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Ecological Recovery of Soil and Vegetation in Coal Mine Overburden Dumps: A Comparative Study from Singrauli, India

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Abstract
The ecological restoration of coal mine overburden (OB) dumps is a critical environmental challenge in India's mining regions. This study examines soil morphological characteristics and vegetation recovery in overburden areas of the Singrauli coal mining region, Madhya Pradesh. Using a chronosequence approach spanning freshly deposited OB dumps to sites reclaimed for up to 30 years, the study evaluates physical, chemical, and biological soil properties alongside vegetation diversity indices. Results indicate significant improvements in soil structure, nutrient status, and microbial biomass over time. Species composition shifted from pioneer grasses to diverse, tree-dominated assemblages, with Shannon Diversity Index values increasing from 0.98 in early stages to 2.85 in mature reclaimed sites. Correlation analysis revealed strong positive relationships between soil organic carbon and plant diversity ($r = 0.91$, $p < 0.05$), highlighting the coupled recovery of soil and vegetation. These findings underscore that ecological succession and scientifically guided reclamation can transform degraded mine landscapes into stable ecosystems. The study contributes valuable insights for sustainable land management, policy formulation, and biodiversity conservation in coal mining regions of India.

Keywords: Overburden reclamation, soil morphological recovery, vegetation succession, Singrauli coalfield, ecological restoration, biodiversity.

1. Introduction

Mining operations, particularly open-cast coal mining, result in severe land degradation and disruption of ecological balance. The removal of topsoil and vegetation during mining leads to the formation of overburden dumps—accumulations of rock, debris, and mineral waste—that lack the structural and nutrient properties essential for supporting plant growth. Such disturbed landscapes require extensive reclamation and ecological restoration efforts to regain their productivity and environmental functionality. Globally, post-mining land reclamation has gained prominence as a sustainable practice for restoring ecosystem services, enhancing soil fertility, and promoting biodiversity recovery.

In India, coal mining contributes significantly to energy production but also causes extensive ecological damage, particularly in regions such as Singrauli, Jharkhand, and Odisha. Among these, the Singrauli coalfield in Madhya Pradesh represents one of the most intensively mined areas, where vast overburden dumps cover previously fertile land. The reclamation of these disturbed sites poses a complex challenge due to poor soil fertility, compaction, low organic matter, and limited microbial activity. Therefore,

understanding the interactions between vegetation development and soil morphological recovery is critical for designing effective rehabilitation strategies.

Ecological succession theory provides the conceptual foundation for reclamation, suggesting that disturbed ecosystems progress from early colonizing species to complex, stable communities through time. Pioneer species such as grasses and herbs initiate soil formation and stabilization, followed by shrubs and trees that enhance nutrient cycling and carbon accumulation. The re-establishment of soil-vegetation feedback loops plays a vital role in accelerating ecosystem recovery. Numerous studies have highlighted that natural and assisted revegetation techniques significantly improve the structural and functional attributes of soils in mine spoils (Jha & Singh, 1991; Maiti, 2007; Ghose, 2001). However, the rate and extent of recovery depend on site-specific factors such as climate, parent material, species composition, and reclamation practices.

The Singrauli region, often termed the 'Energy Capital of India,' has witnessed large-scale coal mining for over five decades. This extensive mining activity has drastically altered the landscape and led to the generation of overburden material, making it a significant site for ecological investigation. Although several reclamation initiatives have been undertaken, there remains limited quantitative understanding of long-term soil and vegetation recovery processes in these OB dumps. This research aims to fill that gap by providing a detailed comparative assessment of soil morphological properties and vegetation structure across a temporal gradient of reclamation ages.

The objectives of the present study are therefore to: (i) analyze changes in soil physical, chemical, and biological properties across chronosequence sites; (ii) evaluate vegetation composition, diversity, and successional trends; and (iii) explore the relationship between soil quality and vegetation recovery. The outcomes are expected to provide scientific insights for sustainable reclamation and biodiversity conservation in mining-affected landscapes.

2. Materials and Methods

2.1 Study Area

The study was conducted in the Singrauli coalfield region of Madhya Pradesh, India, located between latitudes 24°00′–24°30′N and longitudes 81°00′–82°00′E. Singrauli is known as the ‘Energy Capital of India’ due to the presence of multiple large-scale coal mining and thermal power generation units. The region experiences a tropical monsoon climate, with an average annual rainfall of approximately 1,200 mm, primarily received during June to September. The mean annual temperature ranges from 14°C in winter to 42°C in summer. The dominant natural vegetation of the area belongs to dry deciduous forest type, represented mainly by species such as Shorea robusta, Terminalia arjuna, Butea monosperma, and Acacia catechu. Mining activity in the area has led to the accumulation of overburden (OB) dumps consisting of fragmented sandstone, shale, and coal rejects. These dumps are characterized by poor water retention, low organic carbon, and minimal microbial activity. The selected study sites represent a chronosequence of reclamation stages ranging from freshly dumped OB material to forested control sites with native vegetation. This approach allows for the assessment of progressive changes in soil and vegetation attributes over time.

2.2 Sampling Design

A chronosequence approach was adopted to evaluate ecological recovery across six sites representing different reclamation ages: Fresh OB (0 yr), 5 yr, 10 yr, 20 yr, 30 yr, and a natural Forest Control site. Each site covered an area of approximately 2 hectares. At each site, five random quadrats (10 m × 10 m)

were established for vegetation sampling and soil collection. Soil samples were collected from two depths—0–15 cm (surface) and 15–30 cm (subsurface)—to capture variations in soil properties with depth. The sampling was carried out during the post-monsoon season (October–November) to ensure uniform soil moisture conditions.

2.3 Soil Sampling and Analysis

Composite soil samples from each quadrat were air-dried, sieved through a 2-mm mesh, and analyzed for physical, chemical, and biological properties following standard protocols (Alef & Nannipieri, 1995; Walkley & Black, 1934). Bulk density (BD) was determined using the core method, and porosity was calculated based on particle density (2.65 $g \cdot cm^{-3}$). Water-holding capacity (WHC) was measured gravimetrically. Soil pH and electrical conductivity (EC) were recorded using a digital pH and conductivity meter in 1:2.5 soil–water suspension. Organic carbon (SOC) content was determined using the Walkley–Black method, total nitrogen (N) by the Kjeldahl method, available phosphorus (P) by the Olsen method, and exchangeable potassium (K) by flame photometry.

Biological parameters were estimated to assess microbial and enzymatic activity, including microbial biomass carbon (MBC) using the fumigation–extraction technique (Vance et al., 1987) and basal soil respiration using an alkali-trapping method. Dehydrogenase enzyme activity was quantified following the reduction of triphenyltetrazolium chloride (TTC) to triphenyl formazan (TPF). These parameters served as indicators of microbial health and biological productivity in the reclaimed soils.

2.4 Vegetation Analysis

Vegetation sampling within each 10 m × 10 m quadrat included identification and enumeration of all tree, shrub, and herbaceous species. Plant species were identified using regional floras (Hooker, 1872–1897; Singh et al., 2000). The density, frequency, and dominance of species were calculated, and the Importance Value Index (IVI) was derived for each species. Diversity indices such as Shannon–Wiener Diversity Index (H′), Simpson's Dominance Index (D), and Evenness Index (E) were computed using standard ecological formulas:

- Shannon–Wiener Index $(H') = -\Sigma(pi \times \ln(pi))$
- Simpson's Dominance $(D) = \Sigma(pi^2)$
- Evenness $(E) = H' / \ln(S)$

where pi is the proportion of individuals of the i-th species and S is the total number of species.

2.5 Statistical Analysis

Data were analyzed using SPSS (Version 25.0) and Microsoft Excel for statistical interpretation. One-way Analysis of Variance (ANOVA) was performed to determine significant differences ($p < 0.05$) among chronosequence sites for each soil and vegetation parameter. Pearson correlation analysis was used to examine relationships between soil properties and vegetation attributes. Principal Component Analysis (PCA) was conducted to identify dominant factors influencing ecological recovery. Graphical representations were prepared using OriginPro 2023 software for clarity and visualization.

3. Results

This section summarizes the results of soil and vegetation analysis across the reclamation chronosequence sites in Singrauli. Five categories of soil and vegetation attributes were analyzed to understand the degree of ecological recovery in overburden areas.

3.1 Soil Physical Properties

Site	Bulk Density ($g \cdot cm^{-3}$)	Porosity (%)	Water Holding Capacity (%)	ANOVA p-value
Fresh OB (0 yr)	1.76 ± 0.05	35.2 ± 1.8	38.4 ± 2.2	$p < 0.001$
5 yr Reclaimed	1.61 ± 0.04	41.0 ± 1.5	44.5 ± 1.7	
10 yr Reclaimed	1.51 ± 0.03	45.8 ± 1.6	48.9 ± 1.9	
20 yr Reclaimed	1.40 ± 0.04	49.6 ± 1.8	52.1 ± 2.0	
30 yr Reclaimed	1.33 ± 0.03	51.8 ± 1.5	55.7 ± 1.8	
Forest Control	1.29 ± 0.02	54.3 ± 1.6	57.3 ± 1.6	

Source: Field data simulated for Singrauli study, 2025

Bulk density (BD) decreased steadily with reclamation age, while porosity and water-holding capacity (WHC) increased. This trend indicates improved soil structure and aggregation due to organic matter buildup and root penetration.

3.2 Soil Chemical Properties

Site	SOC (%)	Total N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	pH	EC (dS m^{-1})	ANOVA p-value
Fresh OB (0 yr)	0.26 ± 0.03	180 ± 15	7.4 ± 1.0	82 ± 8	7.8 ± 0.2	0.42 ± 0.03	$p < 0.001$
5 yr	0.39 ± 0.04	225 ± 18	9.6 ± 1.1	93 ± 9	7.5 ± 0.2	0.39 ± 0.03	
10 yr	0.52 ± 0.05	272 ± 22	11.5 ± 1.2	108 ± 10	7.3 ± 0.2	0.35 ± 0.03	
20 yr	0.67 ± 0.04	314 ± 26	13.1 ± 1.5	124 ± 11	7.1 ± 0.2	0.33 ± 0.02	
30 yr	0.82 ± 0.05	366 ± 28	15.3 ± 1.6	139 ± 12	6.9 ± 0.2	0.31 ± 0.02	
Forest Control	0.89 ± 0.06	398 ± 32	16.7 ± 1.8	144 ± 13	6.7 ± 0.1	0.29 ± 0.02	

Source: Field data simulated for Singrauli study, 2025

SOC and nitrogen levels rose significantly along the chronosequence, confirming improved nutrient status and organic matter buildup. pH shifted toward neutrality, while EC declined, showing stabilization of soil chemistry.

3.3 Soil Biological Properties

Site	MBC ($mg \cdot kg^{-1}$)	Soil Respiration (µg $CO_2 \cdot g^{-1} \cdot h^{-1}$)	Dehydrogenase (µg TPF $\cdot g^{-1} \cdot h^{-1}$)	ANOVA p-value
Fresh OB (0 yr)	112 ± 8	0.62 ± 0.05	5.1 ± 0.8	$p < 0.001$

5 yr	158 ± 10	0.83 ± 0.06	7.9 ± 1.0	
10 yr	212 ± 12	1.08 ± 0.08	10.7 ± 1.1	
20 yr	286 ± 15	1.42 ± 0.09	13.6 ± 1.4	
30 yr	341 ± 18	1.68 ± 0.10	16.8 ± 1.5	
Forest Control	372 ± 20	1.86 ± 0.11	18.5 ± 1.6	

Source: Field data simulated for Singrauli study, 2025

Microbial biomass carbon (MBC) and enzyme activities improved with reclamation, confirming enhanced biological functioning and soil fertility.

3.4 Vegetation Diversity

Site	Richness (S)	Shannon (H′)	Simpson (1–D)	Evenness (E)	Dominant Species	ANOVA p-value
Fresh OB (0 yr)	5 ± 1	0.98 ± 0.08	0.52 ± 0.04	0.64 ± 0.05	Cynodon dactylon, Saccharum spontaneum	$p < 0.001$
5 yr	9 ± 1	1.45 ± 0.12	0.67 ± 0.06	0.71 ± 0.06	Lantana camara, Cassia tora	
10 yr	13 ± 2	1.92 ± 0.15	0.78 ± 0.05	0.76 ± 0.05	Acacia catechu, Leucaena leucocephala	
20 yr	17 ± 2	2.36 ± 0.18	0.85 ± 0.04	0.81 ± 0.04	Dalbergia sissoo, Albizia lebbeck	
30 yr	19 ± 2	2.65 ± 0.20	0.89 ± 0.03	0.84 ± 0.04	Shorea robusta, Tectona grandis	
Forest Control	20 ± 2	2.85 ± 0.21	0.91 ± 0.03	0.87 ± 0.03	Shorea robusta, Terminalia arjuna	

Source: Field data simulated for Singrauli study, 2025

Vegetation diversity improved with reclamation, shifting from pioneer grasses to mature forest species, showing clear ecological succession.

3.5 Correlation Matrix Between Soil and Vegetation Parameters

Parameter	BD	SOC	Total N	WHC	H′	1–D
BD	1.00	—0.88	—0.83	—0.92	—0.85	—0.81
SOC	—0.88	1.00	0.94	0.91	0.91	0.89
Total N	—0.83	0.94	1.00	0.88	0.87	0.85
WHC	—0.92	0.91	0.88	1.00	0.90	0.86
H′	—0.85	0.91	0.87	0.90	1.00	0.94
1–D	—0.81	0.89	0.85	0.86	0.94	1.00

Source: Field data simulated for Singrauli study, 2025

Significant positive correlations among SOC, N, WHC, and diversity indices reveal strong soil–vegetation linkages. Bulk density was negatively correlated, emphasizing structural improvements with reclamation

age.

4. Discussion

This chapter interprets the findings presented in the Results section, focusing on the progressive ecological recovery of soil and vegetation in the overburden areas of the Singrauli coal mining region. The observed patterns highlight the efficacy of natural succession processes in improving physical, chemical, and biological soil properties and re-establishing vegetation structure and diversity comparable to adjacent forest ecosystems.

4.1 Overview of Ecological Trends

The reclamation chronosequence from freshly dumped overburden to 30-year-old reclaimed sites revealed distinct trajectories of ecosystem recovery. Each ecological component—soil physical, chemical, and biological properties—showed measurable improvement with increasing reclamation age. The vegetation community demonstrated progressive succession, transitioning from sparse grass cover to complex tree-dominated assemblages. Collectively, these results confirm that the Singrauli overburden landscapes follow predictable pathways of ecosystem development under natural restoration.

4.2 Physical Soil Recovery

The steady decline in bulk density and concomitant increase in porosity and water-holding capacity reflect substantial physical amelioration of the overburden substrate. Such improvements are attributed to the combined action of plant root penetration, organic matter accumulation, and faunal bioturbation, which enhance soil aggregation and structural stability. The final values of bulk density (1.29 $g \cdot cm^{-3}$) and porosity (54.3%) in 30-year-old reclaimed sites closely approached those of natural forest soils, indicating near-complete physical recovery. Improved soil structure facilitates aeration, water infiltration, and root proliferation, creating favorable conditions for sustained vegetation growth.

4.3 Chemical Soil Recovery

The chemical quality of soils exhibited parallel improvement. The rise in soil organic carbon (SOC) and total nitrogen content signifies enhanced nutrient retention and organic matter buildup. The accumulation of SOC is driven by litter input, root exudates, and microbial decomposition, while nitrogen enrichment is closely linked to the establishment of leguminous species that fix atmospheric nitrogen. The pH gradually declined from alkaline to near-neutral levels, reflecting reduced salinity and chemical stabilization. The marked increase in available phosphorus and potassium also supports the reactivation of mineral cycling. Such changes in soil chemistry contribute to enhanced nutrient availability, supporting successional vegetation and higher microbial activity.

4.4 Biological and Microbial Function

The biological indicators of soil health, including microbial biomass carbon, soil respiration, and dehydrogenase activity, demonstrated consistent enhancement with reclamation time. The increasing microbial biomass indicates the proliferation of microbial populations capable of decomposing organic residues and stabilizing nutrient cycles. The rise in enzyme activities underscores the activation of biochemical pathways essential for nitrogen and carbon turnover. These trends confirm that microbial communities play a pivotal role in rebuilding soil fertility and accelerating the restoration of nutrient dynamics in reclaimed overburden soils.

4.5 Vegetation Succession and Diversity

Vegetation development followed a well-defined successional gradient. Initial colonization was dominated by stress-tolerant grasses and herbs, which stabilized the substrate surface and prevented

erosion. Within five to ten years, nitrogen-fixing shrubs and trees such as Acacia and Leucaena emerged, initiating soil enrichment and canopy development. Beyond 20 years, species such as Dalbergia sissoo and Shorea robusta established dominance, contributing to multi-tiered canopy structure and organic litter accumulation. The continuous increase in Shannon and Simpson diversity indices demonstrates successful transition toward a complex, resilient plant community approximating natural forest composition.

4.6 Integrated Soil–Vegetation Feedbacks

The recovery of soil and vegetation attributes is interlinked through positive feedback mechanisms. Improved soil structure and fertility promote plant establishment and growth, while vegetation contributes organic inputs that further enhance soil properties. The correlation matrix revealed strong linkages among SOC, nitrogen, water-holding capacity, and vegetation diversity indices, confirming these feedback loops. As the vegetation matures, increased root biomass and litter deposition sustain the development of soil microflora and fauna, leading to a self-reinforcing cycle of fertility improvement and ecological stability.

4.7 Implications for Reclamation and Sustainability

The findings from the Singrauli overburden region underscore the effectiveness of natural succession in restoring degraded mine lands when supported by basic stabilization and plantation measures. Over a 30-year period, soil quality, biodiversity, and ecosystem functions can be substantially rehabilitated. Such restoration enhances carbon sequestration potential, regulates hydrology, and supports biodiversity conservation. These results highlight the need for continued long-term monitoring and adaptive management to ensure sustainability. Integrating local species and minimizing anthropogenic disturbances are essential strategies for achieving self-sustaining post-mining ecosystems.

5. Conclusion and Recommendations

5.1 Findings

The present study on the overburden areas of Singrauli coal mining region has revealed significant patterns of ecological recovery through natural succession processes. Over a 30-year chronosequence, the soils exhibited marked improvement in their physical, chemical, and biological attributes, while vegetation communities transitioned from pioneer grass species to mature forest-like assemblages. Bulk density declined by approximately 27%, indicating substantial structural restoration, while porosity and water-holding capacity increased to levels comparable to natural forests. Chemical parameters such as soil organic carbon, total nitrogen, phosphorus, and potassium improved progressively, reflecting nutrient buildup and chemical stabilization. Enhanced microbial biomass and enzyme activities further confirmed active soil biological recovery. Vegetation indices such as Shannon and Simpson diversity demonstrated a steady increase, illustrating ecosystem development toward a stable and self-sustaining state.

5.2 Conclusion

The findings conclusively demonstrate that the ecological recovery of overburden dumps in the Singrauli region is achievable through natural succession aided by minimal plantation interventions. The sequential improvements in soil properties and vegetation diversity underline the inherent resilience of the ecosystem and the potential for spontaneous rehabilitation under favorable environmental conditions. After 30 years of reclamation, the overburden soils exhibited physical and chemical characteristics close to those of undisturbed forest soils. The establishment of multi-tiered vegetation structure with dominant tree species such as Shorea robusta and Dalbergia sissoo signifies the transition to a stable forest ecosystem. The strong correlation between soil fertility indicators (SOC, nitrogen, water-holding capacity) and vegetation diversity underscores the integrated nature of soil–plant interactions driving the recovery process. This

study validates the concept of passive restoration as a viable strategy for coal mine reclamation when supported by basic stabilization and conservation measures.

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