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ORIGINAL ARTICLE

Reclamation of coalmine spoils with topsoil, grass, and legume: a case study from India

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Abstract

Accretion of carbon (C) and nitrogen (N) content in reclaimed mine soil is a major objective to restore mine soil fertility. The present study investigated the impact of grass and legume seeding in fertility enhancement, nutrient accumulation, and accretion of C and N pool during the early stages of reclamation. Four land covers were studied—unreclaimed mine spoil dump, topsoil dump, and 2-year-old coal mine spoil dumps revegetated with legume (*Stylosanthes hamata*) and grass (*Cenchrus ciliaris*). Results showed that above- and below-ground biomass of legumes as well as biomass C and N contents were significantly higher than grass. Reclaimed mine soils under legumes cover had greater soil organic matter (SOM) (42%), soil organic carbon (SOC) (66%), available N (79%), and total N (62%) than the applied topsoil. The rates of SOC (1.57 Mg SOC ha^{-1} $year^{-1}$) and total N (0.47 Mg N ha^{-1} $year^{-1}$) accumulation were higher under legume than the grass. Soil CO_2 flux was in the order of legume (2.34 ± 0.27 µmol CO_2 m^{-2} s^{-1}) > grass (2.17 ± 0.19 µmol CO_2 m^{-2} s^{-1}) > topsoil (1.23 ± 0.19 µmol CO_2 m^{-2} s^{-1}). Total cost of reclamation was US$ 6761 ha^{-1}, out of which 59% was contributed by technical reclamation and 41% by biological reclamation which includes aftercare and maintenance for 2 years. Legumes showed advantages over the grass species to restore mine soil fertility. Therefore, this study recommends the application of legumes as an initial colonizer to reclaim coal mine spoils.

Keywords Mine reclamation · *Stylosanthes hamata* · *Cenchrus ciliaris* · Soil fertility · Nitrogen accumulation · Soil CO_2 flux

Introduction

Coal production is continuously increasing particularly in developing countries resulting in land degradation and environmental pollution. India produced 662.79 teragram (Tg) of coal during 2016–2017 of which 93% was produced by open strip mining methods (MOC 2018). Open strip mining activities inevitably degrade the land by removing vegetation cover, topsoil, subsoil, and overburden rocks which significantly alters the ecosystem functions by changing the local landscape, increasing soil erosion, reducing biodiversity, and causing land-use change (Zipper et al. 2011; Ahirwal and Maiti 2018a). After mining, the excavated barren lands are backfilled with overburden (OB) materials (internal dumping) and revegetated. The most commonly practiced post-mining land uses in India are agroforestry, fruit orchards, and eco-restoration parks. Mine degraded lands can also be used by the local peoples for agriculture (Ahirwal and Maiti 2016). Sometimes, mine voids are left unmanaged and converted to water bodies. Rehabilitation of the degraded lands is of prime importance to re-establish the attributes of a natural ecosystem.

Soil organic carbon (SOC) and nitrogen (N) are mostly bound in soil organic matter (SOM). The surface of mined land has been subjected to various physico-chemical and biological alterations which causes massive loss of SOM. Topsoil removal and stockpiling during the open strip mining and lack of fresh C input also cause reduction in SOM (Banning et al. 2008). Loss of SOM due to mining activities and its accumulation during the reclamation process is of great importance in nutrient dynamics and fertility of the mine soil. Mine spoil is N deficient (Li and Daniels 1994), and availability of soil N is mainly dependent on

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the decomposition of organic matter. Several methods have been implemented to increase N content of the degraded land and accelerate N fixation. The rate of decomposition of legumes is higher than that of grasses, so legumes increase SOM (Agbenin and Adeniyi 2005). Therefore, long-term reclamation success may depend on the re-establishment of leguminous species which increase the N pool and maintain N cycling on the spoil surface.

Selection of tree species that will grow under harsh conditions and establishment of vegetation cover to stabilize the bare area are the major challenges faced during the reclamation of a degraded site. Most studies in post-mining sites reported the use of exotic species for reclamation (Mukhopadhyay et al. 2014; Ahirwal et al. 2017a), but some native species also showed greater potential to increase soil quality (Agbenin and Adeniyi 2005). Exotic species showed an advantage to survive in stressed mining conditions, whereas native species colonized with time and increased the genetic diversity of the area, regenerating the natural esthetic (Ahirwal et al. 2017a, b). The forestry reclamation approach emphasized the planting of tree species to restore post-mining sites (Burger et al. 2005).

Reclamation strategies using the grass and legume species to improve nutrient-poor mine spoil have gained momentum in recent years. During early stage of reclamation, leguminous species provides N supply in the derelict sites, and thus, it is important to study the early interaction between the impoverished mine spoil and growth of pioneering species (grasses and legumes) in a disturbed ecosystem to monitor the path of natural succession. They improve soil fertility and stability, genetic diversity, and microbial activity (Eisenhauer et al. 2010). The root material added to the soil by grasses and legumes has a positive impact on the modification of soil structure. Dubach and Russelle (1994) reported that decomposition of roots served as the major source of N accumulation and also enhanced soil N by nitrogen-fixing symbiotic bacteria. Therefore, leguminous species have a greater advantage over non-leguminous species to survive well in nutrient-deficient soils (Spehn et al. 2002; Yang et al. 2016).

Grass and legume species have been widely used as a reclamation tool in regions where both temperate grasses and temperate legumes are well adapted. In other climatic areas, persistent combinations of grass and legume mixtures are rare: rather, most studies reported either legumes or grass species alone. The N accumulation rates in various countries using different grass and legume species have been presented in Table 1. Wide variations of N concentration in reclaimed soils around the world are attributable mainly to species traits, age since revegetation, characteristics of the spoil material, and temperature (Maiti and Saxena 1998; Maiti and Maiti 2015; Maiti and Ahirwal 2017). Maiti and Saxena (1998) concluded that fertility enhancements of coal mine spoil depend on the nature of spoil, prevailing climate, and legume used. In a tropical climate, N accumulation rate was higher than in a temperate climate. Montanez et al. (1995) examined the nodulation growth and N_2 fixation rate of soybean (*Glycine max* L. Merrill) at different temperatures (15, 25 and 35 °C), and reported that N_2 fixation and growth of soybean were lowest at 15 °C, and highest at intermediate temperatures (25 °C). Decrease in N_2 fixation was observed even more than dry matter yield at the highest temperature (35 °C). Growth of nodules occurred deeper in soil at 25 °C and 35 °C than at 15 °C.

Despite several advances in reclamation methods in the last decade, most remain unsuccessful in creating the attributes of natural ecosystems. Reclamation by tree plantation was the sole aim of the mining companies in India. Afforestation of mine spoil dumps by fast growing trees has not shown significant recovery of soil nutrients even after 8 years of reclamation compared to the reference site (Ahirwal et al. 2017a). Attempts to improve soil fertility by the pyrolysis of a wide variety of organic residues, weeds, and wastes for subsequent biochar application have been found to be futile in nutrient deficient and low clay content soils (Gonzaga et al. 2018). However, application of a grass-legume mixture is not often used for reclamation purposes. Scarcity of knowledge still persists in the field as how grass and legume species can enhance soil fertility in terms of nutrient storage and cycling in the reclaimed ecosystem. Few studies have reported on the application of grass and legumes to restore mine spoil. We hypothesized that revegetation with legumes as a primary reclamation tool can have greater advantages in restoring N capital in mine soil compared to grasses alone. Therefore, the present study aimed to assess the impact of grasses and legumes as initial colonizer to restore mine soil fertility. The major objectives of the study were to (i) assess the changes in physico-chemical and biological properties of the mine soil revegetated with grass and legume and (ii) to quantify the carbon and nitrogen accumulation capacity of the grass and legume growing on coalmine spoil.

Materials and methods

Study area

The field experiment was conducted at the post-mining sites of Chandan open strip mining project (latitude 23°41′30″N and longitude 86°24′59″E) located in the Eastern Jharia coalfield of the Bharat Coking Coal Limited (BCCL), Jharkhand, India (Fig. 1). The total reclaimed area was 5.71 ha. The experimental area was characterized as having a humid sub-tropical climate. The hot summer season extends from March to June and the winter season from November

Table 1 Rate of nitrogen (N) accumulation using grass and legume species during reclamation of waste materials (coal mine spoils and integrated steel plant waste) in previous studies

Species	Country	Site type	Age (years)	Available N accumulation (mg kg^{-1})	Total N accumulation (mg kg$^{-1)}$	Authors
Grass–legume mixture (*Stylosanthes hamata—Pennisetum pedicellatum*)	India (Raigarh)	Waste dump from integrated steel plant blanketed with soil	0.5	35–72	759–933	Maiti and Maiti (2015)
Grass–legume (*Festuca—Lolium—Trifolium—Sericea*)	USA (Power River Project, Virginia)	Young coal mine soil	1	60.5 (0–5 cm)	nr	Li and Daniels (1994)
Grass–legume (*Brachiaria decumbens—Calopogonium mucunoides*)	Brazil	Tropical pasture	na	nr	60–117[b]	Cadisch et al. (1994)
Grass–legume (*Cynodon—paspalum—Medicago—Indigofera* sp.—*Lespedeza*)	China (Wanxi)	Highway slope	1	nr	500–740	Yang et al. (2016)
Grass–legume (*Stylosanthes humilis—Pennisetum pedicellatum*)	Jharia Coalfields, India	Coal mine overburden dump	2 3	70 225	174 318	Maiti and Saxena (1998)
Grass–legume mixture[c]	Northern Spain	Reclaimed open-pit coal mine	3	nr	1100 (north slope) 900 (south slope)	Alday et al. (2008)
Grass–legume mixture[c]	Northern Spain (Palencia)	Reclaimed open-pit coal mine	6	nr	0.05%[a]	Alday et al. (2012)
Legume (*Lotus corniculatus*)	Lusatian Germany	Coal mining area	5	nr	210–230 (0–10 cm)	Boldt-Burisch et al. (2015)
Legume (*Trifolium arvense*)	Lusatian Germany	Coal mining area	5	nr	180–310 (0–10 cm)	Boldt-Burisch et al. (2015)
Grass (*Calamagrostis epigejos*)	Lusatian Germany	Coal mining area	5	nr	140–150 (0–10 cm)	Boldt-Burisch et al. (2015)

na not applicable, *nr* not reported

[a] Rate of total N accumulation per year in %

[b] Nitrogen fixation rate in kg ha^{-1} year^{-1}

[c] Composition of grasses and legumes (81:19 by weight): grasses (*Festuca* spp., *Avena sativa*, *Secale cereale*, *Lolium perenne*, *Phleum pretense*, and *Poa pratensis*)—legumes (*Trifolium pretense*, *Lotus corniculatus*, *Medicago sativa*, and *T. repens*)

to February. The mean annual temperature of the area is 25.9 °C and the mean annual precipitation is 1306 mm. Most of the rain falls between June and October.

Bharat Coking Coal Limited (BCCL), located in the Dhanbad district of Jharkhand, is the only source of high-grade coking coal in India. BCCL produced 37 million tons of coking coal during 2016–2017 (Ministry of Coal 2018). Coal in the Jharia coalfield comprises four geological measures—Talcher, Barakar, Barren measures, and Raniganj (Lower Gondwana). The Barakar formation contains the most important coal seams and covers an area of 210 sq km. During the Lower Gondwana (extending from the Carboniferous to the Permian), lacustrine and fluviatile sediments comprising sandstones, shales, and coal seams were deposited. Later, during the Triassic to Lower Cretaceous, the Upper Gondwana sediments were also deposited (Chandra 1992). This area is highly affected by underground coal mine fires.

Land cover

The study area is characterized by four land covers: (i) unreclaimed mine spoils, (ii) topsoil with no vegetation cover, (iii) land covered by the legume *Stylosanthes hamata* (L.) Taub., and (iv) land covered by grass *Cenchrus ciliaris* L. (Fig. 2).

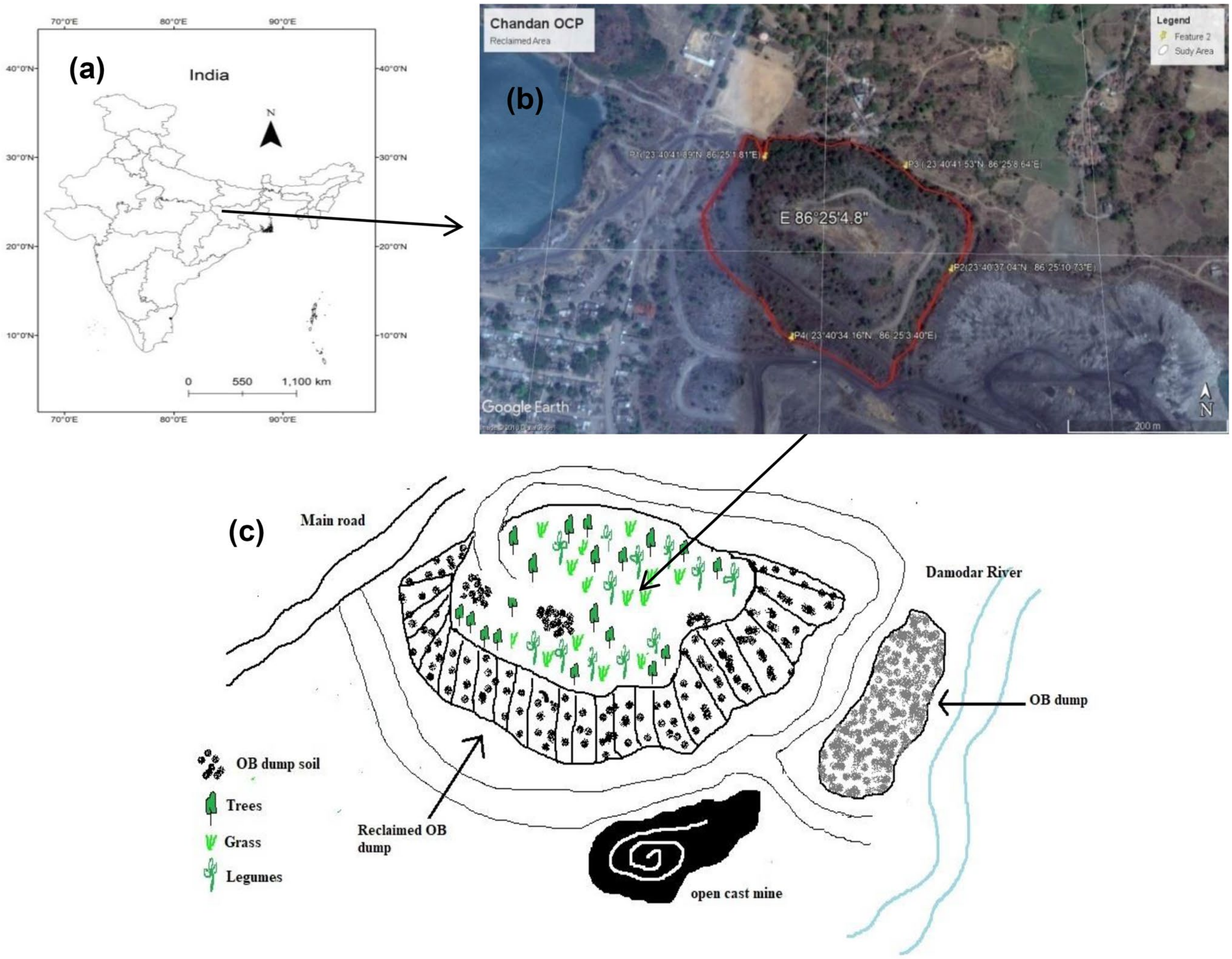
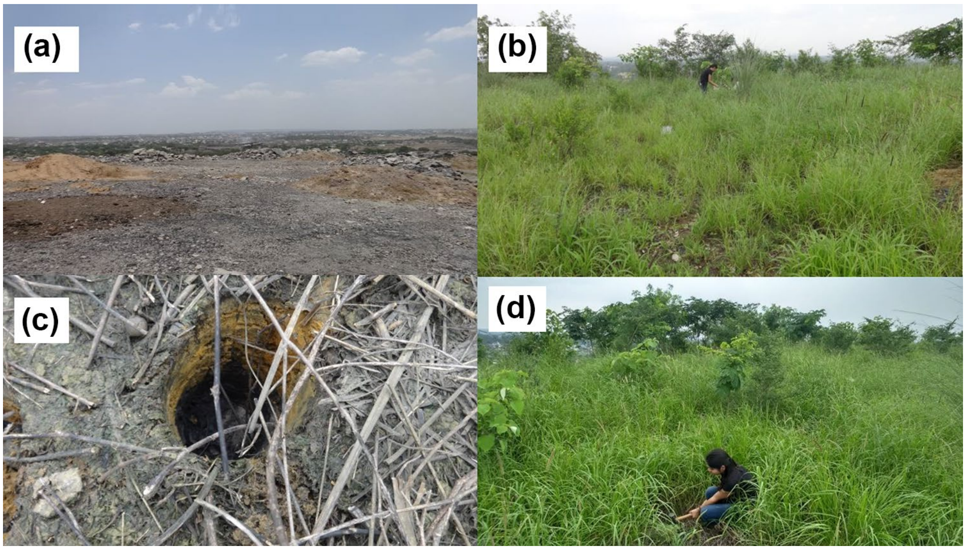


Fig. 1 Location of the study area. **a** India highlights the state Jharkhand, **b** location map of Jharia coalfield showing the sampling point. **c** Schematic diagram of the Chandan open strip mining project in the Jharia coalfield of Bharat Coking Coal Limited (BCCL). OB—Overburden

Fig. 2 A closer view of study sites: **a** unreclaimed mine spoil contains high rock fraction, **b** reclaimed dump showing the growth of grass and legumes with topsoil, **c** accumulation of dry mulch on the revegetated dump, and **d** collection of soil sample from reclaimed site



Unreclaimed mine spoil

Overburden material excavated to reach the coal seam was dumped outside the quarry area. These spoil materials contain a high proportion of rock fragments which are freshly blasted. These dumps were characterized by benching and sloping (generally 28°), and further prepared for revegetation. Unreclaimed mine spoil lacks soil profile and contains higher proportions of coal particles and coarse material due to mechanized open strip mining, overburden removal, and poor reclamation techniques. High bulk density and low moisture content are often attributable to rock fragments and compaction. These spoils are nutrient deficient and show much lesser amounts of NPK compared to the natural undisturbed ecosystem.

Topsoil dump

Topsoil was separately scraped out from the diverted lands before the excavation started and stored in nearby areas as a topsoil dump. Mostly, topsoil was stored near the mining areas and concurrently used for blanketing of mine spoils. If it was stored for a longer time, some natural species colonize the topsoil dump. Once overburden dumps are inactive, topsoil is applied on the dump surface to support vegetation establishment.

Legume cover

After construction of a dump surface, seeds of *Stylosanthes hamata* (L.) Taub. (Fabaceae), commonly known as Caribbean Stylo, were manually applied on the surface blanketed with topsoil (10 cm) without addition of any soil amendments. *S. hamata* is a semi-erect, short-lived, perennial, tropical legume shrub, reaching a maximum height of 100–150 cm, and was the dominant species on the revegetated site. Its stems are slender, multi-branched, non-determinate, and pubescent on one side, but without bristles, leaves are trifoliate with shiny, lanceolate leaflets, 19–37 mm long, and 3–6 mm broad. This is a leafy species suited for forage in tropical and sub-tropical areas having a strong nodulated tap root system which enhances nitrogen accumulation. After dying off, the plants produce mulch which insulates the soil, increases moisture retention capacity, and prevents soil compaction. Mulching enhances soil fertility and supports establishment of plant species in revegetated areas.

Grass cover

Seeds of *Cenchrus ciliaris* (L.) (Poaceae), (syn. *Pennisetum ciliare* (L.) Link), commonly known as "Buffel grass", were applied on the surface before the onset of the monsoon. *C. ciliaris* is a very important tufted tussock-forming perennial pasture grass in the tropics with deep and tough rootstock. The leaves are linear (3–25 cm long and 4–10 mm wide) and the flowers are produced in a panicle 2–14 cm long and 1–2.6 cm wide. It generates comparatively high-value forage with yields between 2 and 18 t dry matter/ha without adding fertilizer. Among the commonly sown grasses in arid areas, it is the most drought tolerant, is easy to establish, and is valuable for erosion control.

Seed germination, vegetation sampling, and analysis

Seed germination tests were carried out to assess the viability of the grass and legume seeds using a standard test method (Maiti 2012). A seed test was performed by placing 20 seeds on a moist absorbent paper in a petri dish. The number of seeds germinated per day was counted continuously for 15 days and expressed as percentage of total seeds (Eq. 1):

$$\text{Seed germination } \% = \frac{\text{No. of seeds germinated}}{\text{Total seeds}} \times 100. \tag{1}$$

Vegetation sampling was done in the post-monsoon season. Five quadrats of 1 m × 1 m were laid randomly under legume and grass cover. The numbers of grass and legume species falling within each quadrat were counted and uprooted carefully to measure biomass, root, and shoot length. Five replicates of grass and legume species were collected from each of the five quadrats. Biomass samples (root, shoot, and leaves) were oven dried at 65 °C for 48 h and weighed till constant weight. Samples were finely ground and passed through a 1 mm sieve to quantify total C and N by the elemental analyzer (Euro EA 3000 Eurovactor, Italy).

Soil sample collection and analysis

Soil sample collection was done in the post-monsoon season by establishing random grids of 10 m × 10 m in each of the four land covers, i.e., unreclaimed mine spoil, topsoil dump, and dumps revegetated with legume and with grass. A total of ten quadrats were laid under legume cover, and within each quadrat, three sub-samples were collected from different locations using a soil corer (10 cm × 6 cm diameter) at 0–10 cm depth. Sub-samples were mixed and homogenized to make one composite sample per quadrat. In a similar manner, a total of 25 samples were collected (10 composite samples under legumes, 5 under grass cover, 5 topsoil, and 5 from unreclaimed dump) for analysis. The area revegetated with legumes cover was greater (approximately double) compared to grass cover. Therefore, ten soil samples were collected from legume cover and analyzed for physico-chemical properties. Separate soil cores were collected to measure soil bulk density. Samples were packed in air-tight sampling bags and carefully brought to the laboratory for analysis.

Samples were air dried at room temperature (25–29 °C) for a week and then lightly crushed in mortar and pestle. Coarse materials (> 2 mm) were separated from the samples and quantities estimated gravimetrically (Maiti 2012). All the soil physico-chemical parameters were analyzed using the fine earth fraction (< 2 mm). Percentage values of coarse and fine fraction were calculated as follows:

$$\%\text{Coarse fraction} = \frac{\text{Weight of coarse fraction} > 2\text{ mm (kg)}}{\text{Weight of coarse fraction} + \text{dry weight of remaining soil (kg)}} \times 100 \tag{2}$$

$$\%\text{Fine earth fraction} = 100 - \text{Coarse fraction }\%. \tag{3}$$

Bulk density was determined by taking the mass of the soil collected in the sampling corer (Blake and Hartge 1986). Soil pH was determined potentiometrically in soil:water (1:2.5, w/v), soil:KCl (1:2, w/v), soil:$CaCl_2$ (1:2, w/v) suspension, and shaken for 30 min and analyzed by the multi-parameter probe (HI2020, Hanna Instruments India). Electrical conductivity (EC) of soil samples was determined in soil:water (1:2.5, w/v) by electrical conductivity meter (HI2020, Hanna Instruments India). Soil organic carbon (SOC) was estimated by oxidizing the soil samples by concentrated H_2SO_4 and titrating against 0.5 N ferrous ammonium sulfate (FAS) solution using the rapid dichromate oxidation technique (Nelson and Sommers 1996). Total soil C (%) was determined by the CHNS-elemental analyzer (Eurovector Euro EA 3000, Italy). Loss-on-ignition (LOI) method was used to estimate SOM by taking 10 g of soil sample in a pre-weighed crucible and igniting in a programmable muffle furnace at 105 °C and 375 °C for 24 h and 17 h, respectively. SOM was calculated by the weight differences obtained between the two temperatures 105 °C and 375 °C.

Plant available nitrogen (N) and total N concentration were determined using a semiautomatic nitrogen estimation system (KJELODIST-EAS VA, Pelican Equipment, India) (Subbiah and Asija 1956). For this, 5 g of soil sample (< 1 mm particle size) was digested with 0.32% $KMnO_4$ and distilled with 2.5% NaOH and titrated against 0.02 N H_2SO_4. Total N was determined by digestion and distillation process by taking 1 g of soil sample digested with concentrated H_2SO_4 and digestion catalyst ($CuSO_4$:K_2SO_4, 1:10) for a time period of 3–4 h (until the milky white precipitate was observed), then distilled with 40% NaOH, and titrated against 0.01 N HCl. Available phosphorus (P) was extracted by the Olsen method and analyzed by spectrophotometer (UV–Vis Spectrophotometer, UV-1800, Simandzu, Japan) as described by Olsen and Sommers (1982). Exchangeable potassium (K^+) and sodium (Na^+) were extracted by 1 N neutral CH_3COONH_4 solution and measured by flame photometer (ESICO-1388, Microprocessor flame photometer, India). Na-saturation method was used to determine cation exchange capacity (CEC) of the soil samples (Jackson 1973).

Soil CO_2 flux measurement

Soil CO_2 flux measurements were carried out by LICOR LI-8100 infrared gas analyzer (LICOR Inc. Lincoln, NE, USA). A polyvinyl chloride (PVC) collar of 20 cm diameter and 10 cm tall was hammered into a flat level surface up to 5 cm depth. The area of soil collar was 314 cm^2 and the volume of the measuring chamber was 1570 cm^3. Prior to the first measurement, all the plant debris and litter present inside the measuring chamber were removed and the collar was left undisturbed for 24 h to minimize the disturbance caused by microbial activity. The observations were recorded continuously for 12 h at every 20 min interval for 90 s. Simultaneously, soil temperature at 10 cm depth was recorded by inserting a temperature probe into the soil (type E thermocouple, p/n 8100-201; 6.4 mm diameter, 25 cm length).

Soil organic carbon and total nitrogen stock

Mine soil contains high amounts of coarse materials which may give erroneous estimates of the nutrients stocks. Therefore, the bulk density of the soil samples was corrected for fine earth materials (< 2 mm) and determined as follows:

$$\text{Bulk density}\left(\text{Mg m}^{-3}\right) = \frac{\text{Sample mass (Mg)} \times \text{Fine earth fraction (\%)}}{\text{Volume of core }(\text{m}^3) \times 100}. \tag{4}$$

To calculate the SOC and total N stock concentrations, corrected bulk density and soil depth were considered and calculated as follows:

$$\text{SOC stock}\left(\text{Mg ha}^{-1}\right) = \text{C}_{\text{conc}}(\%) \times \text{BD}\left(\text{Mg m}^{-3}\right) \times T(\text{m}) \times 100 \tag{5}$$

$$\text{Total N stock}\left(\text{Mg ha}^{-1}\right) = \text{Total N}_{\text{conc}}(\%) \times \text{BD}\left(\text{Mg m}^{-3}\right) \times T(\text{m}) \times 100, \tag{6}$$

where C_{conc} is the soil organic carbon concentration (%); total N_{conc} is the total nitrogen concentration (%); BD is the corrected bulk density (Mg m^{-3}); and T is the thickness of the soil layer (m).

Statistical analysis

Student *t* test was performed to differentiate means of the legume and grass biomass, and nutrient contents. The mean values of the tested variables were compared using one-way analysis of variance (ANOVA). Significant differences between the soil properties of unreclaimed mine spoil, topsoil, legume, and grass were tested using Tukey's post hoc test at $\alpha \leq 0.05$ significance level. All the statistical analyses were carried out using SPSS 21.0.

Results and discussion

Soil physico-chemical and nutritional properties

Establishment of pioneer plant species after revegetation and/or natural succession in a regenerated ecosystem provides an opportunity to monitor and garner information about the influence of plant species on soil development. We studied the 2-year-old reclaimed coal mine soil revegetated with the grasses and legumes, topsoil, and unreclaimed mine spoil, and found significant differences in soil physico-chemical properties under different land covers (Table 2). In the present study, coarse materials (> 2 mm) were significantly ($p < 0.05$) higher under unreclaimed mine spoil (72.05 ± 8.80%) and legume cover (59.53 ± 17.10%) compared to applied topsoil (9.19 ± 4.98%). Higher coarse material under legume cover can be due to the mixing of spoil materials with the applied topsoil during technical reclamation. The percentage of coarse material in a typical mine spoil can be variable at a large scale (30–80%) and mainly depends on the type of rocks, blasting techniques, and process of spoil handling (Sheoran et al. 2010). Maiti and Ghose (2005) opined that the stone content in overburden dumps may be rather high with an average value of 55%. Mine soil properties and pedogenesis are dominated by their technical origin, and therefore, they are classified as Technosol (WRB 2014). Particle-size distributions of the soil under different land covers were studied, and significant differences were found in sand contents among unreclaimed mine spoil,

Table 2 Differences in soil physico-chemical characteristics of unreclaimed mine spoil, topsoil, grass, and legume covers

Soil properties	Unreclaimed mine spoil ($n = 5$)	Topsoil ($n = 5$)	Grass ($n = 5$)	Legume ($n = 10$)
pH (H_2O) (1:2.5; w/v)	8.2 ± 0.1 ab	8.2 ± 0.2 ab	8.3 ± 0.1 a	8.1 ± 0.2 b
pH (KCl) (1:2; w/v)	7.5 ± 0.2 a	7.0 ± 0.2 b	7.6 ± 0.1 a	7.3 ± 0.2 b
pH ($CaCl_2$) (1:2; w/v)	7.7 ± 0.1 a	7.5 ± 0.1 b	7.7 ± 0.1 a	7.7 ± 0.1 a
EC (dS m^{-1})	0.40 ± 0.20 a	0.23 ± 0.03 a	0.35 ± 0.12 a	0.34 ± 0.12 a
Coarse fraction (%)	72.05 ± 8.80 a	9.19 ± 4.98 d	33.04 ± 5.01 c	59.53 ± 17.10 b
Fine fraction (%)	27.95 ± 8.86 d	90.81 ± 4.98 a	66.96 ± 5.01 b	40.47 ± 17.10 c
Sand (%)	82.2 ± 4.30 a	74.2 ± 3.29 c	76.2 ± 3.11 b	79.9 ± 4.70 ab
Silt (%)	14.7 ± 1.21 ab	14.0 ± 2.20 ab	17.3 ± 1.32 a	12.7 ± 2.79 b
Clay (%)	3.12 ± 1.41 c	11.8 ± 2.69 a	6.57 ± 1.83 b	7.43 ± 2.20 b
Bulk density (Mg m^{-3})	2.3 ± 0.10 a	1.4 ± 0.10 b	1.21 ± 0.11 b	1.43 ± 0.43 b
Moisture (%)	4.90 ± 0.27 b	9.42 ± 0.7 a	9.83 ± 1.34 a	11.27 ± 3.24 a
Available N (mg kg^{-1})	18.33 ± 8.55 c	20.53 ± 2.64 b	33.6 ± 5.6 a	98.0 ± 17.95 a
Total N (mg kg^{-1})	235.3 ± 74.6 d	576.6 ± 150 c	1190 ± 210 b	1546.9 ± 328 a
SOC (%)	2.59[a] ± 0.13 a	0.19 ± 0.12 b	0.33 ± 0.03 b	0.56 ± 0.44 b
SOM (%)	NA	1.87 ± 0.51 c	2.25 ± 0.30 bc	3.22 ± 0.82 b
Ex Na (mg kg^{-1})	23.96 ± 9.90 b	63.33 ± 16.65 a	20.8 ± 2.20 b	27.18 ± 8.64 b
Ex K (mg kg^{-1})	147.3 ± 40.5 a	75.66 ± 23.2 b	96.3 ± 15.2 b	157.4 ± 59.3 a
Available P (mg kg^{-1})	0.016 ± 0.003 c	0.016 ± 0.005 c	0.031 ± 0.01 b	0.062 ± 0.061 a
CEC (cmol kg^{-1})	10.84 ± 1.90 b	21.15 ± 1.12 a	17.65 ± 2.52 a	18.7 ± 4.42 a

Alphabetical letters in a same row show significant difference at $\alpha < 0.05$ (Tukey's post hoc test)

NA not analyzed

[a] Higher value of SOC (%) in unreclaimed mine soil is due to presence of coal carbon, which later oxidizes (Nelson and Sommers 1996)

topsoil, and grass cover. Unreclaimed mine spoil contained a higher percentage of sand (82.2%) compared to topsoil (74.2%) and planted topsoil (76.2% under grass and 79.9% under legumes). Clay content was significantly higher in topsoil (11.8%) and lowest in unreclaimed mine spoil (3.1%), while the silt fraction ranged from 12.7 to 17.3% with highest under grass cover and lowest under legumes.

Soil moisture content ranged from 4.90 to 11.27%, where soil under legume showed the highest moisture content (11.27%). Higher moisture content can be ascribed to the accumulation of dead biomass over the soil surface which acts as a shield to evaporation. Lower moisture content in unreclaimed mine spoil can be due to the higher coarse fraction and unimpeded evaporation losses. Bulk density was significantly higher in unreclaimed mine spoil than under different land covers (Table 2). The growth of legumes and grasses improved the soil physical structure particularly moisture and bulk density (Menyailo et al. 2002).

Soil $\mathrm{pH_{water}}$ was alkaline, ranging from 8.0 to 8.2, and was significantly different ($p < 0.05$) under the grass and legume covers. $\mathrm{pH_{Kcl}}$ and $\mathrm{pH_{CaCl2}}$ were found between 7.0–7.6 and 7.5–7.7, respectively. Mine soil was slightly alkaline perhaps due to the basic nature of applied topsoil. Weathering and oxidation of rock fragments can also lead to rapid changes in the mine spoil pH (Sheoran et al. 2010). Maiti and Ahirwal (2017) reported soil pH in the range of 7.2–7.6 in a 2-year-old revegetated site of Jharia coalfield dominated by legume species. Similarly, the study of early growth dynamics of grass species in reclaimed coal mine areas of Northern Spain reported mine soil pH in the range of 8.2–8.3 (Alday et al. 2008). In the current study, electrical conductivity ranged from 0.23 to 0.40 dS $\mathrm{m^{-1}}$, and was not significantly different among the studied land covers. Maiti and Maiti (2015) reported EC in the range of 0.01–0.64 dS $\mathrm{m^{-1}}$ under various grasses and legumes during early stages of revegetation on waste dump.

Available P concentration was found to be higher under legumes (0.062 mg $\mathrm{kg^{-1}}$) compared to unreclaimed spoil. Exchangeable K concentration was significantly greater in soil under grass (157.4 mg $\mathrm{kg^{-1}}$) compared to applied topsoil (75.66 mg $\mathrm{kg^{-1}}$), whereas exchangeable Na concentration was significantly greater in topsoil (63.33 mg $\mathrm{kg^{-1}}$) and lower under grass (20.8 mg $\mathrm{kg^{-1}}$). P and K concentration increased under legume because of the higher SOM and litter decomposition which releases nutrients into the soil (Donahue et al. 1990). CEC was greater in the topsoil (21.2 ± 1.12 cmol $\mathrm{kg^{-1}}$) which may be ascribed to the higher clay content that retains more cations on the surface. Significant differences were not observed in the CEC values of the soils under grass, legume, and topsoil.

Carbon and nitrogen accumulation in reclaimed mine soils

Open strip mining causes degradation of soil quality by removing the topsoil that in turn reduces SOM concentration (Shrestha and Lal 2006). Shrestha and Lal (2011) also reported declined of SOC and N pools in reclaimed mine soils by 52 to 83% and 42 to 75% respectively compared to undisturbed sites. The results reported in the current study showed significant differences in SOM concentration under legumes (3.22 ± 0.82%), grasses (2.25 ± 0.30%), and topsoil (1.87 ± 0.51%) (Table 2). Decomposition of leaf litter releases the bound nutrients into the soil which increases the SOC and N concentration of mine soils over time. SOC concentration in unreclaimed mine spoil was significantly greater (2.59 ± 0.13%) than under the legume cover (0.56 ± 0.44%) probably due to the presence of geogenic C. Young mine soils developed on reclaimed surfaces often contain higher amount of coal particles in addition to OC derived from humification of plants (Ussiri and Lal 2008).

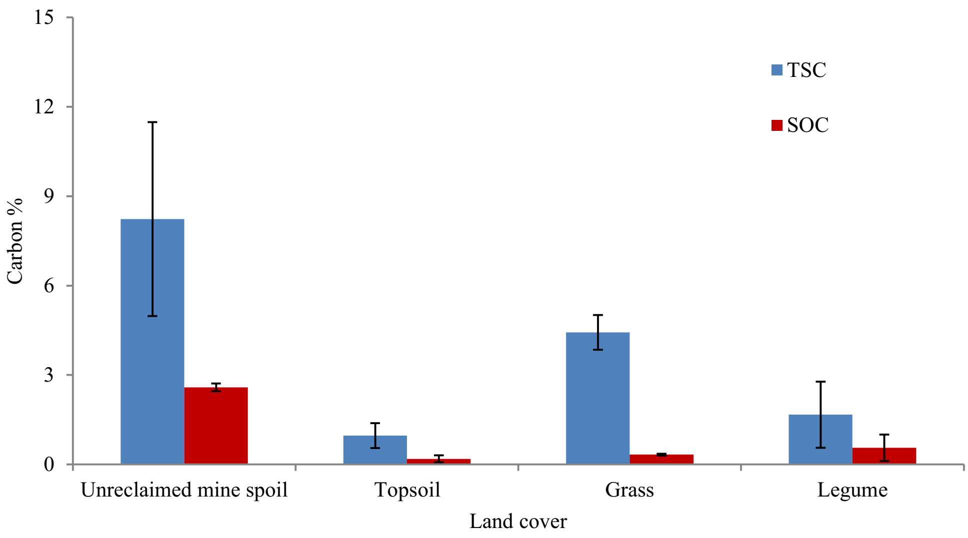


Fig. 3 Variations in total soil carbon (TSC) and soil organic carbon (SOC) percentage under different land covers

Comparative assessment of total soil C (TSC) and SOC concentrations showed that the contribution of SOC to TSC was remarkably higher under the legume cover (33%) than the topsoil (19%) and grasses (7%) (Fig. 3). Higher contribution of SOC to TSC indicates that legumes accumulate more organic C than the grasses, which is mainly attributed to the higher biomass and litterfall. The increase in SOC concentration can be ascribed to the accumulation of leaf litter and its subsequent decomposition to humus (Maiti and Ghose 2005). In the present study, unreclaimed mine spoils revegetated with grass and legumes showed an increment in SOC concentration by 42 and 66%, respectively, than the initial concentration. Maiti and Ahirwal (2017) studied the ecological restoration of post-mining sites in India using grass-legume seed mixtures as initial colonizers, and reported that SOC increased from initial (0.43%) concentration to 1.90% and decomposition of mulch contributed 80% increment in SOC during 3 years of revegetation. Introduction of grasses with legumes contributed to greater surface accumulation of SOC as studies have shown that complementarity between grass and legume species enhances productivity (total biomass and root biomass) resulting in greater soil C accumulation (Fornara and Tilman 2008).

Our study showed significant differences in plant available N under unreclaimed mine spoil, topsoil, and legume (Table 2). Available N was significantly greater in soils under legume (98.0 ± 17.9 mg kg^{-1}) and lowest in unreclaimed mine spoil (18.3 ± 8.5 mg kg^{-1}). Mine soils under legume also showed significantly greater total N concentration (1546 ± 328 mg kg^{-1}) compared to grasses (1190 ± 210 mg kg^{-1}), topsoil (576.6 ± 150 mg kg^{-1}), and unreclaimed mine spoil (235.3 ± 74.6 mg kg^{-1}). The differences in N concentrations may be explained by the higher N fixation and litter accumulation by legumes and their decomposition leads to accelerated biological activity in the soil. The impact of legumes in agricultural systems has been reported in various studies as cultivated legumes fix high amount of nitrogen due to high nodulation bacterial activity, implying that the same activity occurs with forage legumes in uncultivated systems (Georgen et al. 2009).

Legumes can establish well on young mine soils and host Rhizobia species that can fix nitrogen (Boldt-Burisch et al. 2015). Most N required by the plants and soil communities come from N fixation and mineralization of organically bound N. The rooting system of the majority of legumes occurs in the top layer (≤ 20 cm) along with fibrous roots of grasses in early soil development. The topsoil was applied up to a depth of 10 cm in the present experimental plot during technical reclamation. Most roots of the grasses and legumes were found within the top 10 cm layer during the initial stage of revegetation. Therefore, the top 10 cm were studied to assess the impact of revegetation with grass and legumes on the mine soil.

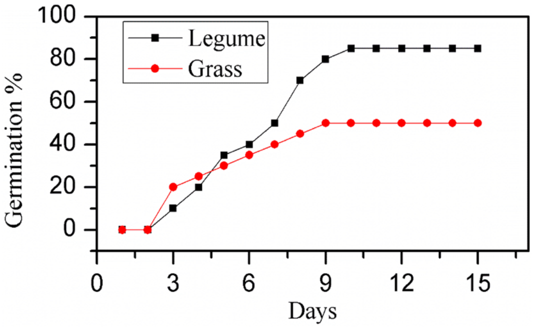


Fig. 4 Germination percentage of the legume and grass seeds in laboratory experiment

Table 3 Characteristics of biomass and distribution of total carbon and nitrogen in different parts of grass (*Cenchrus ciliaris*) and legume (*Stylosanthes hamata*)

Characteristics	Grasses	Legumes	Grass–legume difference (*p* value*)
Shoot length (cm)	36.4 ± 2.88	73.2 ± 9.12	< 0.02
Root length (cm)	11.1 ± 1.74	19.8 ± 2.52	< 0.02
AGB (g m^{-2})	50.3 ± 5.86	144.4 ± 8.38	< 0.01
BGB (g m^{-2})	11.4 ± 2.33	76.8 ± 3.29	< 0.01
AGB:BGB	4.50 ± 0.60	1.88 ± 0.04	< 0.02
AGB –C (%)	28.3 ± 1.81	35.8 ± 2.65	< 0.03
BGB –C (%)	23.0 ± 2.61	23.8 ± 1.79	ns
AGB –N (%)	2.37 ± 0.06	3.65 ± 0.25	< 0.01
BGB –N (%)	1.35 ± 0.05	1.72 ± 0.03	< 0.01

ns non significant, *AGB* above-ground biomass, *BGB* below-ground biomass

*Significant difference was considered at $\alpha < 0.05$ (*t* test)

Carbon and nitrogen accumulation in biomass

Species that can tolerate stress conditions, have a higher germination rate, and are drought resistant will be preferred for reclamation of coal mine spoil. Legume seeds are generally inoculated with N fixing bacteria to enhance growth. In the present study, legume seeds showed a low dormancy period compared to grasses. Approximately 60% of seeds germinated within a week and the rest in 10 days (Fig. 4). No seed germination was observed after 10 days. Legume seeds had an 81% survival rate which was greater than the grass seeds (31%) and thus showed an advantage over grass species. Growth of grass and legume species on the reclaimed OB dump surface was monitored for 2 consecutive years of revegetation. Both the species showed vigorous growth during the monsoon season. We observed that after 1 year, there was approximately 60% vegetation cover which increased to 90% by the end of the second year.

Legumes had a greater root and shoot length, and exhibited significantly ($p < 0.05$) higher biomass compared to grasses (Table 3). Except for root C, the distributions of total C and N in root and shoot of the legumes and grasses were significantly different. Higher biomass contributed by legumes produced greater litter mass that, in turn, increases microbial activity and releases nutrients into the soils. Above-ground biomass of legumes contained 35.8 ± 2.65% C, which was significantly greater than the grasses (28.3 ± 1.81%). The present study showed the 3.65 ± 0.25% N in above-ground parts and 1.72 ± 0.03% N in below-ground biomass of legumes which is significantly higher ($p < 0.01$) than the grasses. Plant inputs of N can occur via above and below-ground residues mainly mulch and rhizo deposits (Fustec et al. 2010). Legume litter has an early and high decomposition rate and high N concentration compared to non-leguminous species (Hattenschwiler et al. 2005). Legumes can fix high amount of nitrogen due to high nodulation bacterial activity in the rhizosphere. Boldt-Burisch et al. (2013) studied the N accumulation potential of three species, *Lotus corniculatus* L., *Trifolium arvense* L., and *Calamagrostis epigejos* (L.) Roth, and reported highest total N content in leaves (33.6 ± 1.4 mg g^{-1}) and root (17.49 ± 4.0 mg g^{-1}) of *L. corniculatus,* i.e., quantity of N accumulation differs, but the pattern between above- and below-ground plant parts is the same.

Soil organic carbon and total nitrogen stocks

During early stages of reclamation, the growth of vegetation cover helps in soil development and accretion of nutrient stock (Shrestha and Lal 2011). Unreclaimed mine spoil had a higher coal fraction that over-estimated the C concentrations, and therefore, it was not considered for C stock calculations in our study. Legumes showed higher SOC stock (3.15 ± 2.38 Mg ha^{-1}) compared to grasses (2.54 ± 0.69 Mg ha^{-1}) and topsoil (2.14 ± 1.18 Mg ha^{-1}). Similarly, soils under legumes had a greater total N stock (0.94 ± 0.76 Mg ha^{-1}) than under the grasses (0.78 ± 0.25 Mg ha^{-1}) and in topsoil (0.72 ± 0.19 Mg ha^{-1}) (Table 4). Initially, the same amount of topsoil which has similar characteristics was applied for both land covers. After 2 years of revegetation, it was observed that SOC concentration was 32% higher under legumes and 19% under grass compared to the applied topsoil. After 2 years of reclamation, legumes showed higher root and shoot biomass that in turn releases more carbon after decomposition. In a similar study, mine soils within 8 years of afforestation with *Prosopis juliflora* exhibit an increase in SOC stock (up to 20 cm depth) from 1.05 to 21.20 Mg ha^{-1} (Ahirwal et al. 2017a).

The rate of SOC sequestration under legumes (1.57 Mg SOC ha^{-1} $year^{-1}$) was higher than grasses (1.27 Mg SOC ha^{-1} $year^{-1}$) in the current study which showed the advantage of planting legumes in increasing SOC stocks and reducing atmospheric C. Study of reclamation of coal mine dump by Ahirwal and Maiti (2018b) reported that afforestation with single or multipurpose tree species showed a rate of SOC sequestration in the range of 1.2–2.8 Mg SOC ha^{-1} $year^{-1}$ which is in range of the present study. Accretion of nutrients and rate of nutrient accumulation in mine soils largely depend on amount of SOM present in soils, age since revegetation, and soil texture especially fine earth materials (Singh et al. 2006; Zipper et al. 2011; Tripathi et al. 2016). Our results showed that soil under legumes and grasses, respectively, had 23 and 8% higher total N stocks compared to the applied topsoil. The rate of soil N accumulation under legumes (0.47 Mg N ha^{-1} $year^{-1}$) is also greater than the grasses (0.39 Mg N ha^{-1} $year^{-1}$). Singh et al. (2006) reported N stock (0.20 Mg N ha^{-1} $year^{-1}$) in the developing coal mine spoil vegetated by young woody plantation. Although previous studies based on tree plantation reported the soil N accumulation ranged between 0.1 and 0.24 Mg N ha^{-1} $year^{-1}$ (Singh et al. 2006; Ahirwal and Maiti 2018b), the present study showed approximately twice the rate of N accumulation in soils. Comparative assessment from the previous studies revealed that revegetation with legumes has similar SOC sequestration but higher N sequestration potential compared to tree species.

Soil CO_2 flux

Open strip mining followed by a reclamation process changes the natural soil properties, which also markedly altered soil respiration. Average soil surface CO_2 flux, surface CO_2 concentrations, and soil temperature under

Table 4 Differences in soil organic carbon (SOC) stock and total nitrogen (N) stock under topsoil, grass (*Cenchrus ciliaris*), and legume (*Stylosanthes hamata*) after 2 years of revegetation

Stock (Mg ha^{-1})	Topsoil	Grass	Legume
SOC stock	2.14 ± 1.18 b (0.44–0.97)	2.54 ± 0.69 b (0.65–1.36)	3.15 ± 2.38 a (0.37–7.99)
Total N stock	0.72 ± 0.19 b (0.44–0.97)	0.78 ± 0.25 b (0.42–1.13)	0.94 ± 0.76 a (0.38–2.99)

Alphabetical letters in a same row show significant difference at $\alpha < 0.05$ (Tukey's post hoc test); values given in parenthesis represent the minimum and maximum values

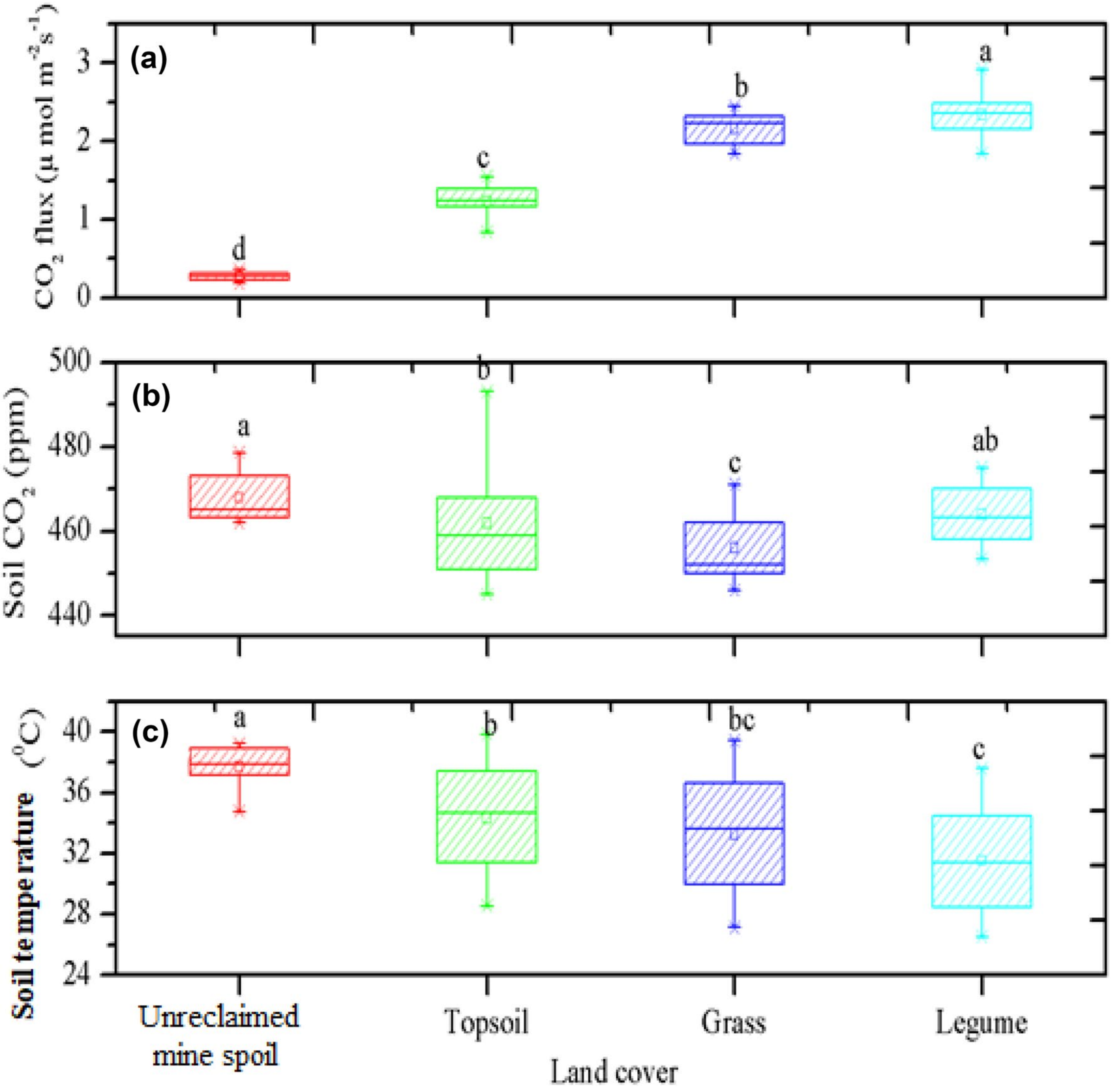


Fig. 5 Differences in **a** soil CO_2 flux (μmol CO_2 m^{-2} s^{-1}), **b** soil CO_2 concentration (ppm), and **c** soil temperature (°C) under different land cover. Alphabetical letters shows significant difference at $\alpha < 0.05$ using Tukey's post hoc test

different land covers were significantly different ($p < 0.05$) (Fig. 5). CO_2 flux under legumes (2.34 ± 0.27 μmol CO_2 m^{-2} s^{-1}) was greater than the unreclaimed mine spoil, topsoil, and grasses which were mainly due to the higher root biomass and associated microbial activity. Soil under legumes and grass recorded 47 and 43% higher CO_2 flux compared to the topsoil and 88–87% higher than unreclaimed mine spoil. Changes in soil CO_2 flux may depend on the land-use pattern, vegetation cover, climatic conditions, and soil substrate (Ahirwal et al. 2017b). Soils under legumes had a greater amount of SOC stocks which decomposes and transfers CO_2 to the atmosphere. Soils under grass had less below-ground biomass compared to legumes that resulted in low soil respiration. Soil CO_2 was mainly produced by roots and microbial activity (Bond-Lamberty and Thomson 2010).

Vegetation cover was not observed on the topsoil dump; therefore, autotrophic respiration was totally absent in this land cover and CO_2 flux was mainly attributed to microbial respiration and natural diffusion processes. Mukhopadhyay and Maiti (2014) studied soil CO_2 flux in natural grassland (11.16 ± 2.16 μmol CO_2 m^{-2} s^{-1}) in India, which is very much higher than the present study. Grasslands have high vegetation cover and high root density which leads to high microbial activity resulting in a high CO_2 flux rate. In the current study, soil CO_2 concentration under legumes, grasses, topsoil, and unreclaimed mine spoil was 464 ± 6.56, 455 ± 7.06, 461 ± 13.2, and 467.9 ± 5.40 ppm, respectively (Fig. 5), and soil temperature under unreclaimed mine spoil was significantly greater than the topsoil, grasses, and

Table 5 Cost of reclamation of coal mine dump blanketed with topsoil and revegetated with grass and legume seeds (area = 5.71 ha)

Activity	Cost in Indian rupees per hectare (US$)
Technical restoration	
1. Fencing of the sites and watering arrangement	60,000 (857)
2. Running cost of vehicle, loader, and auxiliary machinery for grading of dump surface, compact soil on the top surface, and provision of drainage	38,000 (543)
3. Excavation and transportation of topsoil for blanketing the surface of overburden dump (0–10 cm thickness) @ 100 Rs/m^3	100,000 (1429)
4. Cost of fertile topsoil excavated from nearby forest area up to a depth of 0.1 m @ 80 Rs/m^3	80,000 (1143)
Biological restoration	
5. Cost of legume (*S. hamata*) seeds (7.53 kg ha^{-1}) @ Rs. 165/kg	2241 (32)
6. Cost of grass (*C. ciliaris*) seeds (9.45 kg ha^{-1}) @ Rs. 120/kg	1114 (16)
7. Aftercare and maintenance of site for 2 years which includes provision of watch guard, day-to-day unskilled labor charges	131,936 (1885)
8. Scientific advice, analysis of soil parameters, and service charges	60,000 (857)
Total cost of reclamation (per hectare)	473,291 (6761)

Conversion: 1 US$ = Indian Rs 70; US$ have been rounded to nearest $1

legumes. Higher above-ground biomass and canopy cover reduced the soil surface temperature under legume cover.

Cost of reclamation

It is essential to incorporate economically effective reclamation measures that can regenerate attributes of a natural ecosystem at low cost with high throughput. Evaluating the cost of reclamation helps to garner information regarding the economic value of ecosystem services provided by the reclaimed site. It may also provide the approximate capital cost of the compensatory afforestation following diversion of natural forest for mining. Cost of reclamation varies between countries and with the geographic location within a country. There are various factors influencing the cost such as climatic conditions, the height of the dump site, quality of applied topsoil, quality of seeds, sources of water, labor, and aftercare practices.

In our study, the topsoil salvaged from the mining site was used to cover spoil material to a thickness of 10 cm. The cost data provide an estimate to land managers that if the topsoil was purchased (particularly in developed countries), then how much reclamation cost can vary. A total of 20 trips of topsoil were transported to the dump site by Hywa vehicle. The total cost of reclamation was estimated at US$ 6761 ha^{-1}. Technical reclamation including running costs of heavy machinery and vehicles, excavation, and transportation of topsoil accounted for 59% of the total reclamation cost. Biological reclamation constituted 41% of total cost (Table 5). In practice, biological cost varies between 20 and 25% of the total cost of reclamation; however, in the present study, the higher cost (41%) was due to inclusion of 2 years aftercare and maintenance cost and scientific studies. The reclamation cost of US$ 6761 ha^{-1} is very low when compared with US$ 39,730 ha^{-1} reported by Maiti and Maiti (2015), because they used coir-matting on the slopes and higher topsoil thickness (40–60 cm). In the present study, only the top surface of the dump was reclaimed, and thickness of topsoil was limited to 10 cm, even though, in restoration practice, topsoil thickness of 60–100 cm is recommended.

Conclusions

Use of legumes and grasses as initial colonizers aids in the early recovery of degraded coal mine spoil. Legumes showed approximately three times higher biomass accumulation compared to grass species after 2 years of establishment, resulting in a greater amount of organic matter in reclaimed mine soils. Soils under legumes showed 3.15 Mg SOC ha^{-1} and 0.94 Mg N ha^{-1} which was 20 and 17% higher than the grass. Soil respiration was higher under legume cover compared to grass and topsoil, indicating that legumes play a vital role in the enhancement of microbial activity and soil fertility of reclaimed mine soil. Our study showed that legumes planted in topsoil significantly improved the physico-chemical and biological characteristics of the reclaimed mine soil. Therefore, this study concluded that legumes can be used as initial colonizers to restore coal mine spoils and increase mine soil fertility within a short period.

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