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Performance of Vetiver System in Overburden Dump Reclamationof SECL Coal-Mine in India: Influence of Soil Nutrients and Seasonal Variations

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Abstract

Vetiver grass (Chrysopogon zizanioides) is recognised for its adaptability in adverse conditions, making it a suitable choice for reclaiming overburden dumps. However, its effectiveness across different seasons and soil nutrient conditions remains underexplored. A limited understanding of nutrient dynamics in dump spoils may result in poor planning; affecting Vetiver's growth and overall reclamation success. This study assesses the performance of Vetiver in an opencast coal mine dump in the Hasdeo-Arand Coalfield, Korba, India. Vetiver was planted across three sites during different seasons in 2018, and soil properties were analysed before and after the plantation using standard soil testing methods. Growth was measured based on the number of shoots and average shoot height. Pre-plantation soil analysis showed acidic conditions (pH 5.69-6.22) and low organic carbon (0.14-0.30%), nitrogen (130-190 kg/ha), phosphorus (10.85-26.19 kg/ha), and potassium (72-198 kg/ha). Post-plantation, soil pH remained stable, with minimal improvement in organic carbon and minor variations in nitrogen, phosphorus, and potassium. Micronutrient analysis indicated slight reductions in manganese, copper, iron, and zinc levels. Vetiver growth was significantly influenced by seasonal conditions. The highest shoot count (44.8 ± 11.62) was recorded at Site A (monsoon plantation), followed by Site B (39.3 ± 6.3). In contrast, Site C (winter plantation) exhibited poor survival, with the lowest shoot count (22.5 ± 5.07) and significant coverage loss by February 2019. Statistical analysis could show that seasonal factors had a considerable impact on growth, with notable differences in phosphorus and organic carbon levels among sites ($p < 0.05$).

Major Findings: *The findings could indicate that Vetiver plantation should be scheduled during the rainy season for optimal growth, with regular fertilization and protection against invasive grass and shade to sustain long-term establishment in overburden dumps.*

Keywords: *Coal Mine Reclamation, Seasonal Effects, Soil Nutrient Variation, Vetiver Grass*

1.0 Introduction

India is ranking 5th globally in coal reserves, possessing approximately 107.726 billion tons, representing around 9.5% of the world's total coal production[1-3]. As the population and infrastructure expand, India's energy demands are increasingly met by coal, the most economical fuel due to its availability. The Geological Survey of India (GSI) has estimated reserves of 11.704 billion tons of superior-grade coal (4.22% of total reserves) and 276.81 billion tons of lower-grade, highly volatile, non-coking coal. Coal-based thermal power plants generate more than 65% of the country's electricity, creating a high demand for coal[4]. Surface or opencast mining has grown due to its technical and economic advantages, accounting for 70% of India's total coal production[5]. However, this method

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brings several environmental challenges, including soil erosion, vegetation depletion, and the creation of nutrient-poor waste dumps[6].

Spoils in opencast mine dumps often have poor structural stability, limiting water retention and making them prone to erosion[7]. These soils frequently lack essential nutrients such as nitrogen and phosphorus, further inhibiting plant growth and ecosystem recovery. High levels of heavy metals and low organic matter contribute to toxicity and infertility, complicating efforts to establish vegetation[8]. Additionally, the soil pH in mine dumps tends to be highly acidic or alkaline, which limits microbial activity and nutrient availability[9]. Soil compaction and poor aeration further restrict root growth and soil biota, making reclamation difficult[10]. Failures of mine waste dumps, often caused by poor structural integrity and insufficient stabilisation measures, can result in catastrophic losses. Hydrostatic pressures from accumulated water in dump voids weaken stabilising forces, leading to frequent slope failures, especially during the rainy season[8]. While mechanical stabilisation methods like rock bolting, wire netting, and shotcreting offer short-term solutions, bioengineering approaches such as phytostabilisation provide longer-lasting benefits. Phytostabilisation is a remediation technique for contaminated soils and mine tailings, particularly in arid and semiarid regions[11]. It employs tolerant plants and soil amendments to stabilise metal pollutants and reduce erosion[12,13]. Grasses like *Festuca rubra*, *Deschampsia cespitosa*, *Lolium perenne* and Vetiver help establish vegetation covers[12,14]. Amendments such as Thomas basic slags and organic matter improve soil conditions and limit metal mobility. Effective phytostabilisation relies on native, drought, salt, and metal-tolerant plants with minimal shoot metal accumulation[14]. It enhances soil properties by increasing microbial biomass, activity, and functional diversity[14]. Long-term success requires continued research to identify suitable species and refine tailings chemistry[11].

Vetiver grass (*C. zizanioides*) has emerged as a key species in the reclamation of mine waste dumps due to its deep root system, which enhances slope stability and reduces erosion[15]. Vetiver is highly resilient, thriving in semi-arid conditions and tolerating extreme temperature fluctuations[16,17]. Vetiver exhibits moderate salt tolerance, with a salinity threshold of 3-6 dS/m and can withstand soil electrical conductivity up to 47.88 mS/cm[18,19]. It accumulates heavy metals, notably cadmium and lead, primarily in its roots, with a cadmium tolerance of 100 mg/kg in soil[20]. Vetiver demonstrates high nutrient uptake, responding positively to nitrogen applications up to 6000 kg/ha/year without adverse effects at 10,000 kg/ha/year, while phosphorus uptake plateaus above 250 kg/ha/year[21]. The resilience of Vetiver to several adverse conditions is often absent in native grasses[22]. In addition to its ecological benefits, Vetiver contributes to carbon sequestration by enhancing belowground biomass and improving soil organic carbon[23].

Economically, Vetiver holds significant value through its roots, which yield essential oils widely used in perfumery, traditional medicine, and aromatherapy[24]. The cultivation and processing of Vetiver roots also support rural livelihoods by enabling the production of handicraft items like mats, baskets, and ropes, particularly beneficial to local and tribal communities in resource-scarce regions[25]. These multifaceted benefits- ecological, mechanical, and economic- make Vetiver a compelling choice over many native grasses for land rehabilitation and phytostabilisation projects, without posing a threat to biodiversity. Due to these excellent qualities, it has become widely adopted for slope stabilisation and soil erosion control, partly due to its fibrous root system, which can reach lengths of up to 3.5 metres[26]. The universal soil loss Equation (1) is a function of the rainfall erosivity factor (R), soil erodibility factor (K), slope length and steepness factor (LS), vegetation factor (C) and support practices factor (P) as given below:

$$A=R\times K\times LS\times C\times P \qquad \text{Equation (1)}$$

Where A is the average annual soil loss in tonnes/hectare/year[27]. The Vetiver is reported to reduce C from 1 (without vegetation) to 0.1 resulting 90% reduction in soil loss[28,29].

This root structure significantly increases soil shear strength and contributes to slope stability[30,31]. It is known to improve soil cohesion by adding root cohesion to it. Several researchers have quantified the root cohesion of Vetiver to be approximately 0.1-0.3 kPa, 2.7-5.2 kPa and 2.3-8.0 kPa, *etc*[32-34]. In sandy soils, Vetiver can improve the factor of safety by 2-15 %, although its impact is less pronounced in clay soils due to deeper-seated failures[35]. In

India, despite it being an indigenous grass, its use in dump reclamation and phyto-stabilisation is limited. Recently, it has been adopted for environmental protection projects, including riverbank stabilisation and rural economic development through Vetiver Grass Technology (VGT) and dump stabilisation at an iron ore mine[36-40]. VGT has also proven effective in coal mine reclamation through methods like the Miyawaki technique, which involves successive plantings of grass, shrubs, and trees to promote forest regeneration[41,42]. However, dump conditions are extremely challenging for plant growth. The mine dumps in coalfields are often contaminated with heavy metals and coal dust, further complicating reclamation efforts by disrupting the nutrient cycle and hindering microbial activity[43]. These dumps often have high stone content, limiting water retention and exacerbating the leaching of essential minerals and nutrients during rainy periods. These characteristics might negatively affect the sustainability of Vetiver.

The Vetiver plantation improves soil microbes (cellulolytic bacteria, cellulolytic fungi and cellulolytic actinomycetes) that change the nutrients of the soil[44]. Free-living nitrogen-fixing microbes increased from 1.00-2.56 to 2.60- 4.36 log no./g of soil. After one year of Vetiver cultivation, the soil's chemical properties, including organic matter, macronutrients, micronutrients, and moisture content, showed significant changes. Organic matter increased from 0.31-2.34% to 0.49-2.62%, while nitrogen levels rose from 0.008-0.140% to 0.016-0.239%. Similarly, phosphorus content increased from 1.75-5.03 ppm to 3.27-6.96 ppm, and potassium levels improved from 32-163 ppm to 51-247 ppm. Moreover, micronutrients play a crucial role in reducing abiotic stresses, and the foliar application of Zn and Fe, along with N, improves the productivity of crops like Indian mustard and wheat[45-47]. Similarly, the productivity of Vetiver grass depends upon the availability of micronutrients at the dumps. The management of micronutrients in the soil is necessary for nutritional security[48]. However, current research on the nutrient composition of dump soils is limited, making it challenging to determine the necessary soil amendments and monitor nutrient levels for effective Vetiver growth.

The Vetiver growth is also affected by the season of the plantation. Cazzuffiand others studied the growth responses of several grasses with Vetiver and found that Vetiver grows prominently when planted in the months of March and April of the year[49]. Its growth is found to be less when planted during winter, characterised by low soil temperature and lower sunlight intensity. Xu also found that Vetiver slips could not survive winter in China, requiring protection against lower soil temperatures[50]. Moreover, soil redox potential (Eh) varies with season in a way that it elevates (>500 mv), stabilising nitrate and phosphate (nitrification) in dry aerobic conditions, promoting sound growth responses[51]. On the other hand, anaerobic conditions in the rainy season reduce Eh to <300 mV, inflicting reductive dissolution and bioavailability of Fe^{2+} and Mn^{2+}, causing phytotoxicity to Vetiver, stunning its growth in terms of reduced stomatal conductance, photosynthesis, and biomass[52,53]. Iron toxicity harms root physiology, including nitric oxide-mediated potassium efflux and accumulation of reactive oxygen species[54]. Nonetheless, the overburden dumps in India might be subjected to low temperatures during winter. Therefore, it is important to investigate the effects of seasonal plantations on Vetiver.

After successful growth, Vetiver grass demonstrates multifaceted ecological interactions and biodiversity conservation potential through both direct and indirect mechanisms. For example, despite its low palatability, Vetiver's young shoots (protein content 7-12%) are occasionally consumed by goats, sheep, Brahman cattle, swamp buffalo, and fish as a low-maintenance fodder[55]. However, due to its capacity to accumulate heavy metals such as As, Cd, Cr, Cu, and Ni, its use in contaminated areas raises concerns over potential trophic transfer into the food chain[56]. Vetiver clumps create microhabitats that might shelter insects, birds, and small mammals[57]. It might act as protection against harmful animals. In Nepal, farmers observed a reduction in rat burrowing where Vetiver was planted along bunds, and in Papua New Guinea, bush pigs have avoided uprooting Vetiver for over three years, suggesting a natural barrier to some herbivores[58,59]. Additionally, its dense biomass can be periodically burnt in arid regions to manage fire risks and reduce termite infestations, maintaining plant health while supporting fire-adapted ecological functions[60-62].

Therefore, this study is limited to two objectives: (a) To characterise soil nutrients and their variation in the rhizospheric spoils of the dumps planted with Vetiver, and

(b) To survey the Vetiver growth in the different sites with different phases of Vetiver plantation. However, this study does not focus on nutrient balance and cross-correlation of Vetiver growth to different factors influencing the Vetiver growth.

2.0 Materials and Methods

2.1 Study Site Descriptions

South Eastern Coalfields Limited (SECL), a subsidiary of CIL, has an opencast coal mine situated in the Korba district of Chhattisgarh state in India. This coal mine is a part of Hasdeo Arang, an area of about 530 km^2, as shown in Figure 1[63]. The general topography is a flat terrain with mild undulations. The mean sea level ranges from 280m to 300m. This region falls in a dry to moist tropical climate with temperatures ranging from 6° C to 48° C Maximum. Rainfall varies from 1300 to 1600 mm annually. Wind directions are predominantly between NE/NNE directions, and wind velocity readings range between 1.0 to 5.5 km/h[64]. The overburden dump is located between 20°19'10" N and 22°20'47" E. The tongue-shaped dump is shown in the shaded region with a blue location pointer in Figure 1. The enlarged view of the dump has 3 dump benches created for the plantation of Vetiver grass, created by excavating the dump face named Bench I, II and III.

The dump has been empirically estimated to have a perimeter and an area of about 1,071.97 m and 59,252.91 m^2 (Figure 2a). The Benches I, II and III have average slanted heights of 4m, 4m and 8m and bench slopes of



Figure 1. Coal mine (study site) pit boundary showing the location of Dump-13 (blue mark in shaded boundary[65].

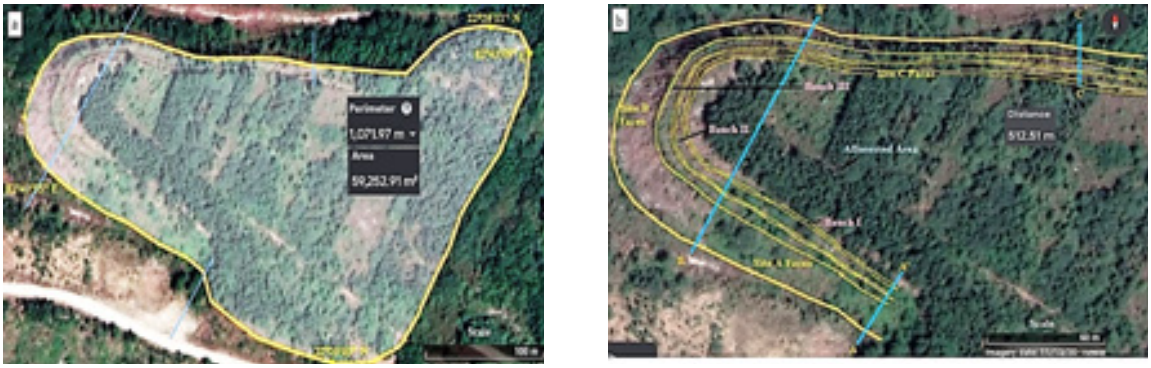


Figure 2. **(a)** The boundaries of the dump **(b)** Benches in enlarged view[65].

Table 1. General observational details of benched slope sites of dump chosen for Vetiver plantation

Names of Benched Slope Faces	Location Between Sectional Lines	Direction	Bench Height (m) (approx.)	Average Bench Slope (Degrees) (approx.)	Length (m) (approx.)	General Condition of Vetiver Plantation
Site A	A-A' and B-B'	North West direction facing towards mine pit	Bench I and II – 4m; Bench III – 8m	Bench I and Bench II 46^{0}32'04"; Bench III - 35^0 30'30"	Bench I - 114.8m;Bench II -124.5m; Bench III -142.6m	Muddy red lateritic sub-soil patches, densely vegetated and bordered by Vetiver grass planted in late September 2018 during the monsoon.
Site B	West-wards to B-B' only	Slightly North in the West direction, joins Site A and Site C in a curvy shape			Bench I - 112.2m;Bench II -124.7m; Bench III, 168.5m	The curvy, tongue-shaped face consists of light grey sandstone and shale fragments, with moderate vegetation, but Vetiver hedges are less prominent than at Site A. The plantation occurred in early October 2018, just after the monsoon.
Site C	B-B' and C-C'	Tending to East-West direction, opposite of Site A			Bench I - 157.6m; Bench II - 159.1m; Bench III- 169.5m,	Similar to Site B, but with very poor Vetiver growth, the plantation occurred in early November 2018, at the start of winter.

46.5°, 46.5° and 35.5° approximately. The periphery of the tongue-shaped dump slope was categorised by sectional lines A-A', B-B' and C-C' and divided into 3 regions according to the span of the Vetiver plantation and postulated as Sites A, Site B and Site C (Figure 2b). The observational details of these sites are given in Table 1.

2.2 Weather Data

The daily and monthly average values of weather parameters such as solar radiation, temperature, relative humidity, rainfall, and atmospheric pressure are recorded with appropriate standardised instruments at the weather station in the opencast mine. The trends of weather

Table 2. Weather (monthly average) report of opencast coal mine from July 2018 to October 2019[66]

Weather Parameters	Units	Min.	Max.	Avg.	Standard Deviation
Solar radiation	W/m^2	104.30	602.40	382.54	168.80
Temperature	°C	18.07	34.75	26.72	4.67
Relative humidity	%	31.23	85.67	52.75	21.52
Atm. rainfall	mm	0.00	570.19	178.74	189.24
Pressure	kPa	96.54	98.78	97.97	0.55

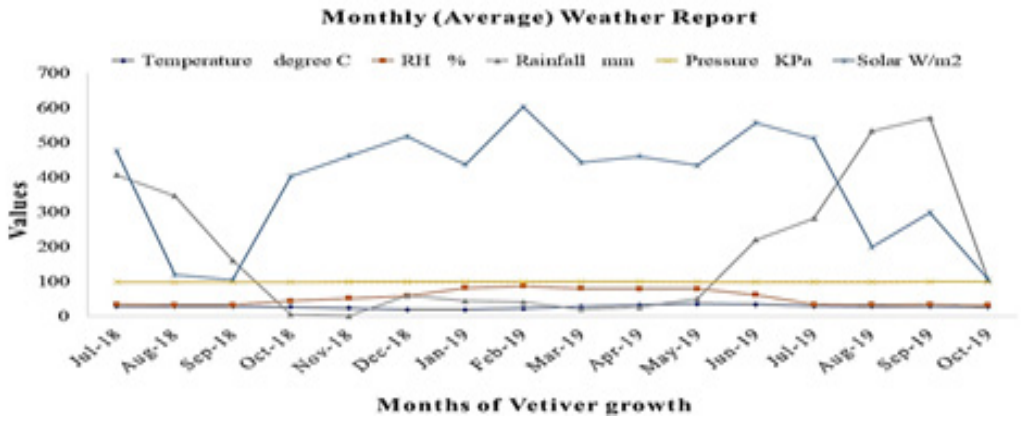


Figure 3. The variations in weather parameters in the growth period of Vetiver in the dump of an opencast coal mine

parameter values are also depicted in Figure 3. The ranges, means and standard deviation of these parameters are given in Table 2.

Due to stressful weather conditions, drip irrigation was installed at the Vetiver plantation site, supported by a 1000-litre water tank placed on the bench floor. This system supplied water directly to the Vetiver slips, delivering 1000 litres every alternate day during non-rainy periods. Irrigation was needed for 135 days throughout the growth phase.

2.3 Plantation of Vetiver on the Dump Sites

Vetiver saplings were created out of the nursery of a two-month-old Vetiver by cutting their roots about 2 inches from the base with half a kilogram of cattle dung as a basal dose with the same amount of nursery soil. The saplings were watered and conditioned for about a week before being transported to dump sites for plantation. The Vetiver saplings were manually planted on the Dump's slopes. The span between plants and row-to-row distance was 30 cm and 100 cm, respectively.

2.4 Method of Sampling and Preparation

The soil samples were randomly taken by grab sampling from all the benches, keeping an eye on colour variation and soil types with the help of a small pick, and it was kept in a plastic bag. It was also ensured that soils were extracted from the rhizosphere at the base of Vetiver grass. After sufficient samples were collected and reduced to one kilogram by mixing soil samples by Coning and Quartering. The samples were kept in clean, distinctive sample bags, labelled with the site name, and carried to Govt. Soil Testing Laboratory at Bilaspur, Chhattisgarh, for further processing and testing. It was air-dried and crushed with a wooden pestle and then filtered with a 2mm sieve as per standard practice to store samples of about half kilograms of each site in clean plastic jars.

2.5 Chemical Analysis

The chemical analysis of spoil samples is done in the Soil Testing Lab at Bilaspur in Chhattisgarh. The soil testing methods and processes are described below:

Spoil *pH* was determined by mixing soil and distilled water solution (1:2.5) for 30 minutes and using a glass electrode pH meter[67]. The spoil's Electrical Conductivity (EC) was determined by using an electronic electrical conductivity meter by dipping in clarified samples left for 30 min. The Organic Carbon (OC) of spoil samples was determined by using potassium dichromate and ferrous ammonium sulphate (Mohr's salt) as the standard procedure (Walkley and Black Method)[68]. Available nitrogen (Avail. N.) was determined by the standard process of the Kjeldahl method[69]. Available phosphorus (Avail. P) was extracted by using 0.5M $NaHCO_3$ (pH 8.5) and estimated as described in Olsen *et al.*[70]. The available phosphorous (The Avail. P) was determined using the method described by Bray and Kurtz[71]. Available

potassium (Avail K) was extracted by shaking with neutral standard ammonium acetate for 5 minutes at a constant temperature (25° C) according to the method postulated by Hanway and Heidal[72]. Available Sulphur (Avail. S.) is extracted by *Gum acacia* and $CaCl_2$ as extractants and determined using a spectrophotometer known as the Turbidimetric method[73,74]. Available Boron (Avail. B.) was determined using the hot water method per Berger and Truog[75]. Available micronutrients zinc(Zn),Copper (Cu), Manganese (Mn) and Iron (Fe) were extracted by Diethylene-Triamine-Penta-Acetate (DTPA) method and measured by spectrophotometry[76].

2.6 Survey of Vetiver Growth

The Vetiver growth is measured in terms of plant height using plain tape and the number of leaves by manual counting of the shoot towards the end of the 4th test, around the end of November 2018. Photographs of the existing dump sites with Vetiver grass were taken after three months in February 2019.

3.0 Results and Discussions

3.1 Conditions of Dump Soil Nutrients

The results of soil nutrient tests in pre-plantation and post-plantation phases at various sites are given in Tables 3 and 4. The comparative results found from the above tests for different dump sites are as follows:

3.1.1 Soil pH

The suitable pH range for the growth of forages and most horticultural plants is 6.0 to 7.5[77,78]. The pH at various sites ranged from 5.7 to 6.55, which is favourable for plantation. The mean pH values showed a slight decrease from 6.09 to 6.05 and from 6.22 to 6.2 during the pre-and post-plantation of Vetiver, likely due to anion leaching from rain. Site A and B showed a slight decrease in pH, with averages of 6.225 and 6.2, respectively. Site C had the lowest and most constant pH, averaging 5.69, likely due to poor vegetation and lack of Vetiver hedge. The overall pH

Table 3. The soil properties as found before the plantation of Vetiver at the dump sites

Soil Properties	Site A			Site B			Site C		
	Test I	Test II	Average	Test I	Test II	Average	Test I	Test II	Average
pH	6.38	5.8	6.09	6.55	5.9	6.225	5.68	5.7	5.69
Electrical Conductivity (EC) (dS/m)	0.22	0.25	0.235	0.34	0.17	0.255	0.2	0.3	0.25
Organic Carbon (OC) (%)	0.15	0.28	0.215	0.3	0.21	0.255	0.15	0.14	0.145
Avail. N (Kg/Hectare)	220	160	190	140	120	130.00	145	122	133.5
Avail. P (Kg/Hectare)	15.63	12.64	14.135	19.52	10.85	15.185	26.19	23.33	24.76
Avail. K (Kg/Hectare)	95	184	139.5	110	198	154	72	136	104
Avail. S (ppm)	9.05	22.66	15.855	18.23	22.43	20.33	13.9	26.75	20.325
Avail. Zn (ppm)	1.99	2.41	2.2	1.63	2.42	2.025	2.04	4.49	3.265
Avail. B (ppm)	5	4	4.5	1	3	2	4	2	3
Avail. Fe (ppm)	37.14	28.43	32.785	11.31	24.22	17.765	19.56	10.12	14.84
Avail. Mn (ppm)	43.42	22.08	32.75	30.44	18.55	24.495	37.45	7.24	22.345
Avail. Cu (ppm)	0.58	0.34	0.46	0.6	0.23	0.415	0.28	0.12	0.2
Days between tests	34 days *i.e.*, from 21st February to 27th March in the year 2018								

Table 4. The soil properties as found after the plantation of Vetiver at the dump sites

Soil Properties	Site A			Site B			Site C		
	Test III	Test IV	Average	Test III	Test IV	Average	Test III	Test IV	Average
pH	6.3	5.8	6.05	6.5	5.9	6.2	5.68	5.7	5.69
Electrical Conductivity (EC) (dS/m)	0.2	0.3	0.25	0.3	0.2	0.25	0.2	0.3	0.25
Organic Carbon (OC) (%)	0.15	0.3	0.225	0.3	0.3	0.3	0.15	0.14	0.145
Avail. N (Kg/Hectare)	225	163	194	150	125	137.5	145	122	133.5
Avail. P (Kg/Hectare)	14.33	11.64	12.985	18.81	9.85	14.33	26.19	23.33	24.76
Avail. K (Kg/Hectare)	89	179	134	100	190	145	72	136	104
Avail. S (ppm)	10	22.5	16.25	17.5	21.25	19.375	13.9	26.75	20.325
Avail. Zn (ppm)	1.99	2.3	2.145	1.6	2.28	1.94	2.04	4.49	3.265
Avail. B (ppm)	6	3	4.5	1	4	2.5	4	2	3
Avail. Fe (ppm)	37.12	27.89	32.505	10.26	23.73	16.995	19.56	10.12	14.84
Avail. Mn (ppm)	42.11	22.02	32.065	29.45	18.73	24.09	37.45	7.24	22.345
Avail. Cu (ppm)	0.55	0.149	0.3495	0.73	0.114	0.422	0.28	0.12	0.2
Days between tests	66 days *i.e.*, from 23rd September to 28th November in year 2018.								

Abbreviations used: Avail. - Available; ppm - parts per million; dS/m - Deci-siemens per meter.

change was minor and insignificant over the eight and a half-month of observation.

3.1.2 Electrical Conductivity (EC)

The Electrical Conductivity (EC) varied from 0.2 to 0.25 dS/m at Site A, rising insignificantly before remaining almost constant at 2.2 dS/m before and after the plantation. At Site B, EC showed a distinct fall from 0.34 to 0.17 dS/m, and then recorded 0.3 to 0.2 dS/m before and after plantation. Site C exhibited similar trends to Site A, with EC varying from 0.2 to 0.3 dS/m, faintly rising in both phases. This indicates that Vetiver grass did not significantly alter the EC. The average EC increased at Site A, decreased at Site B, and remained constant at Site C in both phases.

3.1.3 Organic Carbon (OC)

It is found to rise from 0.15-2.8 % to 0.15% to 0.3% (on average 0.215-0.145 %, *i.e.*, decreasing slightly) before and after the Vetiver plantation at Site A. The same is firstly found decreasing, on the contrary, in Site B, from 0.3% to 0.21%, then maintaining a level of 0.3%. It is slightly higher than that of Site A. However, it is the almost unchanging level of 0.15-0.14% in both phases and the lowest level from all the sites. This lack of OC might be due to the absence of Vetiver grass due to its very poor growth and death overtime, which prevented the Vetiver from producing and conserving organic carbon. Average OC values show that it is improving in Site A and Site B but are almost constant in Site C, owing to the vegetation of Vetiver in those sites in the pre- and post-plantation phases.

3.1.4 Available Nitrogen (Avail. N)

Available nitrogen, a crucial macronutrient for plant growth, is a key constituent of proteins necessary for plant cells. At Site A, the available nitrogen was initially higher but decreased at the same rate during the pre- and

post-plantation phases, dropping from 220 to 160 kg/ha and 225 to 163 kg/ha, respectively. Sites B and C showed more stable nitrogen levels, also experiencing reductions of 20-25 kg/ha. Site B's levels decreased from 145 to 122 kg/ha in the pre- and post-plantation phases. Similarly, Site C decreased from 140 to 120 kg/ha pre- and 145 to 122 kg/ha post-plantation phase. The yearly consumption of available nitrogen in the study sites was significantly lower (about 40-50 kg/ha/year) compared to the tolerable limit of 6000 kg/ha/year, while still supporting appreciable growth of Vetiver grass. The mean values across these sites indicate a faint improvement in available nitrogen in both phases[21].

3.1.5 Available Phosphorous (Avail. P)

Available phosphorous, a macronutrient required for plant growth, is needed in lesser quantities than nitrogen. At Site C, it varied from 26.19 kg/ha to 23.33 kg/ha during the pre- and post-plantation phases. Site B showed a range of 19.52 kg/ha to 10.85 kg/ha in the pre-plantation phase and 18.81 kg/ha to 9.85 kg/ha in the post-plantation phase. Site A displayed a similar trend to Site B but with lower levels and less variation, ranging from 15.63 kg/ha to 12.64 kg/ha pre-plantation and 14.33 kg/ha to 9.85 kg/ha post-plantation. Overall, available phosphorous decreased at all sites in both phases, with the average values showing a slight decrease at Sites A and B, and remaining almost constant at Site C.

3.1.6 Available Potassium (Avail. K)

Available potassium is another essential macronutrient for plants. At Site A, its levels increased from 110 kg/ha to 198 kg/ha pre-plantation and from 110 kg/ha to 190 kg/ha post-plantation. Site B showed similar trends, varying from 95 kg/ha to 184 kg/ha pre-plantation and from 89 kg/ha to 179 kg/ha post-plantation. Site C displayed lower levels compared to Sites A and B, ranging from 72 kg/ha to 136 kg/ha in both phases. The average values indicated a slight decrease in available potassium at Sites A and B, but remained almost constant at Site C.

3.1.7 Available Sulphur (Avail. S)

Available sulphur, important after NPK for plant growth, was enriched in the pre-and post-plantation phases. At Site A, levels increased from 9.05 ppm to 22.43 ppm pre-plantation and 10 ppm to 21.25 ppm post-plantation. Site B showed variations from 18.23 ppm to 22.43 ppm pre-plantation and 17.5 ppm to 21.25 ppm post-plantation. Site C displayed the highest levels, varying from 13.9 ppm to 26.75 ppm in both phases. The results suggest an unrealistic enrichment likely due to the addition of sulphur from dump spoils.

3.1.8 Available Zinc (Avail. Zn)

Available zinc, a micronutrient, was least abundant at Site A, varying from 1.99 ppm to 2.41 ppm and 2.3 ppm in both phases. Site B showed levels from 1.63 ppm to 2.42 ppm pre-plantation and from 1.6 ppm to 2.28 ppm post-plantation. Site C constantly increased, ranging from 2.04 ppm to 4.49 ppm in both phases. Thus, available zinc levels increased during both phases, with the maximum variation observed at Site C. The average values slightly decreased at Sites A and B, while remaining almost constant at Site C.

3.1.9 Available Boron (Avail. B)

Available boron, an essential micronutrient for enhancing nutrient availability, varied from 5-4 ppm pre-plantation to 6-3 ppm post-plantation at Site A. At Site B, levels increased from 1-3 ppm pre- and 1-4 ppm post-plantation. Site C showed a decrease from 4-2 ppm in both phases. The average values indicated no variation at Sites A and C but an improvement at Site B during Vetiver growth.

3.1.10 Available Iron (Avail. Fe)

Available iron, essential for chlorophyll production, decreased from 37.14 ppm to 28.43 ppm pre-plantation and from 37.12 ppm to 27.89 ppm post-plantation at Site A. Contrarily, Site B showed an increase from 11.31 ppm to 24.22 ppm in both phases. Site C experienced a decrease from 19.56 ppm to 10.12 ppm in both phases.

3.1.11 Available Manganese (Avail. Mn)

Available manganese, crucial for photosynthesis, decreased from 43.42 ppm to 22.08 ppm pre-plantation and from 42.11 ppm to 22.02 ppm post-plantation at Site A. Site B showed a reduction from 30.44 ppm to 18.55 ppm pre-plantation and from 29.45 ppm to 18.73 ppm post-plantation[79]. Site C experienced a decrease from

37.45 ppm to 7.24 ppm in both phases. The average values slightly decreased at Sites A and B but remained almost constant at Site C.

3.1.12 Available Copper (Avail. Cu)

Available copper, essential for enzyme activation in photosynthesis, decreased from 0.58 ppm pre-plantation to 0.58 ppm post-plantation and from 0.55 ppm to 0.149 ppm at Site A. Site B showed a decrease from 0.6 ppm to 0.23 ppm pre-plantation and from 0.73 ppm to 0.114 ppm post-plantation. Site C decreased from 0.28 ppm to 0.12 ppm in both phases. The average available copper values indicated a greater decrease at Site A, a slight decrease at Site B, and remained unaltered at Site C, corresponding to the vegetation of Vetiver grown.

3.2 Statistical Analysis

Nutrient values from various sites of dump were analysed using an unpaired student's t-test for 2 samples with unequal variances of different sites at any phase and using a paired t-test between pre- and post-plantation phases, assuming a mean difference of zero. The results of the statistical (p-value) analysis are given in Table 5.

In the pre-plantation phase, the p-values ranged from 0.04 to 0.4 between any 2 sites ($p > 0.05$), indicatingthe differences in most nutrient values are not statistically significant except for the available phosphorous ($p = 0.04<0.05$) between site A and site C. Similarly, the same for post-plantation ranged from 0.02 to 1.00 between any 2 sites except for organic carbon between site B and C

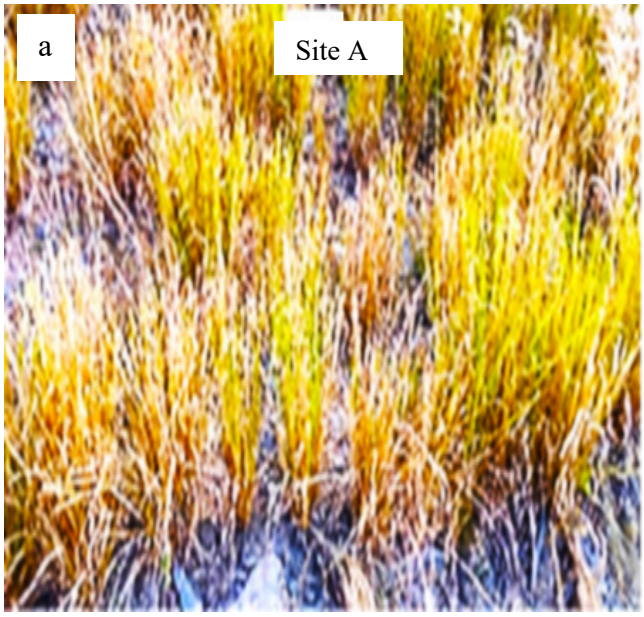
Table 5. The significance test (p-value analysis) of nutrient levels at the dumpsites

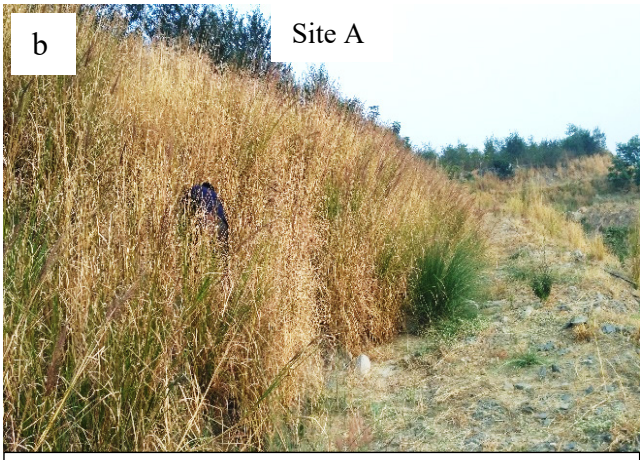
Soil Properties	P-values for Pre - plantation phase (α = 0.05)			P-values for Post-plantation Phase (α = 0.05)			P-values for Pre- and Post-plantation Phases in the Same Site (α = 0.05)		
	Sites A and B	Sites B and C	Sites A and C	Sites A and B	Sites B and C	Sites A and C	Site A	Site B	Site C
pH	0.79	0.35	0.40	0.74	0.34	0.39	0.50	0.50	0.50
EC	0.85	0.97	0.82	1.00	1.00	1.00	0.74	0.91	0.50
OC	0.67	0.74	0.48	0.50	0.02	0.48	0.50	0.50	0.50
Avail. N	0.27	0.16	0.28	0.29	0.84	0.28	0.16	0.20	1.00
Avail. P	0.85	0.89	0.04	0.82	0.23	0.03	0.08	0.11	0.50
Avail. K	0.84	0.69	0.59	0.88	0.54	0.65	0.06	0.07	0.50
Avail. S	0.63	0.64	0.68	0.71	0.91	0.69	0.61	0.15	0.50
Avail. Zn	0.74	0.76	0.54	0.66	0.47	0.53	0.50	0.37	0.50
Avail. B	0.20	0.13	0.35	0.45	0.81	0.50	1.00	0.50	0.50
Avail. Fe	0.21	0.15	0.11	0.21	0.82	0.12	0.48	0.22	0.50
Avail. Mn	0.58	0.46	0.64	0.57	0.93	0.65	0.47	0.61	0.50
Avail. Cu	0.86	0.57	0.23	0.86	0.60	0.59	0.40	0.96	0.50

(p =0.02) and available phosphorous between site A and site C (p =0.03). However, in the pre-and post-plantation phases of Vetiver, all the nutrient parameters had p > 0.05, not showing statistically significant differences. This suggests that nutrient variation during the Vetiver growth phase was negligible, likely due to low nutrient uptake or leaching from water action at the dump.

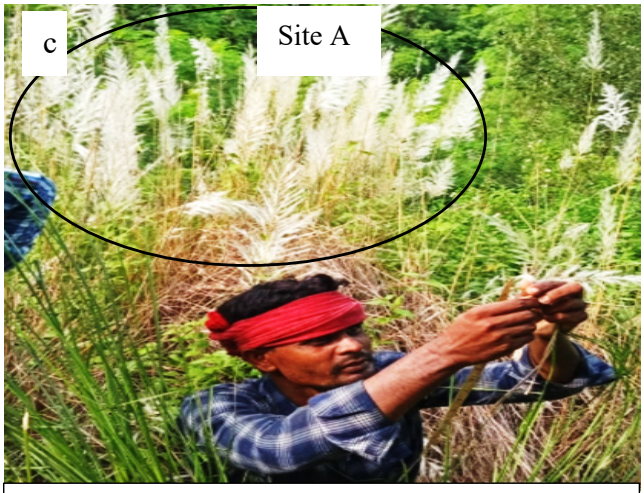
3.3 The Growth Response of Vetiver in Dump Sites

The Vetiver grass exhibited a growth range of 1.5 to 2 m, with an average height of 180 ± 11 cm (based on 20 plants) during the study period. The number of leaves per Vetiver bunch varied across different sites. At Site A, it

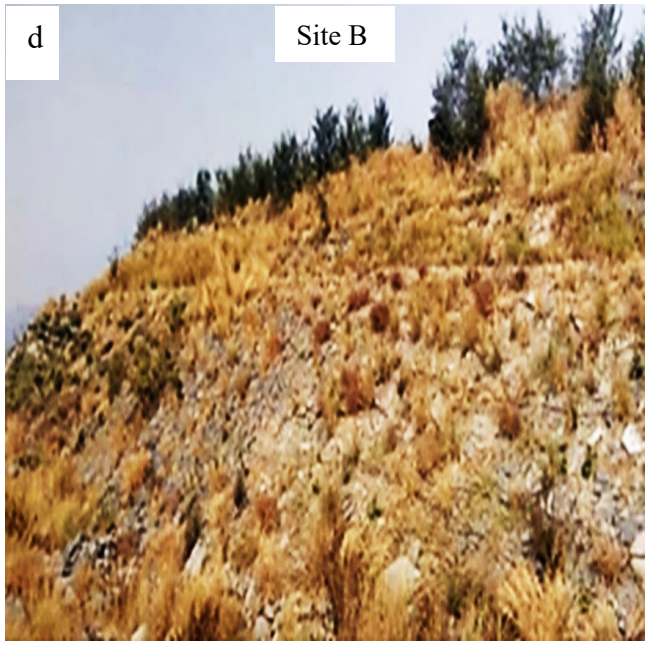




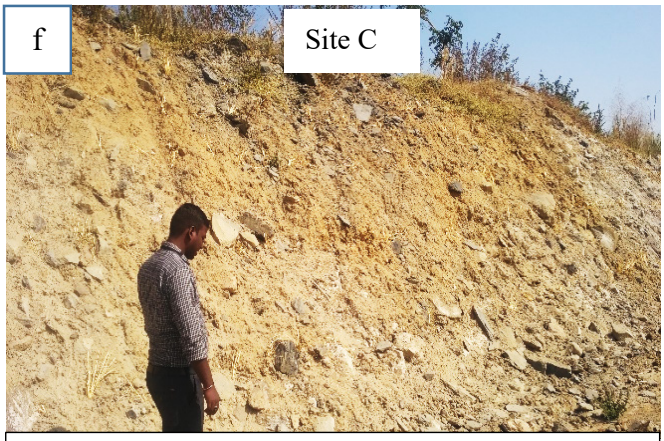
Growth of Vetiver (Site A, as seen from Site B) after the rainy season (Dec 2018): Vetiver has grown profoundly in two to three months at Dump 13



Measurement of shoot height in Site A after the rainy season (Dec 2021): The Vetiver field had been outcompeted by native weeds, as shown in circles.



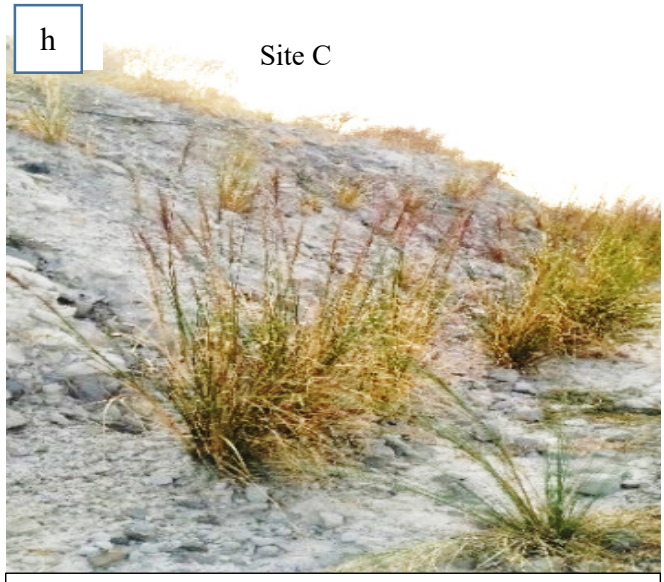




Premature failure of Vetiver (Site C, from rear end) after the rainy season (Nov. 2018): Vetiver could not survive the delayed plantation and dry winter seasonal effects.



Spoil sample collection using grab sampling (Site B) after the rainy season (Dec 2018): Vetiver has grown well in two to three months at Dump 13.



Vetiver Growth (Site C) after the rainy season (Dec 2018): Vetiver has grown moderately to poorly in two to three months at Dump 13.

Figure 4. The growth responses of Vetiver grass at various dump sites at different phases.

ranged from 26 to 67, with an average of 44.8 ± 11.62 (20 plants). At Site B, the leaf count ranged from 24 to 50, averaging 39.3 ± 6.3 (20 plants). Site C recorded a lower range of 14 to 32 leaves, with an average of 22.5 ± 5.07 (20 plants). The mean number of leaves for the samples for Site A and Site B are significantly not different ($p = 0.08$) but the same for Site A and Site C ($p = 7.610^{-11}$) and Site B and Site C ($p = 3.8910^{-8}$) are significantly

different. The growth conditions of the Vetiver were documented through photographs, as shown in Figure 4.

Notably, Site C experienced significant Vetiver coverage loss by the end of February 2019.

However, Site A and Site B were found with well-grown Vetiver hedges. Site C faced lesser Vetiver pasture growth, as mentioned earlier, which could be due to late plantation and unhealthy saplings owing to water stress caused by this delay in the plantation. This Vetiver growth is pictorially shown in Figure 4.

4.0 Conclusions

This study demonstrates that Vetiver Grass Technology (VGT) can achieve satisfactory growth in the challenging conditions of overburden dumps, even within a semi-arid climate with mild temperature variations. Applying irrigation and a basal fertiliser dose of compost (approximately half a kilogram per plant) was sufficient for the healthy establishment and sustenance of Vetiver grass. Notably, Site A, where planting occurred at the onset of the monsoon season, exhibited the most robust Vetiver hedgerows, followed by Site B, while Site C, planted at the onset of winter, showed the least growth. These findings underscore the importance of seasonal timing, with the rainy season proving to be the most conducive for Vetiver plantation, whereas planting during winter may lead to suboptimal growth and higher mortality rates.

The study also reveals that Vetiver can thrive in the nutrient-poor soils of mine dumps, but its long-term survival without ongoing fertilisation and irrigation is questionable. Dense foliage was achieved with healthy slips planted at less than 30 cm spacing, provided adequate fertilisation and irrigation were maintained. However, care should be taken to avoid shading, as Vetiver growth can be negatively impacted. Open, unshaded slopes are ideal for Vetiver plantations aimed at reclaiming mine dumps.

Soil analysis before and after Vetiver plantation indicated that the dump soil's macronutrient content (NPK) was extremely low, with Organic Carbon (OC) at only 4-5 % of typical mine soil levels. In contrast, micronutrient levels were relatively higher, with Mn ranging from 100-118 %, Cu from 51-52 %, Zn from 151-359 %, and Fe from 205-207 % compared to local soils. The soil pH was slightly acidic and slightly decreased over time, suggesting that Vetiver may contribute to stabilising soil pH. While there was a slight increase in available nitrogen during the Vetiver growth period, other nutrients such as phosphorus, potassium, zinc, and manganese showed slight decreases, likely due to leaching and uptake by the plants. The variability in Electrical Conductivity (EC), available sulfur, and copper suggests potential inconsistencies in soil sampling and the influence of external factors such as mine dust.

Importantly, the statistical analysis revealed that although nutrient levels varied among the sites, these variations were not statistically significant between the pre- and post-plantation phases. This suggests that Vetiver's effect on soil nutrient levels may be limited, particularly under the stressful conditions of overburden dump slopes, despite its survival ability in such environments. Vetiver grass exhibited site-specific variations in leaf count, with averages of 44.8±11.62 at Site A, 39.3±6.3 at Site B, and 22.5±5.07 at Site C. Moreover, Site C showed the lowest leaf count and significant coverage loss by February 2019, indicating weaker growth and establishment

In summary, while Vetiver grass demonstrates the potential for mine dump reclamation, its contribution to soil nutrient improvement remains limited. Optimal reclamation outcomes require planting during the rainy season, coupled with proper fertilisation and irrigation: approximately 59 mg/L N, 15.2 mg/L P, 36.1mg/L K in irrigating water and 5.77 g/kg Ca and 2.55 g/kg Mg as amendments could lead to longevity of Vetiver[18]. The spoil pH must be maintained at a 6-7 range for efficient nutrient uptake by Vetiver[80]. The Vetiver must be protected from invasive native grasses and the shade of trees for its success. Further research should focus on additional soil amendments and the combinations of other plant species to enhance long-term ecological restoration of mine-affected areas.

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6.0 Author Contributions

All authors contributed to the study design. Field experiments and drafting of the first manuscript were done by Gurudev Choudhary. The analysis of experimental results was performed by Om Narayan Singh. The study concept and editing of the manuscript were performed by Krishnendu Mandal. All authors have read and agreed to the published version of the manuscript.

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