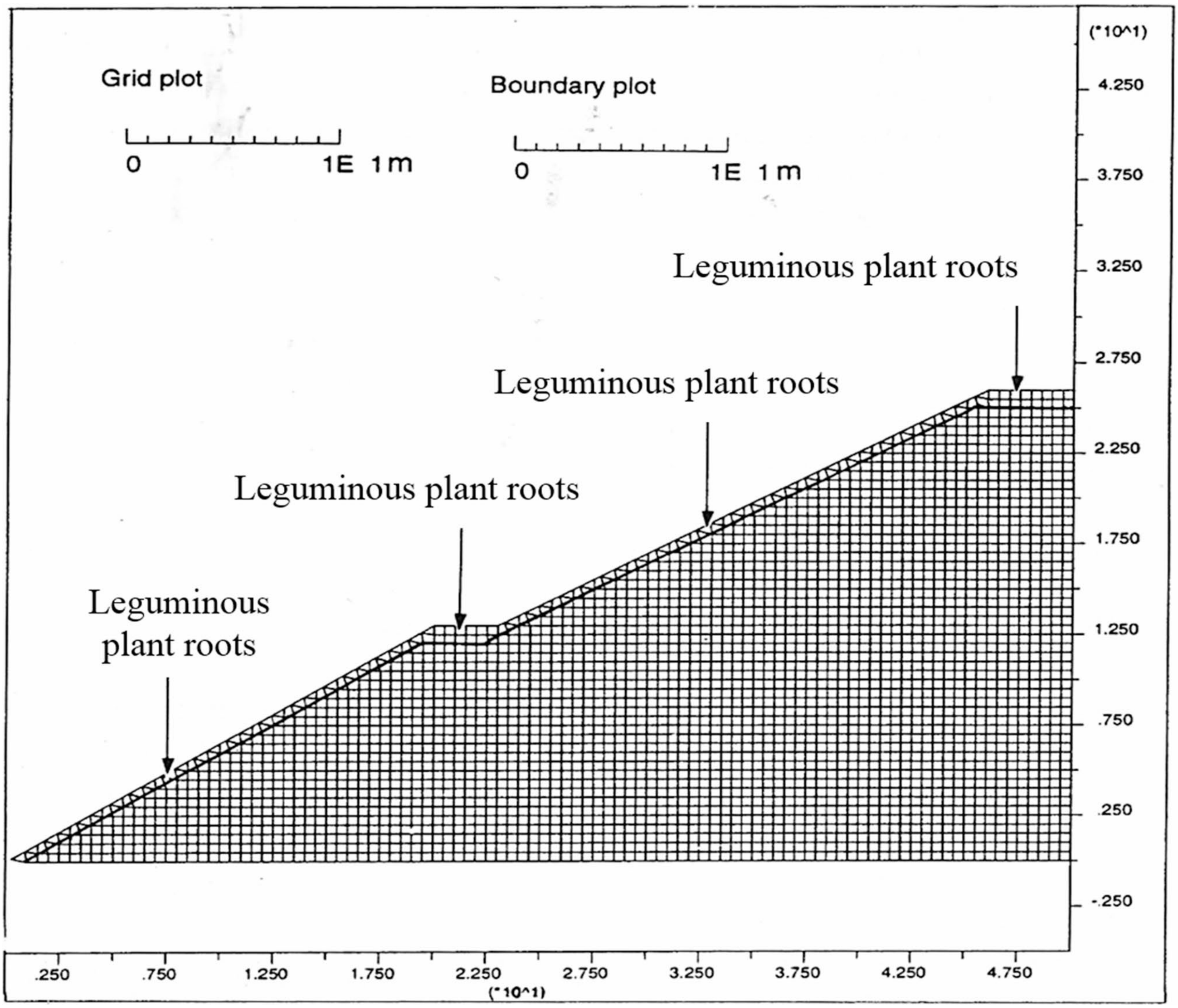

Fig. 8 Relation between normal and shear stresses during sliding stage

Using the value of P_{max}, P_{min}, lengths and weight of slices, the values of cohesion (c) and friction angle (φ) have been calculated from the following equations:

$$c = (P_{max} - P_{min}) / (b\ X) \tag{3}$$

$$Tan\ \varphi = \{(m\ A) - B - (c\ X)\} / \{(m\ B) + A\} \tag{4}$$

Where,

$m = P_{max} / (b\ W)\ ;\ A = W\ Cos\ \theta_{n;}\ B = W\ Sin\ \theta_{n;}\ X = \sum_i^n x_n$

In-situ jack shear test results are summarised in Table 7. Cohesion (c) varied from 64.0 to 122.8 kN m^{-2} and angle of internal friction (φ) ranged from 32 to 34.6 degree before plantation and after 18 years of plantation on dump slope.

2.6 Ecological services

The ecological services were monitored through support services, necessary for the achievement of all structural and functional services of ecosystem. Generally, no quantification is done during monitoring, as they are expressed through indirect use value (Liekens et al. 2010). However, in this study, the ecological services were evaluated based on the services with direct use value. A format listed in Table 8 is given to 100 adjacent dwellers with 21 listed direct use values with comments of never (0%), rare (1–10), seldom (11–49%), and often (50–100%).

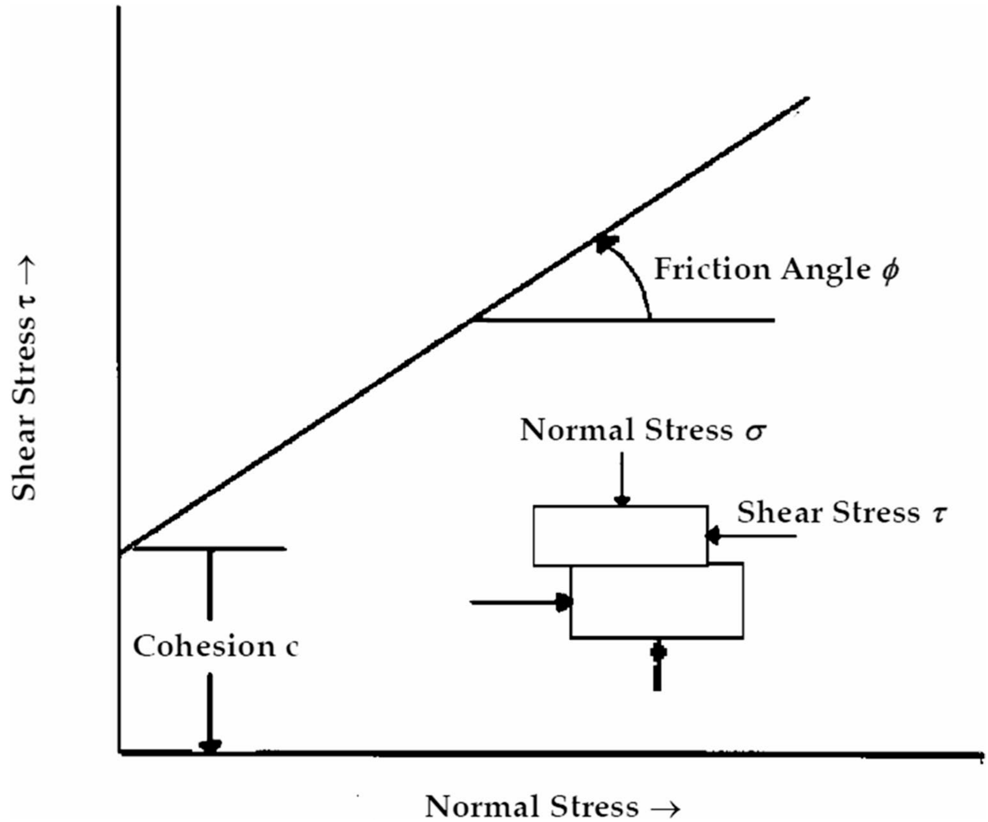

Fig. 9 In-situ jack shear test diagram

Table 1 Physico-chemical characteristics of forest, grassland and mine spoils before re-vegetation

Parameters		Forest	Grassland	ECL(before revegetation)	BCCL(before revegetation)
Texture (%)	Sand	64.0	61.0	68.0	72.0
	Silt	32.0	30.0	28.0	25.0
	Clay	12.0	9.0	4.0	3.0
Moisture (%)		9.77	7.2	5.0	4.0
Bulk density ($Mg\ m^{-3}$)		1.06	1.31	1.75	1.76
Porosity (%)		36.0	34.0	33.8	34.2
pH		5.38	6.2	7.13	7.52
EC (Siemens/m)		0.019	0.021	0.108	0.173
Organic C (%)		0.86	0.65	0.20	0.17
Organic C (kg/ha)		9.11	8.5	3.5	2.99
Total N (%)		0.32	0.14	0.062	0.032
Total P (%)		0.035	0.020	0.008	0.004
Available K ($mg\ g^{-1}$)		46.4	57.3	177.6	131.2
Total Fe (%)		2.56	3.5	7.7	6.5
Total Cu (%)		0.21	0.18	0.55	1.84
Total Mn (%)		1.2	2.5	24.1	10.05
Total Zn (%)		0.26	0.21	0.85	2.58

2.7 Statistical analysis

The mean data from the re-vegetated mine spoil was used to calculate variance and least significant difference following Snedecor and Cochran (1967) and SPSS (1997).

3 Results

3.1 Physico-chemical properties

The physico-chemical properties of soil/spoil at the different 'test' sites are given in Table 1 and Table 2.

The forest and wasteland soils were slightly acidic, whereas the dumped spoil at both mining sites were slightly alkaline. After re-vegetation, there was an increase in organic C by 125 and 250% in ECL and by 82 and 282% in BCCL after 6 and 18 years, respectively. Total N increased in the ECL and BCCL soils by 37 and 94% and 66 and 181%, respectively. Similarly, total P was increased by 63 and 125% in ECL and 250 and 275% in BCCL sites after 6 and 18 years, respectively.

In comparison to the native forest soil after 18 years, the organic C, N and P contents were 47, 63 and 49% lower for

Table 2 Physico-chemical characteristics of mine spoils after re-vegetation

Parameters		ECL			BCCL		
		6 yrs	12 yrs	18 yrs	6 yrs	12 yrs	18 yrs
Texture (%)	Sand	66	65	65	70	68	67
	Silt	29	28	26	26	26	25
	Clay	5	7	9	4	6	8
Moisture (%)		6.2	7.5	8.7	6.8	8.8	9.2
Bulk density (Mg m^{-3})		1.4	1.23	1.18	1.36	1.19	1.10
Porosity (%)		35	38	41	36	38±0.04	37
pH		5.8	5.46	5.45	5.6	5.9	5.8
EC (Siemens/m)		0.022	0.024	0.024	0.021	0.024	0.024
Organic C(%)		0.45	0.64	0.70	0.31	0.52	0.65
Organic C (kg/ha)		6.3	7.87	8.26	4.22	6.2	7.15
Total N (%)		0.085	0.11	0.12	0.053	0.082	0.09
Total N (kg/ha)		1.19	1.35	1.42	0.72	0.97	0.99
Total P (%)		0.013	0.017	0.018	0.014	0.013	0.015
Total P (kg/ha)		0.18	0.21	0.21	0.19	0.15	0.16
Available K (mg g^{-1})		112	65	62	95	55	52
Total Fe (%)		5.4	3.2	2.8	4.94	3.4	2.9
Total Cu (%)		0.38	0.26	0.22	0.44	0.28	0.24
Total Mn (%)		3.6	2.2	1.8	3.2	2.0	1.6
Total Zn (%)		0.68	0.32	0.29	0.56	0.28	0.26

the ECL and by 51, 72 and 57%, at the BCCL mine sites, respectively. In comparison with the grassland, the organic C, N and P contents were 7, 14 and 10% lower for the ECL, and 13, 36 and 25% for the BCCL mine sites. The SOC content in the re-vegetated mine spoils are shown in Table 2. The change in total essential nutrients in the re-vegetated mine spoils at 6 and 18 years is compared with the forest and grassland soils in Table 3.

3.2 Below ground biomass

Below ground biomass (BGB) in the forest, grassland and mine spoil is given in Table 4. There was an increase in BGB by 380 and 945%, and by 300 and 993% in ECL and BCCL sites at 6 and 18 years after re-vegetation, respectively. However, even at 18 years, BGB in the ECL and BCCL soils were lower than in the forest soils by 26 and 46%, and 1.65 and 28%, than in the grassland soils, respectively.

3.3 Growth performance

Tree growth provides a relative volume index of basal area, and overall plant productivity and this was studied at the sites of interest (Table 5). The measured increase at ECL after 6 and 18 years ranged from 194 to 345% and 392–695%, and at BCCL from 214 to 429% and 73–662%, respectively. Tree growth was fast in the first six years of planting, and then stabilised between 6 and 18 years, with all species showing a similar growth trend. *D. sisoo* grew the tallest and *Acacia sp.* the shortest at all sites. However, plant height and girth at the ECL and BCCL sites was lower compared to the forest site.

3.4 Microbial biomass C

The Microbial biomass C (MBC) recorded in the test sites after re-vegetation is given in Table 6. Microbial biomass C in the re-vegetated sites at 6 and 18 years was found in

Table 3 Plant available nutrients in the revegetated mine spoils compared to forest, wasteland and non-revegetated mine spoils

Plant available nutrients	Forest		Grassland		Non-revegetated mine spoils			
	ECL	BCCL	ECL	BCCL	ECL		BCCL	
					6 yrs	18 yrs	6 yrs	18 yrs
K	(+)74	(+)65	(+)68	(+)56	(-)37	(-)65	(-)27	(-)60
Fe	(+)67	(+)54	(+)61	(+)46	(-)30	(-)64	(-)24	(-)55
Cu	(+)62	(+)88	(+)67	(+)90	(-)31	(-)60	(-)76	(-)87
Mn	(+)90	(+)88	(+)89	(+)75	(-)85	(-)92	(-)68	(-)84
Zn	(+)69.4	(+)90	(+)75	(+)92	(-)20	(-)66	(-)78	(-)90

(+) = Higher; (-) = Lower

Table 4 Below-ground (root) biomass and plant available (mineral) - N in forest, grassland and mine spoils after different ages of revegetation

Sites	Belowground (root) biomass(gm^{-2})	Plant available (mineral)-N ($\mu g\ g^{-1}$)
Forest	566±18.0	18.5±0.5
Grassland	425±24.0	12.3±0.5
ECL Mine spoil		
2 yrs.	40±7.0	2.4±0.2
4 yrs.	68±5.7	3.6±0.2
6 yrs.	192±12.0	5.4±0.3
8 yrs.	212±14.0	5.9±0.2
10 yrs.	260±12.0	6.5±0.2
12 yrs.	289±8.0	6.6±0.2
18 yrs.	418±9.0	10.2±0.2
BCCL Mine spoil		
2 yrs.	28±5.0	1.6±0.2
4 yrs.	42±4.6	2.1±0.2
6 yrs.	112±6.4	2.9±0.2
8 yrs.	154±10.2	3.7±0.2
10 yrs.	187±12.0	4.9±0.2
12 yrs.	289±24.0	5.3±0.3
18 yrs.	306±9.0	8.9±0.3

the range 157 to 372 kg/ha at ECL and 121 to 292 kg/ha at BCCL. This increase of 2.4 times at both sites occurred over a period of 6 years. However, in comparison to the forest and grassland sites, MBC in both the re-vegetated sites remained lower. After 18 years, the ECL site had MBC values of 45 and 9% lower than the forest and grassland sites, respectively, whereas the MBC at the BCCL site was 54 and by 24% lower, respectively.

Table 6 Microbial biomass C (μg/g) in forest, grassland and mine spoils (after different ages of revegetation)

Revegetation age (yrs.)	Forest	Grassland	ECL	BCCL
0	554±25	260±12	65±4	49±3
2	558±25	265±12	88±4	65±3
4	556±26	278±13	97±5	76±3
6	551±26	289±12	112±5	89±4
8	565±28	296±13	117±5	99±4
10	570±27	306±13	131±5	128±5
12	575±28	325±13	185±5	149±5
18	578±28	347±12	315±7	265±6

3.5 Shear strength properties

The shear strength characteristics of the overburden dump slope material, specifically cohesion (c) and the angle of internal friction (φ), were determined to be 64.0 (±4.0) kN m^{-2} and 32.0 (±1.5) degree prior to plantation. (Table 7). After a period of 18 years following plantation, the cohesion (c) and angle of internal friction (φ) increased to 122.8 (±4.3) kN m^{-2} and 34.6 (±1.8) degree, respectively.

Table 5 Plant height increment (m) of selected trees on grassland and mine spoils after different ages of revegetation

Site	Species	2 yrs.	4 yrs.	6 yrs.	8 yrs.	10 yrs.	12 yrs.	18 yrs.
Wasteland	*Dalbergia sissoo*	3.15	5.26	6.50	8.90	10.23	11.75	12.90
ECL		2.97	4.80	5.79	7.0	7.87	8.69	9.70
BCCL		2.76	4.60	5.40	6.55	7.50	8.0	9.10
Wasteland	*Albizzia lebbeck*	2.40	4.56	4.88	6.78	8.10	10.36	11.50
ECL		2.43	3.85	4.88	5.86	6.99	7.32	8.90
BCCL		1.60	2.90	3.80	5.10	5.80	6.20	7.80
Wasteland	*Acacia nilotica*	1.70	2.86	3.53	4.18	6.60	5.64	6.80
ECL		1.73	2.45	3.53	4.18	4.93	5.64	6.50
BCCL		1.23	1.90	2.80	3.85	4.10	4.95	5.70
Wasteland	*Leucena leucocephala*	3.20	5.60	6.40	8.20	10.80	11.36	12.40
ECL		3.01	4.91	5.87	7.14	8.13	9.12	10.30
BCCL		2.50	4.30	5.10	6.85	7.60	8.30	9.50
Wasteland	*Azadirachta indica*	2.40	4.10	6.10	7.76	8.48	10.45	11.30
ECL		3.01	4.91	5.87	7.14	8.13	9.12	10.20
BCCL		2.06	2.80	4.0	5.45	6.25	7.60	8.70
Wasteland	*Delonix regia*	1.90	3.50	4.75	5.90	6.50	7.50	8.40
ECL		1.73	3.08	4.05	4.82	5.52	6.01	7.50
BCCL		1.50	2.10	2.95	3.90	4.30	4.90	6.10
Minimum		1.23	1.9	2.8	3.85	4.1	4.9	5.7
Maximum		3.2	5.6	6.5	8.9	10.8	11.75	12.9
Average		2.29	3.80	4.79	6.09	7.10	7.94	9.07
Standard deviation		0.63	1.14	1.18	1.53	1.82	2.14	2.12
Two-tailed P values, computed at a 95% confidence level with respect to 2nd year values			1.63033E-09	3.77772E-12	7.7156E-12	1.20804E-11	4.17945E-11	1.76655E-12

Table 7 Results of in-situ (jack) shear test

Test period	Cohesion (*c*) in kN m^{-2}	Angle of internal friction (f) in degree
Before plantation	64.0 (± 4.0)	32.0 (± 1.5)
After 3 years of plantation	73.1 (± 3.2)	32.6 (± 1.3)
After 6 years of plantation	87.3 (± 4.1)	32.9 (± 1.7)
After 12 years of plantation	108.0 (± 6.0)	33.5 (± 2.2)
After 18 years of plantation	122.8 (± 4.3)	34.6 (± 1.8)

4 Discussions

4.1 Physico-chemical properties

The organic carbon (OC) in non-re-vegetated mine spoil was lower than in the forest and grassland soils. There exists an inverse relationship between soil bulk density and soil organic matter content (Davidson et al. 1967). Plants increase soil organic matter, lower bulk density and moderate soil pH after their establishment on mine spoil (Gill et al. 2009). They also bring mineral nutrients to the surface of the soil and accumulate them in a form that is bioavailable (Singh et al. 1989; Singh et al., 1991b).

The OC content increased gradually after re-vegetation in the mine waste and grassland. This reflected the accumulation of organic matter associated with leaf litter and root decomposition. However, the OC content in the re-vegetated mine spoils were lower than the forest and grassland soils.

We observed that the mean bulk densities of the ECL and BCCL spoils were higher than the soils in the forest and grassland control sites. Bauer and Black (1981) and Voroney et al. (1981) reported an increase in bulk density when land is put to use. Interestingly, mine sites are often water-limited due to their soils exhibiting lower water holding capacities resulting from a comparative increase in coarse material or compaction by e.g. site traffic and heavy machinery movement (Carter and Ungar 2002; Rodrigue et al. 2002; Tripathi et al. 2016).

An increase in OC of 3.5–3.8 times occurred over a period of 18 years in both the revegetated mine spoils. Increasing soil organic matter is accompanied by an increase in the soil formation, as organic matter has a density around one quarter that of mineral soil. An increase in organic matter, therefore, is usually accompanied by a reduction in soil bulk density (Tunstall 2010; Tripathi et al. 2016). George et al. (2010) and Gellie et al. (2017) observed organic matter accumulated in the topsoil with increasing time since restoration, developing a trajectory towards a native soil carbon profile.

The nature of various organo-mineral associations and their location and distribution within soil aggregates determine the extent of physical protection and chemical stabilisation of SOC (Gjisman and Sanze 1998). Clay-sized organo-mineral complexes often show greater accumulations (and subsequently more rapid loss rates) than silt sized particles, indicating that silt-SOC is more stable (Christensen 1996). The same mechanisms also play a major role in the stabilisation and retention of SOC in mined soil.

4.2 Below ground biomass

The increasing BGB in re-vegetated mining spoil indicated the gradual recovery of soil 'components' with time after re-vegetation. However, even after 18 years, BGB in mining spoil was lower than in the native forest and grassland soils, most likely reflecting higher plant succession rates.

Below-ground biomass has direct positive impacts on soil organic carbon and nitrogen via exudation and upon mortality (Tripathi and Singh, 2008; Tripathi et al. 2016), and upon the structure and functioning of the above ground community (Wardle et al. 2004). An increase in BGB along an age gradient for re-vegetated mining spoil could be attributed to an increase in leaf litter fall followed by decomposition and higher root turn over (leading to increase in organic matter). Several ant nests (20 nos m^2) and termite mounds (x3 numbers m^2) were also observed in 18 years of revegetated sites. It has been considered that it helps in decomposition of fallen leaves and twigs of the plant and enhances infiltration of water for root growth. According to Evans et al. (2011) termite and ants play important role to enhance the fertility of the soil in dry climate. The role of bird and soil faunal droppings and excreta may also be important, as according to Singh et al. (1996), bird droppings enhance the nutrient yield in re-vegetated mining spoil. Further, the exudation of roots resulting from 'stressed' soil conditions may be important. An increase in spoil depth after root proliferation also helps in the enhancement of total rooting volume (including fine roots), thereby increasing above- and below-ground biomass production (Ma et al. 2022; Rhoades et al., 2001).

4.3 Growth performance

The morphometric plant data given in Table 5 shows a sharp increment in growth heights of leguminous trees (e.g., *D. sisoo*, *A. lebbek*, *L. leucocephala*, *Acacia sp.*). These are higher tolerant species, having nitrogen fixing capacities to cope-up with the impoverished mining spoils (Singh et al. 1996). *L. leucocephala* can fix about 100 kg ha^{-1} yr^{-1} nitrogen (Wild, 1987), while Kumar et al. (2010) opined that *L. leucocephala* and *A. indica* support mycorrhizae, which help in mining spoil reclamation. Further, proliferated root checks the soil erosion and maintain the soil productivity resulting into improve plant growth and carbon stock in biomass along an age gradient.

A t-test was utilized to evaluate the statistical significance of the increase in plant height between the growth observed after 2 years and that after 4, 6, 8, 10, 12, and 18 years of plantation. The two-tailed P values, calculated at a 95% confidence level, resulted in values less than 0.05 across all instances (Table 5). This P value, which falls below the standard significance threshold of 0.05, indicates statistical significance. Such results imply a notable difference in plant height increment after 4, 6, 8, 10, 12, and 18 years of plantation compared to the increment observed after 2 years. The average increments in plant height were recorded as 2.29, 3.80, 4.79, 6.09, 7.10, 7.94, and 9.07 m after 2, 4, 6, 8, 10, 12, and 18 years of plantation.

The establishment of a vegetative cover and the proliferation of roots are regulatory factors in the reconstruction of an ecosystem in mining soil, as they improve the physical and biological diversity of these disturbed sites (Tripathi et al., 2012b). Tree planting is an excellent strategy for the reclamation of mining spoils, because the trees not only provide long-term ecosystem stabilisation and impart potential ameliorative effects on soil quality but also have potential commercial and aesthetic value (Torbert and Burger 1993; Ashby 1987; Tripathi and Singh 2007). Established vegetative cover can be self-sustaining as it can spread and reproduce under severe conditions (Singh et al. 2002), because it improves soil aeration, water infiltration and reduce soil runoff and accelerates vegetative succession of herbaceous layer (Tripathi et al. 2016). The selection of suitable plant species helps to thrive on metallophyte with biological mechanisms on the toxic mining substrates (Kafle et al. 2022; Whiting et al. 2004). Further, re-vegetation helps early succession pioneer species, grasses and legumes to invade in the nutrient-deficient soil conditions. The grass also helps in stabilisation of soil and acts as an early nurse crop for vegetation growth.

4.4 Microbial biomass C

Microbial activities lead to the development of microbial biomass carbon (MBC). MBC development helps physically stabilise the soil and alters its chemistry, including the availability in plant available nutrients. This in turn stimulates root proliferation and plant growth (Singh et al. 2012).

The microbial biomass reflected in organic carbon was 4.85% and 5% in the ECL and BCCL sites, respectively indicating that more stressed mining spoil has greater contribution. However, the forest and grassland sites reflected 6.7% and 5.34% of MBC, respectively. Yin et al. (2000) found that the arrival of bacterial species along a restoration gradient that included a mine spoil, restored mining land and undisturbed forest depend on time since disturbance. Hence, microbial biomass increased along an age gradient in comparison to forest and wasteland sites.

Microbial biomass forms a small portion of total SOC, but mediates its transfer among inputs, the low fraction organic carbon and organo-mineral high fraction organic carbon. As a result, the rates of C transfer and its transformation are influenced by biological factors, soil temperature and moisture (Post and Kwon 2000).

As microbes have a high tolerance towards stress conditions (as found in mining impacted soils), they are well adapted to enhance soil recovery (Farrar and Reboli 1999; Suzina et al. 2004). According to Paul and Clark (1996) most of the nutrient requirements of plants are met through mineralised soil-organic nutrients provided by the microbial community hence soil microbial biomass recovery seems to be faster. Plant-microbe interactions and C, N cycles also play major roles in the amount of carbon stored in biomass (Shi et al. 2022). Plants provide C for microbial activity and soil-C builds via rhizo-deposition and litter fall. Microbial activities directly affect SOC concentrations but indirectly influence plant C accumulation via the N cycle.

Soil microbial processes strongly regulate the net primary production of an ecosystem (Romero et al. 2023; Singh 1993). Microbial biomass is the most important parameter used to characterise biological soil processes (Tripathi and Singh 2009), but has been used, to a much lesser extent, as a measure of the carbon turnover potential of soils.

4.5 Overburden dump stability

The shear strength properties of the overburden dump slope material, particularly cohesion and angle of internal friction, were enhanced from 64.0 to 122.8 kN m^{-2} and from 32.0 to 34.6 degrees, respectively, following 18 years of plantation on the overburden dump slope. This improvement is attributed to the self-compaction of the dump material over time and the reinforcement provided by the growth of tree roots in the upper layer of the dump material.

The numerical modelling exhibited maximum displacement of elements near the crest (top portion) of the dump slope. Hence, the crest of the dump is the best area to assess the dump failure that mostly occurs during rainy season after significant movement. The stability assessment was based upon changes in slope angle, stress, and the FOS before and after revegetation. In its original state (without revegetation) the dump was unstable with a FOS value 0.94.

The unstable dump (FOS < 1.0) was regraded by terracing and benching, which reduced the overall angle of slope from 35º to 31º. The slope angles and heights of each of the two individual benches were 33º and 13 m, with a berm width of 3 m (Fig. 10) with a FOS of 1.4. Revegetated dump top and slope resulted in reduced stress concentration near the surface of the dump slope with increase in age exhibiting substantial increase of FOS value from 1.4 to 1.6 and 1.9 after 6 and 18 years, respectively (Fig. 11). This enhancement may be due to the proliferation of plant roots that bind

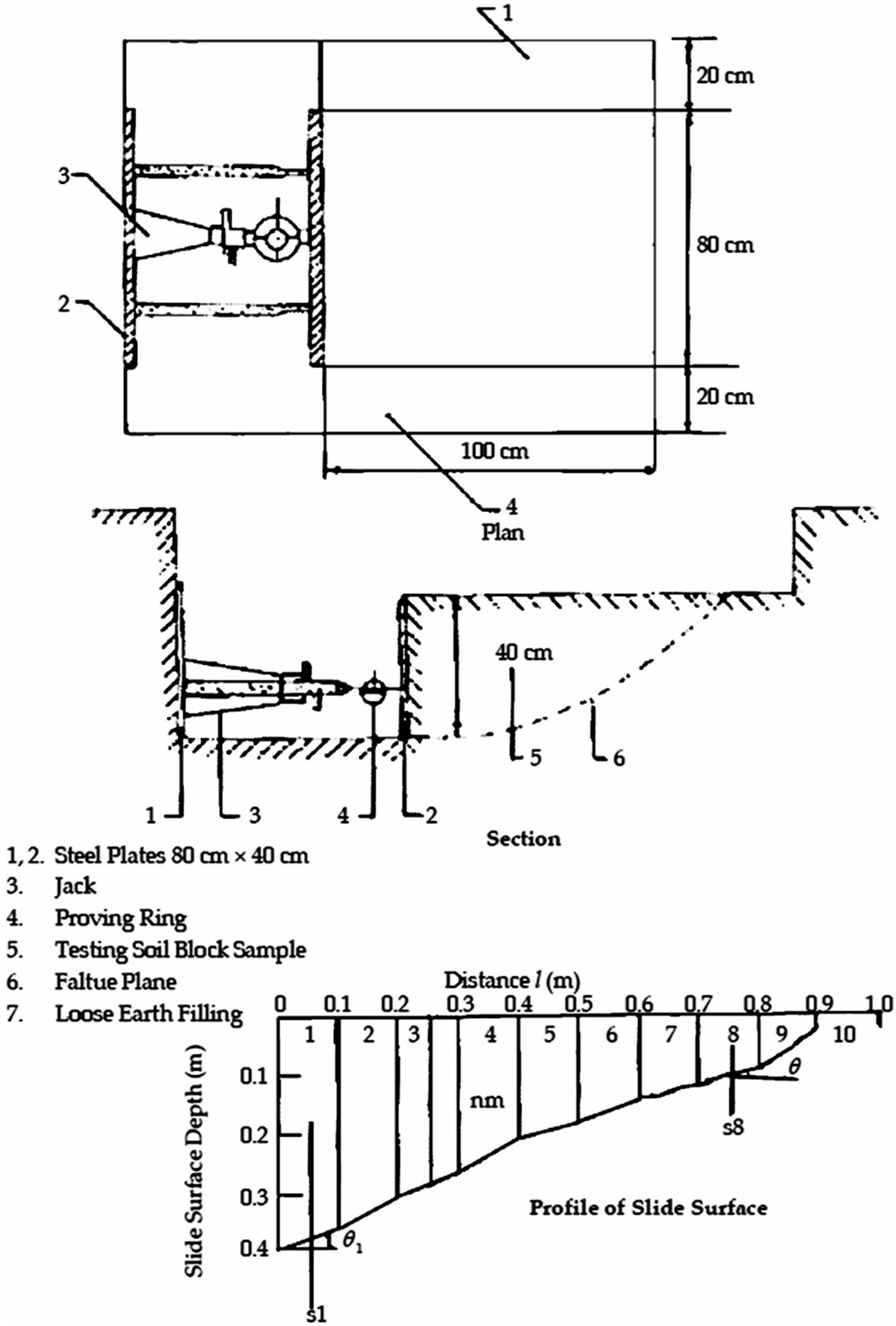

Fig. 10 Geometry of the regarded portion of the dump

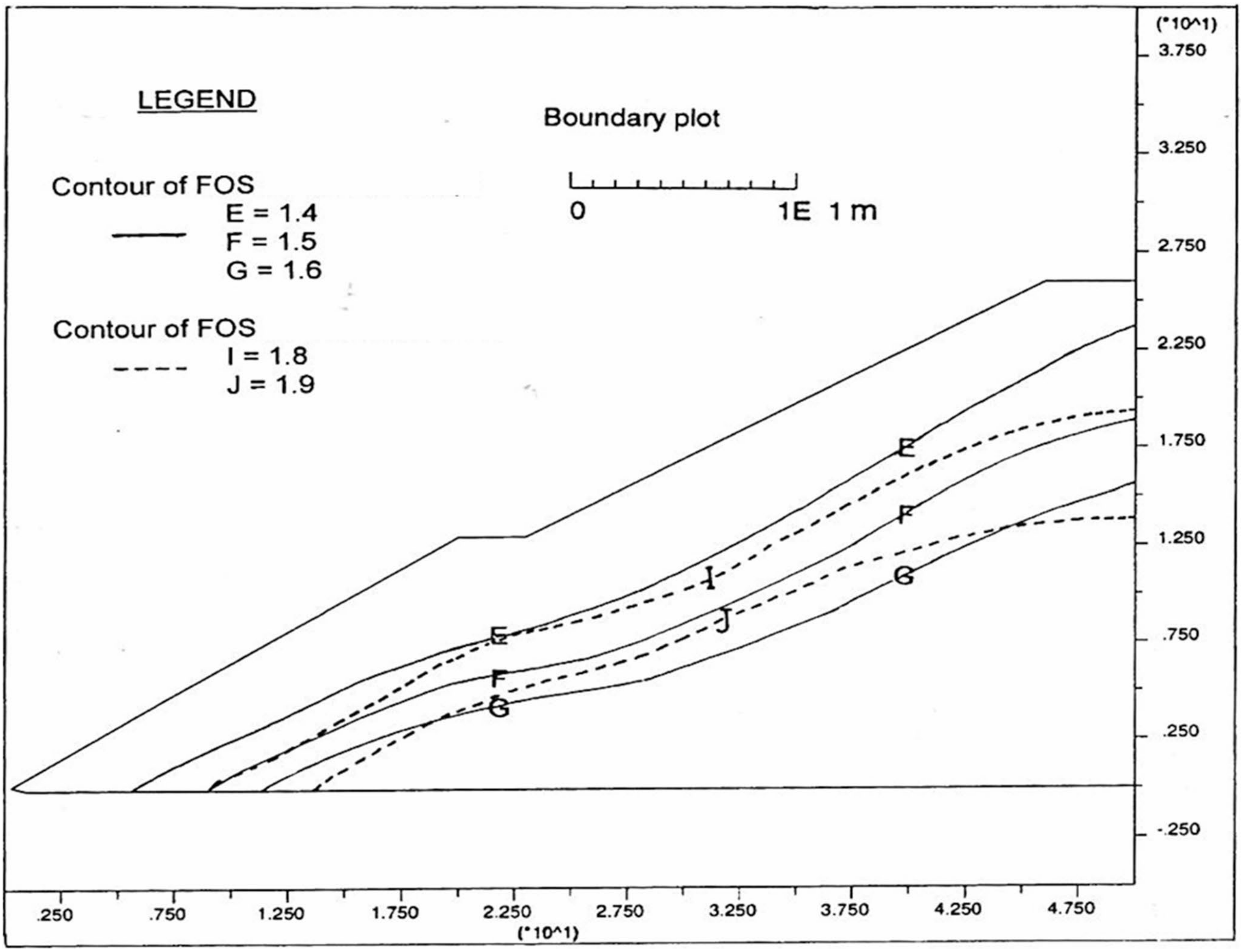

Fig. 11 Factor of safety for the barren and reclaimed dump slopes (E=No vegetation; F, G, I, J=3, 6, 12 and 18 year of revegetation)

the spoil leading to an improvement in shear strength of the dump, modifying the path of critical failure surface.

Studies report the stabilisation of dump slopes with fly ash from coal power stations (e.g., Roshan et al. 2023; Gupta and Singh 2018). It would be interesting to explore if this type of stabilisation strategy could incorporate plantation with suitable species to regain the ecological services and achieve a sustainable ecosystem recovery.

There exists a strong relationship between strength (as seen with increasing cohesion), microbial biomass C and below ground biomass (Fig. 12). With an increase in age of re-vegetated dump, these key parameters increased proportionately and are shown to be inter-related.

4.6 Ecological services by re-vegetation

Ecological restoration is the human-facilitated repair of a degraded ecosystem that reinstates many natural ecological services in repaired ecosystems. Re-vegetation on mining waste dump areas reduces land exposed to reduce intense solar radiation, soil run-off and the atmospheric temperature. This, in turn, attracts several micro flora and fauna as the vegetation establishes over a period. The establishment of micro flora and fauna accelerates numerous ecological services via decomposition and nutrient release activities. This further enables the succession of grass species on the mining dump.

Over a period, our general observation indicated that the role of ants and termites is very crucial in litter decomposition facilitating soil formation via carbon storage and nutrient recycling. The establishment of vegetation roots in five years and a gradual increase in soil organic carbon stock reduced the sediment and soil run-off on mining dump. The roots along with soil invertebrates improved the WHC, soil infiltration and facilitated the regeneration of native grasses available to herbivores for grazing. The building up of soil flora and fauna in the re-vegetated ecosystem attracts mollusks (snails), reptiles (lizards, snakes), bird species (dove,

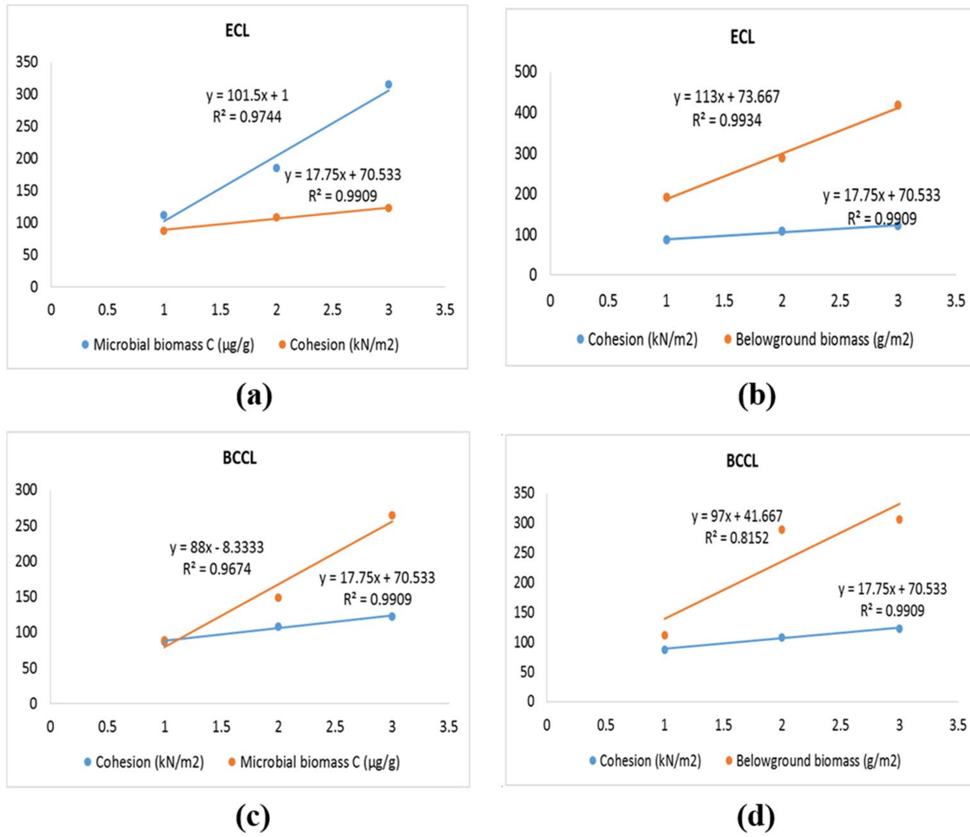

Fig. 12 relationship between various parameters of revegetated mine spoils ECL (**a**, **b**); BCCL (**c**, **d**) (**b**)

common myna, parrot, sparrow, etc.) and the flying insects helping in pollination. Further, over an increasing period of vegetation establishment, the occurrence of mammals (mouse, wolf, jackal, hyena) was observed. It is interesting that revegetation accelerates the regeneration of local species, breeding of wild animals and prevents the alien species from growing.

The social survey indicated that the re-vegetation on mining dump substantially developed the ecological services over a period (Table 8). The recovery of services is seen facilitating a self-sustaining ecosystem on mining dumps, including the structural and functional components. The tree species over a period also attenuated dust and enhanced the aesthetic beauty of the site. Hence, re-vegetation significantly helped the recovery of the damaged ecosystem, but further work is required to understand how complete restoration can be fully restored.

5 Conclusions

Land impacted by mining is deprived of soil moisture, plant nutrients and microbial activity and are prone to leaching and run-off erosion. The natural recovery of these ecosystems, through vegetation succession, is a long-term and gradual process. The managed re-vegetation of mining-spoil dumps can reverse the act of land degradation, help to accelerate ecosystem recovery, stabilise the slope and exert a positive effect on establishment of structural and functional traits.

The selective screening of appropriate plant species is important to the success of revegetation. As observed earlier and in present study, the establishment of leguminous and herbaceous/grass species on a spoil dump will accelerate the ecosystem recovery process. The root matrices developed following re-vegetation provide a habitat for soil organism establishment, carbon storage and essential plant nutrient production. The development of plant and microbial biomass is complementary and helps physical stabilise mining spoil and enhance soil fertility. The above- and below- ground biomass provides a myriad of biophysical and biochemical processes, including moisture retention, reduced bulk density, soil organic matter built-up, increased nutrient turn-over, soil cohesion and shear strength. These effects eventually reduce the water run-off erosion and lead to the development of a stable ecosystem.

The integration of physico-chemical and biological properties of non- and re-vegetated mining spoils helps to assess the factor of safety and critical failure of surface as indicators of mining spoil dump stabilisation and ecosystem recovery. These indicators can be used to elucidate the

Table 8 Ecological services before and after 18 years of revegetation

Ecological component	Before revegetation	After revegetation	Social impact after reclamation (%)
Aesthetic	Negative	Positive	100
Movement (Humans)	Never	Often	62
Movement (domestic animals)	Rare	Often	75
Termite occurrence	Rare	Often	55
Ants	Rare	Often	75
Butterfly	Rare	Often	52
Annelids	Never	Seldom	50
Mollusks	Never	Seldom	35
Amphibians	Never	Seldom	37
Reptiles	Rare	Often	42
Birds	Rare	Often	79
Wild Mammals	Seldom	Often	52
Pollinating insects	Never	Often	62
Domestic Fuel	Never	Seldom	34
Domestic animal Browse	Never	Often	51
Dust pollution	Often	Never	78
Soil erosion control	Often	Never	75
Organic storage	Never	Often	71
Sedimentation in water bodies	Often	Seldom	70
Soil microbial activity	Seldom	Often	-

geotechnical and ecological engineering processes pertinent for mining spoil and degraded ecosystem management. New insights on the development of soil fauna in restored mining spoil should be used to further understand ecosystem development, and how the results of managed restoration can be improved. The ecological services improve substantially in terms of biodiversity, quality of life re-establishment and the attitude of local dwellers towards mining. However, the full recovery of the ecological services and ecosystem is still an enigma.

Author contributions Raj S Singh and Nimisha Tripathi conceptualised the research and performed the laboratory experiments. All four authors equally contributed to analysis of data, numerical modelling and technical writing of the manuscript.

Funding supports by the Ministry of Environment & Forests, New Delhi (India), CMPDIL, Ranchi and Council of Scientific & Industrial Research (CSIR), New Delhi are acknowledged.

Declarations

Competing interests The authors declare no competing interests in this work and the manuscript.

References

Ashby WC (1987) Forests. In: Jordan WR II., Gilpin ME, Aber JD (eds) Restoration ecology: A synthetic approach to ecological research. Cambridge University Press, Cambridge, UK, 342 pp., ISBN, 0521337283, 9780521337281

Bauer A, Black AL (1981) Soil carbon, nitrogen and bulk density comparisons in two cropland tillage system after 25 years and in virgin grassland. Soil Sci Soc Am J 45:1166–1170

BCCL, 2017. Vegetation Cover Mapping of Jharia Coalfield based on Satellite Data of the Year-2016. https://bcclweb.in/files/2017/08/jhariaCFmaps2016.pdf. Accessed 03 Nov 2025.

Bhaduri D, Sihi D, Bhowmik A, Verma C, Munda S, Dari B (2022) A review on effective soil health bio-indicators for ecosystem restoration and sustainability. Front Microbiol. https://doi.org/10.3389/fmicb.2022.938481

Bradshaw AD (1997) Reclamation of mined land using natural processes. Ecol Eng 8:255–269

Brady NC (1985) The nature and properties of soils, 8th edn. Eurasia Publishing House, New Delhi

Carter CT, Ungar IA (2002) Aboveground vegetation, seed bank and soil analysis of a 31- year-old forest restoration on coal mine spoil in southeastern Ohio. Am Midl Nat 147:44–59

Chaulya SK, Environmental management of overburden dump stability - an integrated study. Ph. D., Thesis (1997) Department of Mining Engineering, Institute Technology, Banaras Hindu University, Varanasi, India

Christensen BT (1996) Carbon in primary and secondary organo – mineral complexes. In: Carter MR, Stewart BA (eds) Structure and organic matter storage in agricultural soil. Adv. Soil sci. CRC Lewis, Boca Raton, pp 97–166

Collen B, Nicholson E (2014) Taking the measure of change. Science 346:166–167

Davidson JM, Fenton G, Pinson DI (1967) Changes in organic matter and bulk density with depth under two cropping system. Agron J 59:375–378

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: JW Doran, DC Coleman, DF Bezdicek and BA Stewart (eds.) defining soil quality for a sustainable environment. SSSA Special Publ. 35, SSSA, Madison, WI

Evans TA, Dawes TZ, Ward PR, Lo N (2011) Ants and termites increase crop yield in a dry climate. Nat Commun 2. https://doi.org/10.1038/ncomms1257

Farrar W, Reboli A (1999) The genus bacillus: medical. In: Dworkin M (ed) The prokaryotes: an ecolving electronic resource for the Microbiological Community, release 3.0, 3rd edn. Springer-, New York. NY, USA, https://doi.org/10.1007/0-387-30744-3.

Gellie NJC, Mills JG, Breed MF, Lowe AJ (2017) Revegetation rewilds the soil bacterial microbiome of an old field. Mol Ecol 26(11):2895–2904

George S, Kelly R, Greenwood P, Tibbett M (2010) Soil carbon and litter development along a reconstructed biodiverse forest chronosequence of South-Western Australia. Biogeochemistry 101:197–209

Gill JS, Sale PWG, Peries RR, Tang C (2009) Changes in soil physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments. Field Crops Res 114:137–146

Gjisman AJ, Sanze II (1998) Soil organic matter pools in volcanic ash soil under fallow or cultivation with applied chicken manure. Eur J Soil Sci 49:427–436

Goh EKH, Aspinall TO, Kuszmaul JS (2007) Spoil dump design and rehabilitation management practices (Australia). Int J Surf Min Reclam Environ 12:57–60

Gupta T, Singh TN (2018) Geo-hydrological stability analysis of fly ash stabilised overburden dump slopes in opencast coal mines using finite element analysis. Int J Adv Sci Eng Inf Technol 8(2):405–410

Hribar J, Dougherty M, Ventura J, Yavorskyu P (1986) Large scale direct shear tests on surface mine spoil. In: Proceedings of International Symposium on Geotechnical Stability in Surface Mine, A. A. Balkema, Calgary, Rotterdam, pp. 295–303

https://doi.org/10.1016/j.envadv.2022.100203 (accessed on 13/04/2025)

Jenkinson DS, Ladd JN (1981) Microbial biomass in soil: measurement and turnover. In: Paul EA, Ladd JN (eds) Soil Biochemistry, vol Vol. 5. Dekker, New York, pp 415–471

Jenkinson DS, Powlson DS (1976) The effects of biocidal treatment on metabolism in soil- V. a. method for measuring soil biomass. Soil Biol Biochem 8:209–213

Kafle A, Timilsina A, Gautam A, Adhikari K, Bhattarai A, Aryal (2022) N.

Kumar A, Raghuwanshi R, Upadhyay RS (2010) Arbuscular mycorrhizal technology in reclamation and revegetation of coal mine spoils under various revegetation models. Engineering 2:683–689

Kumar A, Das SK, Nainegali L, Reddy KR (2023) Phytostabilization of coalmine overburden waste rock dump slopes: current status, challenges, and perspectives. Bull Eng Geol Environ. https://doi.org/10.1007/s10064-023-03159-7

Lambe TW, Whitman RV (1979) Soil mechanics. Wiley, New York

Larson WE, Pierce FJ (1994) The dynamics of soil quality as a measure of sustainable management. In: JW Doran, D.C. Coleman, DF Bezdicek and BA Stewart (eds.) Defining soil quality for a sustainable environment. SSSA Special Publ. 35, pp. 37–51 SSSA, Madison, WI

Liekens I, Schaafsma M, Staes J, De Nocker L, Brouwer R, Meire P (2010) Economische waardering van ecosysteemdiensten, een handleiding. Studie in opdracht van LNE, Afdeling Milieu-, Natuur- en Energiebeleid, maart

Ma W, Tang S, Dengzeng Z, Zhang D, Zhang T, Ma X (2022) Root exudates contribute to belowground ecosystem hotspots: A review. Front Microbiol 5:13:937940. https://doi.org/10.3389/fmicb.2022.937940

Masoudian MS, Zevgolis IE, Deliveris AV et al (2019) Stability and characterisation of spoil heaps in European surface lignite mines: a state-of-the-art review in light of new data. Environ Earth Sci 78:505. https://doi.org/10.1007/s12665-019-8506-7

Ministry of Coal (2021) Provisional Coal Statistics http://coalcontroller.gov.in/writereaddata/files/download/provisionalcoalstat/provisional-coal%20statistics-2020-21.pdf (accessed on 12/04/2025)

Mohalik N, Khan AM, Kumar A, Ray SK, Mishra D, Varma NK, Sahay N (2019) Optimisation of ventilation system for prevention of spontaneous heating/fire during extraction of Thick coal seam – a CFD approach. J Mines Metals Fuels 67:452–460

Nayak S, Mishra CSK (2024) Organic and biofertilizer interventions in iron mine spoil for nutrient fortification with facilitation of microbial exoenzyme activity and plant growth. Int J Ecol Environ Sci 50(4):591–600. https://doi.org/10.55863/ijees.2024.0121

Pal SK, Vaish J, Kumar S, Bharti AK (2016) Coal fire mapping of East Basuria Colliery, Jharia coalfield using vertical derivative technique of magnetic data. J Earth Syst Sci 125(1):165–178

Park J, Kim I, Kang JK (2021) Root reinforcement effect on cover slopes of solid waste landfill in soil bioengineering. Sustainability 13(7):3991. https://doi.org/10.3390/su13073991

Paul EA, Clark FE (1996) Soil microbiology and biochemistry, 2nd edn. Academic Ress C.A, San Diego, p 368

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Glob Change Biol 6:317–328

Ranjan V, Sen P, Kumar D, Sarsawat A (2015) A review on dump slope stabilization by revegetation with reference to indigenous plant. Ecol Process 4:14. https://doi.org/10.1186/s13717-015-0041-1

Rhoades JD (2001) http://www.netl.doe.gov/publications/proceedings/01/carbonseqterr/graves.pdf. (accessed on 20/03/2025)

Rodrigue JA, Burger JA, Oderwald RG (2002) Forest productivity and commercial value of pre-law reclaimed mined land in the Eastern United States. North J Appl For 19:106–114

Romero F, Hilfiker S, Edlinger A, Held A, Hartman K, Labouyrie M, Heijden M (2023) Soil microbial biodiversity promotes crop productivity and agro-ecosystem functioning in experimental microcosms. Sci Total Environ., 885, 163683, ISSN 0048-9697 https://doi.org/10.1016/j.scitotenv.2023.163683

Roshan P, Meena RK, Abhishek P (2023) Stability Analysis of Slope Induced with Coal Ash Dykes. Hydraulic and Civil Engineering Technology VIII M. Yang (Eds.). https://doi.org/10.3233/ATDE230836

Rowell DL (1994) Soil Science: Methods & Applications, Published by Routledge, ISBN 10: 0582087848 / ISBN 13: 9780582087842

Shi J, Gong J, Li X, Zhang Z, Zhang W, Li Y, Song L, Zhang S, Dong J, Baoyin T (2022) Plant–microbial linkages regulate soil organic carbon dynamics under phosphorus application in a typical temperate grassland in Northern China, Agriculture, Ecosystems & Environment, 335, 108006, ISSN 0167-8809, https://doi.org/10.1016/j.agee.2022.108006. Accessed on 10 Mar 2025.

Singh RS (1993) Effect of winter fire on primary productivity and nutrient concentration of dry tropical savanna. Vegetatio 106:63–71

Singh A, Banerjee S (2024) Reform of land laws to enable land repurposing for just transition. International Forum for Environment, Sustainability and Technology (iFOREST), New Delhi, India

Singh JS, Raghubanshi AS, Singh RS, Srivastava SC (1989) Microbial biomass acts as a source of plant nutrients in dry tropical forest and savanna. Nature 338:499–500

Singh RS, Raghubanshi AS, Singh JS (1991a) Nitrogen-mineralisation in dry tropical savanna: effects of burning and grazing. Soil Biol Biochem 23:269–273

Singh RS, Srivastava SC, Raghubanshi AS, Singh JS, Singh SP (1991b) Microbial C, N and P in dry tropical savanna: effects of burning and grazing. J Appl Ecol 28:869–878

Singh JS, Singh KP, Jha AK (1996) An integrated ecological study on revegetation of mine spoil. Final Technical Report submitted to the Ministry of Coal, Government of India, New Delhi

Singh AN, Raghubanshi AS, Singh JS (2002) Plantations as a tool for spoil restoration. Curr Sci 82:1436–1441

Singh RS, Tripathi N, Chaulya SK (2012) Ecological study of revegetated coal mine spoil of an Indian dry tropical ecosystem along an age gradient. Biodegradation 23:837–849

Snedecor GW, Cochran WG (1967) Stastical methods. 8th ed. Lowa State Unversity press Ames. IA. p. 503

SPSS (1997) Quantitative data analysis with SPSS for windows: A guide for social scientists. Routledge, London

Suzina NE, Mulyukin AL, Kozlova AN, Shorolhova AP, Dmitriev VV, Barinova ES, Mokhova ON, El-Registan GI, Duda VI (2004) Ultrastructure of resting cells of some non- spore- forming bacteria. Microbiology 73:435–417

Thakur K, Parihar NS, Sood H (2024) Bio-stabilisation of slopes: a review. E3S Web Conf. https://doi.org/10.1051/e3sconf/202459601019

Torbert JL, Burger JA (1993) Commercial forest land as a post-mining land use: A win-win-win opportunity for coal operators, landowners, and society in the central Applachians. Natl. Mtg. Am. Soc. Surf. Min. Rec. Spokane, WA

Tripathi N, Singh RS (2007) Mining industry and sustainable development. J J Dev Manage Stud 5:2245–2262

Tripathi N, Singh RS (2008) Ecological restoration of mined-out areas of dry tropical environment, India. Env Mon Assess 46:325–337

Tripathi N, Singh RS (2009) Influence of different land uses on soil nitrogen transformations after conservation from an Indian dry tropical forest. CATENA 77:216–223

Tripathi N, Singh RS (2011) Ecological study of revegetated mine spoil of dry tropical environment. Chapter XI, AK Ghosh and A Watve (eds.) Optimizing Biodiversity and Social Security in Indian Mining Areas. A.K. Ghosh and A. Watve (eds) Volume II. Naturenomics Balipara Tract and Froniter Foundation (BTFF). 92–104 pp. Jamshedpur: India, Publisher: Steel city Press

Tripathi N, Singh RS (2012a) Impact of savannisation on nitrogen mineralisation in an Indian tropical forest. For Res 1(3):1–10

Tripathi N, Singh RS, Chaulya SK (2012b) Dump stability and soil fertility of a coal mine spoil in Indian dry tropical environment: a long-term study. Environ Manage 50(4):695–706

Tripathi N, Singh RS, Hills CD (2016) Soil carbon development in rejuvenated Indian coal mine spoil. Ecol Eng 90:482–490

Tunstall B (2010) Measuring soil carbon. www.eric.com.au. (accessed on 05/05/2025)

Voroney RP, Van Veen JA, Paul EA (1981) Organic dynamics in grassland soils. Part II. Model validation and simulation of the long-term effects of cultivation and rainfall erosion. Can J Soil Sci 61:211–224

Wardle DA, Bardgett RD, Klironomos JN, Setälä H, Putten WH, van der Wall DH (2004) Ecological linkages between aboveground and below ground biota. Science, special issue: Soils- The Final Front34(5677):1629–1633

Wild A (1987) Soils and the environment: an introduction, Low Price Edition, Cambridge, p 287

Whiting SN, Reeves RD, Richards D, Johnson MS, Cooke JA, Malaisse F (2004) Research priorities for conservation of metallophyte biodiversity and their potential for restoration and site remediation. Restor Ecol 12(1):106–116

Yin B, Crowley D, Sparovek G, De Melo WJ, Borneman J (2000) Bacterial functional redundancy along a soil reclamation gradient. Appl Environ Microbiol 66:4361–4365

Zhang B, Hu G, Xu C, Hu C, Zhong C, Chen S, Zhang Z (2024) Effects of natural vegetation restoration on soil physicochemical properties in tropical karst areas, Southwestern China. Forests 15(7):1270. https://doi.org/10.3390/f15071270