# Effect of grass species root for enhanced slope protection in amended coalmine overburden dump soil

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# Abstract

## Background and Aims

Surface protection of coalmine overburden (OB) dumps against shallow slope failures can be achieved through a cost-effective and sustainable solution, i.e., vegetative cover. Hence, small scale study is needed to study the survival, growth performance, and root distribution of plants prior to conducting pilot scale study.

## Methods

In the present study, three plant species *Dendrocalamus strictus* (Bamboo grass), *Cymbopogon citratus* (Lemon grass), and *Chrysopogon zizanioides* (Vetiver grass), an endemic grass species are studied for the slope stabilization potential of OB dumps in Jharkhand, India. Growth characteristics and root architecture of grasses grown for five months under six varying proportions (treatments) of overburden, cow dung, and garden soil were studied.

## Results

It was found that Vetiver grass had the highest root area ratio, followed by Bamboo grass and Lemon grass. The maximum root cohesion was found to be 1 kPa for Bamboo grass, 7.33 kPa for Lemon grass, and 9.24 kPa for Vetiver grass among different treatments.

## Conclusions

Treatment condition with 80% overburden and 20% cow dung was suggested to be the best soil mix for optimum growth of the chosen grasses which have the potential to mitigating surficial movement of soil mass on the overburden dumps through root reinforcement.


# 1. Introduction

The open-cast coal mining activity generates a high volume of waste rock material (non-plastic) known as coalmine overburden (OB) present between the coal seams that must be continuously removed for undisrupted mining operations (Bagińska et al. 2020; Kumar et al. 2023b). The OB generation is followed by transporting it through haul vehicles and loosely dumping it at the storage site in the vicinity of the mined area. This continuous process leads to the formation of dumps extending up to 120 m in height (Fig. 1), which are prone to gully erosion, instability, and other adverse environmental impacts (Pedrol et al. 2010). In India, in the year 2021-22, approximately 700 Mt of coal production generated around 1700 million cubic meters (MCum) OB (Ministry of Coal 2021). The OB materials are highly heterogenous owing to their shape, gradation (Fig. 1 (inset)), method of extraction, and mineralogical composition

(McQuillan et al. 2018). The geometry of the OB dump is liable to be modified by erosion, which may introduce structural instability, ultimately leading to slope failure. Therefore, emphasis must be given to mitigate these negative impacts (Zhang et al. 2019). Shallow slope failures are common feature of OB dumps, often leading to disruption in mine activities, loss of lives, and monetary losses.

Mechanical slope stabilization (retaining wall, gabions, etc.) methods are associated with high cost and decreasing efficiency. The biological reclamation using vegetation (bioengineering) is a more sustainable, aesthetically appealing and cost-effective approach to cope with the problems of the OB dump (Gerhardt et al. 2009; Li et al. 2016; Robinson et al. 2015; Sheoran et al. 2016). Plants' slope stabilization function includes mechanical (root) reinforcement (present study), hydrological reinforcement, and interception (Qin et al. 2022; Wang et al. 2020). Soil reinforcement to improve the shear strength through plant roots depends on the root distribution, root density, and root strength. Flexible, fibrous, and densely distributed roots are the most effective in soil reinforcement (Bordoloi and Ng 2020). The tensile roots mobilize the shear strength due to the soil-root interface friction (Adhikari et al. 2013; Bischetti et al. 2009). Different plant types (grass, shrub, tree) have been extensively used across various soil types and terrains to prevent shallow slope failure (Dupuy et al. 2005; Genet et al. 2010). However, the use of vegetation to mitigate shallow OB dump slope failures and quantification has not been emphasized and the literature on the same is insignificant

Due to the hostile environment (nutrient deficiency) in OB material, the efficacy of slope stabilization using vegetation greatly depends on the plant type and species selection for their survival and growth. Thus, the choice of native plants that can withstand the harsh growing environment of the OB is preferred. Grasses and shrubs with shallow roots show easy and early growth compared to the trees with deep roots that require longer growing time (Leung et al. 2015). Fine grass roots penetrate the soil and form a dense network that can bind soil particles together, making the soil more resistant to erosion and landslides (Bordoloi and Ng 2020). The nutrient deficiency in the OB is generally fulfilled by using external aid such as biochar, cow dung, topsoil, and other organic wastes (Juwarkar and Singh 2007, Kuka et al. 2013; Maiti and Saxena 1998; Spargo and Doley 2016). Hence, it becomes essential to quantify the correct amount of external amendment to be used for maximum growth. Existing biological reclamation studies on coal OB mainly comprise ofplant traits being used for extraction of heavy metals, land reclamation and eco-restoration (Arshi 2017; Pandey et al. 2021; Srivastava et al. 2014). Previous studies on coalmine OB related to vegetation in the context of geotechnical applications (such as slope stabilization) have not included information on root morphology or suitable testing methods for measuring the in-situ shear strength of vegetated OB dumps (Chaulya et al. 2000; Rai and Shrivastva 2014; Singh 2000). Rai and Shrivastva (2011) explored the slope-stabilizing potential of trees using large in-situ shear test equipment. Estimating the enhanced shear strength of trees on a sloping surface using a large shear apparatus becomes challenging. Therefore, an indirect approach based on the root distribution and tensile strength is more suitable in this scenario (Wu et al. 1979). Kumar et al. (2023a) studied the growth potential of *Dendrocalamus strictus* (Bamboo grass) under different proportions of coalmine overburden and amendments. The study gave promising results in terms of growth and root reinforcement. However, the chosen grass species may not alone suffice the requirements of OB dump slope stabilization as the cohesion values obtained in the study are low. Therefore, it is useful to explore other grass species which can impart a higher root cohesion and can be used in conjunction with Bamboo grass for the reclamation of OB dumps. Emphasis can be given to choosing plant species with different root architecture. The literature highlighting the importance of root architecture in improving the soil strength is scanty in this domain. The work related to the use and survival of grass species on the coalmine OB dumps is missing. Therefore, a preliminary study is needed to ascertain the survival and growth characteristics of the plants on a small scale in the hostile OB environment prior to conducting a large scale retoration programs, as they greatly affects the efficiency and extent of the stabilization program. Some other negative environmental impact which result due to mining activities are desertification, loss of flora and fauna, siltation of the water bodies in the vicinity, and contamination of ground water are also of great worry (Goswami 2015). The added benefit of vegetation beyond slope stabilization can be utilized without much extra efforts to minimize these adverse impacts through the creation of vegetative barriers to arrest the eroded debris from being discharged into the waterbodies, dust suppression, improving the aesthetics of the area, and containing the heavy metal leaching into the water table. The versatility of vegetation using suitable plant species to tackle multiple negative environmental impacts arising due to mining gives a strong motivation to use this technique for the remediation of mined land (Kumar eta al 2023b).

This work aims at studying the growth characteristics and root traits of three native grass species (Poaceae family) to the Jharkhand, India region, namely: *Dendrocalamus strictus, Cymbopogon citratus, and Chrysopogon zizanioides* having common names as Bamboo grass (*BG*), Lemon grass (*LG*), and Vetiver grass (*VG*), respectively under different soil conditions to understand their slope stabilizing potential. Plantation pots containing six varying ratios of overburden, cow dung, and garden soil were used as the growth substrate. A comparative study of the selected grasses has been presented in terms of plant biomass/length, root density, root architecture, root tensile strength, and root cohesion under different proportions of amendments. The results were utilized to select the optimum amendment quantity while using the grasses for the OB dump stabilization in field. It was hypothesized that the selected grass species would provide surficial reinforcement to the top surface of the OB dump through their root and shoot biomass, thus mitigating shallow slope failures.

# 2. Materials and methods

### Growth substrates and plant species

Cow dung as the organic amendment (OA) and garden soil (GS) were used for amending the OB to prepare the growth substrate in this study. The OB was collected from Bharat Coking Coal Limited (BCCL) Colliery, Jharkhand, India, having latitude and longitude of 23°48'12.5"N and 86°19'32.0"E, respectively. Tropical dry and wet climate prevails in the region, with peak temperatures reaching up to 48$^{o}$ C during the summer months and an average annual rainfall of approximately 1241 mm in the monsoon months. The locally available dry cow dung manure was used as a supplement for the nutrient deficit OB, while the garden soil was collected from the nursery in IIT (ISM) Dhanbad. The physico-chemical properties of the growth substrates and textural distribution of all the three materials used in this study are shown in Table 1.

The saplings of BG were obtained from BCCL, while tillers of lemon grass and vetiver grass were obtained from Shristi Solutions, Prayagraj, India. The propagation of LG and VG plants in the form of tillers is fast and convenient. These plant species were chosen based on their utility in eco-restoration and their tolerance against the harsh existing environment of OB (Singh 2000). Figure 2 (inset) shows the initial state of the Bamboo grass sapling and Lemon and Vetiver grass tillers that were later placed in the plantation pots.

Table 1
Physico-chemical and textural characteristics of coalmine overburden (OB), organic amendment (OA), and garden soil (GS)

| Property | Material | | |
|---|---|---|---|
| | Overburden (OB) | Organic Amendment (OA) | Garden Soil (GS) |
| Physico-chemical Properties: | | | |
| pH | 7.60 | 6.60 | 7.10 |
| Organic Carbon (%) | 1.15 | 5.80 | 2.14 |
| Electrical Conductivity (dS/m) | 0.08 | 0.92 | 0.15 |
| Total Nitrogen (%) | 0.003 | 1.210 | 0.120 |
| Available Potassium (ppm) | 52.44 | 8.20 | 72.48 |
| Available Phosphorus (ppm) | 3.49 | 482.38 | 8.95 |
| Texture Distribution: | | | |
| Silt and clay (%) | 19.13 | - | 77.27 |
| Sand (%) | 43.07 | - | 22.73 |
| Gravel (%) | 37.80 | - | 0.00 |

The dimensions of each polyethelene pot used in this study are as follows: depth = 0.30 m, bottom diameter = 0.14 m, and top diameter = 0.25 m with a weight of 0.346 kg.

## Materials preparation

Material preprocessing was done for OB and OA. Larger fractions of the OB were removed by sieving it through 31.5 mm Indian Standard sieve, thus limiting the largest fraction to one-tenth of the largest dimension of the pot due to space restriction. The lumps of OA were crushed until no lumps were seen. No preprocessing was given to GS. Six varying proportions of OB, OA, and GS were prepared and designated as treatments T1-T6, as shown in Table 2. Treatment T1 comprised only OB, while T6 consisted of only GS. Treatments T2, T3, T4, and T5 consist of 20%, 16.67%, 33.33%, and 28.57% OA and 0%, 16.67%, 0%, and 14.28% GS, respectively. Each of the three plant species was planted under each treatment condition in triplicates. Therefore, the average values are presented. Material mixing was carried out through hand-held equipment (shovels) until a homogeneous mix was obtained. The nomenclature T1BG stands for the bamboo grass grown under T1. Similar notations are used for other plants throughout the paper. The soil mixes were exposed to the ambient environment for acclimation for 10 days. The experiment spanned 150 days, from July to November. The start of the experiment was marked by planting the grasses in the pots at the on-set of the monsoon season. Water requirement was met mostly through precipitation, while manual watering was done intermittently on non-precipitation days. The saplings and the tillers were placed in the pot soil and watered on the tenth day, recorded as the experiment's start date. No additional OA or GS was supplied to any plant till the experiment was terminated.

## Plant monitoring and its physical characteristics

Table 2
Growth substrates mix ratio by weight (kg)

| Treatments | Overburden (OB) | Organic Amendment (OA) | Garden Soil (GS) |
|---|---|---|---|
| T1 | 1 | 0.00 | 0.00 |
| T2 | 1 | 0.25 | 0.00 |
| T3 | 1 | 0.25 | 0.25 |
| T4 | 1 | 0.50 | 0.00 |
| T5 | 1 | 0.50 | 0.25 |
| T6 | 0 | 0.00 | 1.00 |

The shoot height (cm) of all the plants was recorded weekly. At the end of the experiment, the plant roots were carefully washed and examined for the total root depth (cm), root density (*RD*, kg/m$^3$), and root volume (*RV*, cc) to understand the effect of the amendment. Tensiometer was used to record the root suction of each plant continuously, where the tensiometer reading was directly related to the root suction values. Zero value implies no suction which increased with time due to evapotranspiration. The washed roots were suspended freely in the air and root depth was measured. The root density is defined as:

$$\mathrm{RD} = \frac{M_d}{V}$$

1

Where $M_d$ = dry root mass, and $V$ = volume of the soil sample ($m^3$).

## Root distribution and root area ratio

The entrapped soil in the roots was washed off with the water jet, and the roots were examined for root distribution. The roots were placed on white board with 2 cm x 2 cm square grids to better understand the roots' lateral and vertical extent (Fig. 3). Root diameter was measured at every 2 cm depth using a digital vernier calliper having the least count of 0.01 mm. The measurements were recorded and placed under different root diameter classes. The roots having a diameter greater than 0.1 mm were accounted for during the computation of the root area ratio (*RAR*), which is defined as the root area ($A_r$, $m^2$) divided by the cross-sectional area of soil ($A$, $m^2$) at any depth and is expressed as follows (Leung et al. 2015):

$$RAR = \frac{A_r}{A} = \frac{\sum_i^n A_i}{A}$$

2

Where $n$ = total number of roots at any depth and $A_i$ is the area of the $i^{th}$ root. The root hairs were not considered due to the difficulty in their precise diameter measurement, which eventually kept the calculation on the safer side during the estimation of root cohesion.

## Root tensile strength

The root morphology of all three plant species revealed that *BG* has mostly rigid roots, while *LG* and *VG* consist of only flexible roots. The roots having $d > 1.5$ mm in the Bamboo grass were not tested for their tensile strength as they slipped off from the grips before rupture (Saifuddin et al. 2015; Stokes et al. 2009). Therefore, for each plant species, the root diameter ($d$) considered in the root reinforcement model ranged between 0.05–1.5 mm. The roots were tested on the same day of root washing to prevent decay. It is noteworthy that this study did not consider the variation of $T_r$ due to the root moisture change. A servo motor-based universal testing machine (UTM) attached with a 0.5 kN “S-type” load cell (least count: 0.0001 kN) was used for determining the root tensile strength. Sandpaper and rubber membrane was used while gripping the root to prevent slippage and stress concentration, respectively (Leung et al. 2015). A sudden drop in the load was recorded at the root rupture, marking the end of the testing. Figure 4 shows the UTM assembly used in this study. A constant strain rate of 10 mm/min was given until the root rupture. The root's load response (kN) was measured against the elongation through the data acquisition system (DAS). The root tensile strength ($T_r$, MPa) was defined as the ratio of peak tensile force ($F_p$, kN) to the root cross-sectional area ($A_{rr}$, $m^2$) at the location of rupture (Mattia et al. 2005):

$$T_r = \frac{F_p}{A_{rr}} = \frac{4F_p}{\pi d^2}$$

3

Where $d$ (mm) is the root diameter at the rupture point.

The roots that snapped near the grips were discarded, and the test was repeated. Root testing aimed to establish a statistical relationship between $T_r$ and $d$ through the power equation (Gray and Sotir 1996):

$$T_r = ad^{-b}$$

4

Where $a$ is a scale factor and $b$ is the rate of strength decay which are the species-specific empirical constants. The same tensile testing methodology was adopted for all the plants to eliminate the variation in $T_r$ (Bischetti et al. 2005).

### Root cohesion

The high tensile strength roots (compared to soil) permeate the soil and form a dense root-soil matrix, adding strength to the soil (Liu et al. 2020; Ni et al. 2019; Waldron 1977) that mobilizes the shear force in the soil due to the soil-root interface friction. Hence, there is an increase in shear strength compared to the non-vegetated soil, known as root cohesion ($c_r$) (Abe and Ziemer 1991; Mattia et al. 2005; Operstein and Frydman 2000; Stokes et al. 2008; Yang et al. 2016). Wu et al. (1979) proposed a root reinforcement model for quantifying the $c_r$, which has been widely used ever since then under different soil conditions and terrains (Adhikari et al. 2013; De Baets et al. 2008; Mattia et al. 2005; Waldron and Dakessian 1981). However, this approach has not been employed for estimating the $c_r$ on the coal OB dumps, where conducting large in-situ tests in the existing conditions is challenging. The assumptions in this model include the perpendicularly oriented, fully flexible root fibers to the plane of shear with constant thickness, simultaneous mobilization of root tensile strength with small strain, and unaltered soil friction angle due to the introduction of roots (Leung et al. 2015). The shear strength of the root-reinforced soil ($s_r$, kPa) as per Mohr-Coulomb can be expressed as follows:

$$s_r = s + c_r$$

5

Where $s$ (kPa) is the shear strength of bare soil, and $c_r$ (kPa) is the extra shear strength due to the roots (root cohesion).

A major assumption in Wu approach is that all roots attain their ultimate tensile strength at the same time during shearing, which has been shown in multiple experiments to be unrealistic since it overestimates the improved shear strength (Docker and Hubble 2009, Fan and Su 2008). If the negative exponent ($b$) of the $T_r$ vs. $d$ curve is higher, the overestimation is less (Adhikari et al. 2013; Pollen and Simon 2005). The $b$ values obtained in the present study are almost two times that obtained in other studies (Bischetti et al. 2005; Burylo et al. 2011; Hudek et al. 2010). Also, in the present study, the $d$ range is narrow (0.05-1.5mm); therefore Wu approach is preferred over the fiber bundle model. The shear strength due to the total mobilization of root tensile strength is expressed as:

$$c_r = t_r(sin\theta + cos\theta tan\varphi)$$

6

Where $t_r$ = full mobilized root tensile stress per unit area of soil (kPa), $\theta$ = angle of shear distortion in the shear zone (°), and $\phi$ = soil friction angle (°). The value of sin $\theta$ + cos $\theta$ tan $\phi$ has been found to be insensitive to the normal ranges of $\theta$ and $\phi$. It generally lies in the range of 1.03–1.3. An average value of 1.2 was used in this study. It was assumed that roots are firmly held in position and follow the breakage mechanism during the shear force application. The $t_r$ can be expressed as the product of the root tensile strength and root area ratio.

$$t_r = T_r.RAR$$

7

Therefore, Eq. (6) can be written as:

$$c_r = 1.2RAR.T_r$$

8

To consider the variability of roots with varying diameters, Eq. (8) can be written as:

$$c_r = 1.2\sum_{i=1}^{n} T_{ri}\left(\frac{A_{ri}}{A}\right)$$

9

Where $A_{ri}$ and $T_{ri}$ are the root area and tensile strength of the $i^{th}$ root out of $n$ roots. The variation of $c_r$ with depth for each plant can be calculated using Eq. (9).

### Statistical analysis

The data were analyzed using *IBM SPSS Statistics V26*. Levene's test for homogeneity of variance, homogeneity of regression slopes criteria, and observation independence was checked before performing the Analysis of Covariance (ANCOVA) analysis. A significance level ($\alpha$) of 0.01 was adopted to study the effect of the treatment condition on *RAR*, $T_r$, and $c_r$ with their respective covariates. The linear regressions of log (*RAR*) and log ($c_r$) against log (depth) and log ($T_r$) against log ($d$) were used in ANCOVA. The empirical constants ($a$, $b$) for each plant were obtained through a power law curve-fitting on the tensile testing data ($T_r$ and $d$). The adjusted $R^2$ values were referred to for the goodness of fit.

## 3. Results

### Effect of the amendment on growth characteristics

Indigenous species are prioritized over exotic species when choosing plants for reclamation purposes due to their greater likelihood of integrating and adapting to the local environment. Out of 18 plants (six plants of each species), only the Vetiver plant under T5 treatment died. Hence, six plants in BG and LG and five plants in VG were studied. The growth performance of the grasses was assessed in terms of shoot and root length (Fig. 5). The highest shoot height in each grass species was exhibited by T1BG (138.3 cm), T4LG (117.02 cm), and T2VG (102.80 cm). The root depth data revealed that the maximum root depth was observed in T2VG (88.46 cm), followed by T2BG (54.47 cm) and T4VG (50.93 cm) among all six plants in each species.

The fresh and dry root/shoot biomass was recorded for 17 plants, and an intra plant species comparison has been made. Figure 6(a) shows the fresh and dry shoot biomass, while Fig. 6(b) shows the fresh and dry root biomass of BG, LG, and VG under six different treatment conditions. The fresh and dry shoot biomass of Lemon grass was the highest, followed by Bamboo grass under each treatment except for T1, where Bamboo grass shoot biomass was higher. Vetiver grass possessed the minimum root and shoot biomass under each treatment. Among all the plants, T5LG had the highest fresh (1044.00 gm), and dry (240.00 gm) shoot biomass and fresh (532.00 gm) and dry (131.80 gm) root biomass. Intra species root density (*RD*) comparison among all the plant types (Fig. 7 (a)) showed that the Bamboo grass yielded the maximum *RD* under treatment condition T2 (14.14 kg $m^{-3}$), while the highest *RD* for Lemon grass was achieved under T5 (16.68 kg $m^{-3}$) among all five plants (excluding the control, T5). The Vetiver grass had the least *RD* and *RV* under each treatment condition. Overall, the minimum *RD* and *RV* for each species were obtained under treatment condition T1. Maximum *RV* was seen in Bamboo grass under each treatment compared to the other two plant species (Fig. 7(b)). The variation of root suction versus time for each plant of BG, LG, and VG shown in Fig. 8 indicates that the Lemon grass plants took the least time to achieve the highest root suction, followed by Bamboo grass (intra species), whereas Vetiver plants took the maximum time. Evaporation was assumed to be same for each plant.

## Root tensile strength

The load versus elongation response was recorded by the DAS for each root to determine the peak load sustained before rupture. The root diameter at rupture was used to calculate the tensile strength $T_r$ (MPa) as per Eq. 3. The statistical summary of the tensile test showing the number of roots tested (*N*), *d* range, $T_r$, *a*, and *b* are presented in Table 3. $T_r$ and *d* data for each plant was plotted, and curve fitting using the power decay law (Eq. 4) was done to determine the empirical constants for each plant. Figure 9 (a), (b), and (c) shows the variation of $T_r$ and *d* for each plant under BG, LG, and VG, respectively. A similar trend between the tensile strength and root diameter has been reported in previous studies for other plant species (Genet et al. 2010; Mattia et al. 2005). The tested diameter range for Bamboo grass roots was 0.12–0.96 mm, Lemon grass was 0.05–0.56 mm, and Vetiver grass was 0.08–1.08 mm. Thin roots ($d <$ 1.5 mm) were found to have higher $T_r$ than thick roots. The highest average "*a*" value was observed for Lemon grass plants (42.60) followed by Bamboo grass plants (25.41). Vetiver grass plants showed the least average a value (20.88) and the highest average "*b*" value (-1.64).

Table 3
Regression summary of (curve fitting) $T_r$ vs $d$ by power law ($y = ax^{-b}$) for all three plant species ($p < 0.001$)

| Treatment | Species | *N* | *d* range (mm) | Mean $T_r$ (MPa) | *a* | *b* | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|
| **T1** | BG | 22 | 0.16–0.95 | 83.03 | 24.53 | -1.34 | 0.96 |
| | LG | 26 | 0.12–0.30 | 265.75 | 57.65 | -0.98 | 0.53 |
| | VG | 20 | 0.08–1.35 | 184.57 | 15.77 | -1.65 | 0.85 |
| **T2** | BG | 25 | 0.15–0.96 | 113.67 | 23.35 | -1.44 | 0.87 |
| | LG | 36 | 0.09–0.43 | 333.89 | 32.13 | -1.43 | 0.88 |
| | VG | 15 | 0.10–0.90 | 191.59 | 8.48 | -2.07 | 0.97 |
| **T3** | BG | 30 | 0.20–0.93 | 78.83 | 29.67 | -1.11 | 0.67 |
| | LG | 33 | 0.10–0.56 | 204.87 | 54.08 | -1.00 | 0.74 |
| | VG | 15 | 0.11–1.08 | 146.92 | 27.28 | -1.40 | 0.91 |
| **T4** | BG | 30 | 0.12–0.93 | 70.73 | 23.88 | -1.34 | 0.91 |
| | LG | 35 | 0.14–0.56 | 152.44 | 15.64 | -1.75 | 0.65 |
| | VG | 15 | 0.13–0.85 | 138.01 | 34.74 | -1.40 | 0.86 |
| **T5** | BG | 24 | 0.15–0.92 | 59.88 | 27.19 | -1.23 | 0.96 |
| | LG | 35 | 0.05–0.48 | 275.92 | 51.59 | -0.98 | 0.85 |
| | VG | - | - | - | - | - | - |
| **T6** | BG | 22 | 0.15–0.90 | 110.1 | 23.89 | -1.46 | 0.93 |
| | LG | 12 | 0.06–0.38 | 213.99 | 44.48 | -1.01 | 0.98 |
| | VG | 15 | 0.22–0.95 | 89.87 | 18.14 | -1.65 | 0.89 |

The root tensile strength comparison showed that the highest mean $T_r$ for Lemon grass was 333.89 MPa (T2LG), for Bamboo grass, it was 113.67 MPa (T2BG), and for Vetiver grass, it was 191.59 MPa (T2VG). The mean $T_r$ under T1 treatment for BG, LG, and VG plants was 83.3 MPa, 265.75 MPa, and 184.57 MPa, respectively. The T2 treatment condition was found to be the most effective in producing high tensile strength roots under each plant species despite using the least amendment quantity as compared to other treatment conditions having a higher percentage of OA or GS or both. The ANCOVA analysis for $T_r$ against $d$ as its covariate was performed. The result for Bamboo grass was insignificant ($F_{5,146} = 0.90$, $p = 0.99$). The ANCOVA for Lemon grass was not performed, as the assumption was not satisfied. The result obtained for Vetiver grass was significant ($F_{4,74} = 4.30$, $p < 0.01$).

## Root distribution and root area ratio (RAR)

The soil shear strength depends on the root architecture (Yen 1987). Figure 3 shows the closeup view of roots from each species. The root distribution of all the plants was carefully recorded against the depth. Maximum root concentrations were found at 14–18 cm depth in Bamboo grass, 2–10 cm depth in Lemon grass, and 4–8 cm depth in Vetiver grass. Based on different root diameter classes, the dominant *d* range for *BG*, *LG*, and *VG* were 0.1-1.0 mm, 0.1–0.5 mm, and 0.1–0.75 mm, respectively. Figure 10 (a, b, and c) show the variation of *RAR* with depth for each grass species.

Highest *RAR* was observed for the Vetiver grass (T2VG: 4.57%) at 2 cm depth due to the concentration of roots in a narrow region (V-type root), followed by Bamboo grass (R-type root) and Lemon grass (M- type root). The *LG* and *VG* plants grown under treatment T1 having only OB showed the least *RAR* compared to the RAR of the same plant species under other treatments. In contrast, the intra species comparison showed that T1BG exhibited the highest *RAR.* Root area ratio beyond the depth of maximum root concentration decreases with the increase in depth (De Baets et al. 2008). The *RAR* influence became negligible beyond 22 cm depth for *BG*, 10 cm depth for *LG*, and 25 cm depth for *VG* plants.

ANCOVA analysis on the root area ratio was performed against the depth (*z*, cm) as its covariate. The assumptions of independence of observations, homogeneity of variance, and homogeneity of regression slopes were tested and found satisfactory at $\alpha$ equal to 0.01. The result for Bamboo grass shows that *RAR* among all six plants was insignificant ($F_{5,83}$ = 0.87, $p = 0.50$). For Lemon grass, the analysis ($F_{5,83}$ = 16.96, $p < 0.01$) gave a significant result. Lastly, the ANCOVA result for Vetiver grass was insignificant ($F_{4,67 = 0.56}$, $p = 0.691$).

## Root cohesion

In the present study, root cohesion is computed indirectly using the root tensile strength and root area ratio (Eq. 9). This approach has been widely used for varieties of plant species (grass, shrub, and tree) under different terrains and soil conditions (Comino et al. 2010; De Baets et al. 2008; Docker and Hubble 2008; Hudek et al. 2010; Leung et al. 2015; Mahannopkul and Jotisankasa 2019). For Bamboo grass plants, only the flexible roots were considered for $c_r$ estimation (Kumar et al. 2023a). However, all roots of Lemon grass and Vetiver grass were used. Figure 10 (a’, b’, and c’) shows the variation of cr with depth for BG, LG, and VG, respectively. It was found that the minimum root cohesion was present in the plant grown in the substrate having only OB (T1: 0% OA and/or GS) for all three species as compared to other treatment conditions. The maximum $c_r$ (1 kPa) for Bamboo grass plants was observed in T5BG at 16 cm depth. For Lemon grass plants, the highest $c_r$ (7.33 kPa) was concentrated at 3 cm depth in T3LG. T2LG had the maximum $c_r$ of 6.10 kPa at 3 cm depth. The maximum $c_r$ (9.24 kPa) for Vetiver grass was found in T2VG at 6 cm depth with *RAR* equal to 2.25%.

The ANCOVA analysis was performed for the effect of treatment on the cr against depth (*z*, cm) as its covariate. The result for Bamboo grass showed that there was a significant effect ($F_{5,83}$ = 3.01, $p = 0.01$)

of treatment on the $c_r$ with depth as the covariate. For Lemon grass, the analysis ($F_{5,83}$ = 15.03, $p$ < 0.01) showed that the treatment significantly affected the root cohesion. The ANCOVA result for Vetiver grass showed no significant effect ($F_{4,67}$ = 2.78, $p$ = 0.03) of treatment on the $c_r$.

# 4. Discussion

### Growth characteristics

From the data available in Fig. 5, it can be observed that the root depth under similar growing conditions is highest in Bamboo and Vetiver grass and second highest in Lemon grass under treatment condition T2 which has the least quantity of amendment, i.e., OA (20%) and GS (0%) as compared to T3, T4, and T5. This shows that the excessive use of organic amendments in plants can have disadvantages such as nutrient imbalance which may lead to slow plant growth. Thus, it is important to optimize the amendment application rates to ensure healthy plant growth. T2 treatment condition yields a maximum root growth which also takes care of the cost and availability aspects of the organic amendment and garden soil. The shoot height of all the three grasses under T2 substrate are comparable or better than T1 (except T1BG), T3, T4, and T5. Considering the scale (field) and growth duration (2 years) of the study conducted by Singh (2000) on Mudidih OB dump (same dump site in the present study), the shoot height values reported for Lemon (80 cm), Vetiver (75 cm), and Bamboo (250 cm) are lower for Vetiver and Lemon grass while higher for Bamboo grass when compared with the present study. Better growth observed in the present study in lesser growth duration (150 days) is due to the use of organic amendment which was missing in the above-mentioned study. Hence, treatment T2 can be used as the most suitable amendment proportion to attain maximum growth of the chosen plant species under field conditions.

The minimum root and shoot biomasses for all the species were observed under treatment condition T1. This may be attributed to the retarded growth as an implication of nutrient deficiency. Based on the overall shoot and root biomass data (Fig. 6), it was observed that the best growth among all the three grass species was achieved under the growth substrate T5 which was due to the highest percentage of OA (28.57%) and GS (14.28%) compared to other treatment conditions. Based on the results of root biomass, root density, and root volume, it can be stated that the Bamboo grass plant species is superior among all the three plant species which is due to its genetic characteristics i.e., tall, woody stems exhibiting rapid growth. The limited growing space in the pot may have stunted the growth of BG plants. The other two species (LG, VG) are leafy plants with a maximum height of 60–150 cm under natural conditions which is been believed to have been achieved in this controlled study. The rate of achieving a higher state of root suction was highest in LG plants mainly due to the higher fresh shoot biomass (leaves) that help in transpiration and a greater number of fine roots ($d$ < 1.5 mm) that aid in faster water absorption (Fig. 8). The root suction in BG was lower than LG due to its lesser fresh shoot biomass. Higher $RD$ and $RV$ in BG were mostly due to rigid and thick ($d$ > 1.5 mm) roots which do not foster water absorption as readily as the finer roots. Vetiver grass showed minimum root suction due to the minimum root and shoot growth among all the three grass species.

### Root tensile strength

The root diameter range was small and hence the number of roots tested for each plant was less (due to similar $T_r$) than in other studies (Adhikari et al. 2013; Leung et al. 2015). The mean $T_r$ was highest for LG plant compared to the other two plant species under each treatment condition due to its finer roots (Table 3). The same was confirmed by $T_r$ vs. $d$ relationship (Fig. 9) which followed the power law as discussed in other studies (Bischetti et al. 2005; De Baets et al. 2008; Mattia et al. 2005). The shape of the curves highlights the significant role of finer roots that exhibit higher strength per unit area. This aspect has not been explored in the previous studies for the plants cultivated on coal mine OB. A higher cellulose content causes the finer roots to possess higher $T_r$ (Genet et al. 2005). It can be observed from Table 3 that the tensile strength of all the three plant species is maximum under treatment condition T2. This implies that over-application of amendments may also retard the root mechanical response. ANCOVA analysis output for VG plants was significant which signifies that there is an effect of treatment on the root tensile strength when the diameter is considered a covariate. However, the ANCOVA analysis output for BG plants was insignificant meaning there is no effect of treatment on the root tensile strength. the species displaying a high scale factor (*a*) and a low decay rate (*b*) are deemed the most resilient against tension (Bischetti et al. 2005; De Baets et al. 2008). However, it is crucial to emphasize that the interpretation of “*a*” and “*b*” values should be considered together.

### Root area ratio

Different plant species exhibit distinct root morphology. Grasses have fibrous root architecture whereas, trees generally possess a taproot system with a dominant main root. Roots in unfavorable soil conditions tend to exhibit elongated structures with reduced branching, while roots in healthy soil have the ability to develop and branch more effectively. T1BG exhibited the least number of flexible roots and the greatest number of thicker rigid roots, which could have been due to the plant’s inability to develop new roots (poor root development) due to nutrient scarcity. *RAR* of up to 2% has been reported in previous studies for grasses and shrubs (De Baets et al. 2008; Leung et al. 2015). However, in the present study, a *RAR* as high as 4.5% is achieved (for T2VG) due to the near vertical propagation of the roots (VG roots) and lateral root spread limited to the wall of the pot (for BG and LG). The statistical analysis reveals that there is no treatment effect on the *RAR* of BG and VG, while there is an effect of treatment on the *RAR* of LG plants. It may be due to the restriction in growth opportunities for BG and VG as they have a deeper root influence in field conditions compared to LG.

### Root cohesion

The BG and LG plant root have vertical as well as lateral spread of the roots, whereas the VG plant root show only vertical spread. It may be noted that for the BG plants, only the root having $d < 1.5$ mm were used in $c_r$ calculation, while the complete root diameter range was utilized for LG and VG plants. The minimum root cohesion values obtained for all the three plant species under treatment condition T1 without any amendment was anticipated considering the challenging growing condition of the overburden. It may be due to the least root growth and lesser finer roots due to nutrient scarcity. The highest cr value in for each plant species (intra) was found at a depth where a better distribution of finer roots was observed. For BG, LG, and VG roots, it was present at 16 cm (RAR: 1.8%), 3 cm (RAR: 0.4%), and 6 cm (RAR: 2.25%), respectively. For T3LG, the significant contribution to the $c_r$ was from the roots in the diameter range $0.25 < d \leq 0.50$ mm. For T2VG, the root diameter contributing to the root cohesion ranged between $0.50 < d \leq 1.00$ mm. The influence of root reinforcement became negligible beyond 25 cm depth for all plants. A comparatively higher root cohesion was obtained for Lemon grass and Vetiver grass plants than for Bamboo grass (Kumar et al. 2023a) plants due to a higher number of high-tensile flexible roots. The statistical analysis showed that there was an effect of treatment condition on root cohesion for BG and LG plant roots when the depth was considered as a covariate, whereas for VG plant roots, it had no effect.

# 5. Conclusions

The mechanical reinforcement provided by the plant roots can hold the topsoil and palliate shallow slope failures. Three grass species namely *Dendrocalamus strictus* (Bamboo grass: *BG*), *Cymbopogon citratus* (Lemon grass: *LG*), and *Chrysopogon zizanioides* (Vetiver grass: *VG*) were chosen to study their growth characteristics and root trait for providing early surface protection at different locations on the OB dump. The aim of the study was to optimize the amendment quantity to obtain high root and shoot biomass yield. The root morphology and extensive tensile testing were used to estimate the root cohesion i.e., the extra strength (shear) imparted by the roots to the soil. The following conclusions were drawn from this study:

- The least growth of each plant was observed under the treatment condition having only overburden (T1). This clearly shows the need for external amendment to boost the growth.
- The highest shoot biomass for both *BG* and *LG* was obtained for the treatment condition with 28.57% OA and 14.28% GS (T5). Maximum shoot yield for *VG* was found under treatment condition having 33% OA and 0% GS (T4).
- It was observed that the growth substrate having 80% OB and 20% OA (T2) was found to produce comparable growth while eliminating the use of GS which is scarce and adds extra cost.
- Root suction was dependent on the plant biomass. Hence, the highest root suction was observed in *LG* plants followed by *BG* plants and the least in *VG* plants.
- Highest *RAR* among the three species was seen in *VG* plants owing to their thin flexible roots and least lateral extent. The *RAR* for *BG* plants was mostly due to the hard, rigid roots. The least *RAR* was exhibited by the *LG* plants. The depth of maximum *RAR* for *BG*, *LG*, and *VG* was 2–10 cm, 2–5 cm, and 2–15 cm, respectively.
- The root diameter was inversely proportional to the tensile strength and the relationship follows power law decay. Lemon grass roots under each treatment showed the highest mean $T_r$ followed by the Vetiver grass plants due to the fine, flexible roots. The maximum mean $T_r$ for each species was

obtained under the T2 treatment condition (80% OB and 20% OA). The strength decay coefficient *b* was highest in Vetiver grass (-1.64) and the least in Lemon grass (-1.19).

- Inter and intra plant species comparison for the root cohesion revealed that minimum reinforcement was provided by the plants grown under treatment without amendment (T1) due to the retarded growth (fewer roots). The variation of $c_r$ with depth showed that the maximum increase in strength was observed mostly in the top 10 cm depth due to a higher the presence of greater number of high tensile roots. The maximum $c_r$ (kPa) for each plant species in the descending order based on the root architecture are as follows: V-type (9.24 kPa, Vetiver grass), M-type (7.33 kPa, Lemon grass), and R-type (1 kPa, Bamboo grass).

In this study, a comparative study utilizing three grass species was undertaken under a controlled environment to assess the survival with minimum external aid, growth potential, and the extent of root reinforcement based on their root morphology and tensile response (indirect approach). Based on the root architecture of the plants, their location on the slope can be decided to maximize the extent of stabilization. The *LG* and *VG* plant species used in this study overperformed the *BG* plant species in terms of root cohesion used by (Kumar et al. 2023a). The accuracy of this method for the chosen plants yet needs to be established using a shear test on plants grown under similar conditions to decide a reduction factor for a better approximation of $c_r$. Further, this study can be useful in the implementation of slope stabilization programs on a pilot scale under field density conditions which is the limitation of this study. Complementing field studies investigating the spatial arrangement of these grasses in conjunction with shrubs and trees can be performed with respect to the barren dumps to study its efficacy against shallow landslides. Simoultaneously, an effort can be made to quantify the addition benefits of vegetative cover used for slope stabilization on other environmental problems arising due to coal mining.

# Abbreviations

| |
|---|
| OB: Overburden |
| BG: Bamboo grass |
| LG: Lemon grass |
| VG: Vetiver grass |
| OA: Organic amendment |
| GS: Gasrden soil |
| BCCL: Bharat Coking Coal Limited |
| RD: Root density |
| RV: Root volume |
| $M_d$: Dry root mass |
| V: Volume of soil sample |
| RAR: Root area ratio |
| $A_r$: Root area |
| A: Cross-sectional area of soil at any depth |
| n: Total number of roots at any depth |
| $A_i$: Area of $i^{th}$ root |
| d: Root diameter |
| $T_r$: Root tensile strength |
| UTM: Universal testing machine |
| $F_p$: Peak tensile force |
| $A_{rr}$: Root cross-sectional area at rupture |
| a: Scale factor |
| b: Rate of strength decay |
| $c_r$: Root cohesion |
| $s_r$: Shear strength of root-reinforced soil |
| s: Shear strength of bare soil |
| $t_r$: Full mobilized root tensile strength unit area of soil |
| θ: Angle of shear distortion in the shear zone |

| |
|---|
| ϕ = Soil friction angle |
| ANCOVA: Analysis of Covariance |
| α: Significance level |
| R: Statistical measure |
| N: Number of roots tested in tensile test |

# Declarations

### Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.

### Data availability

This article has all the data that were created or evaluated during this investigation.

### Acknowledgements

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# Figures

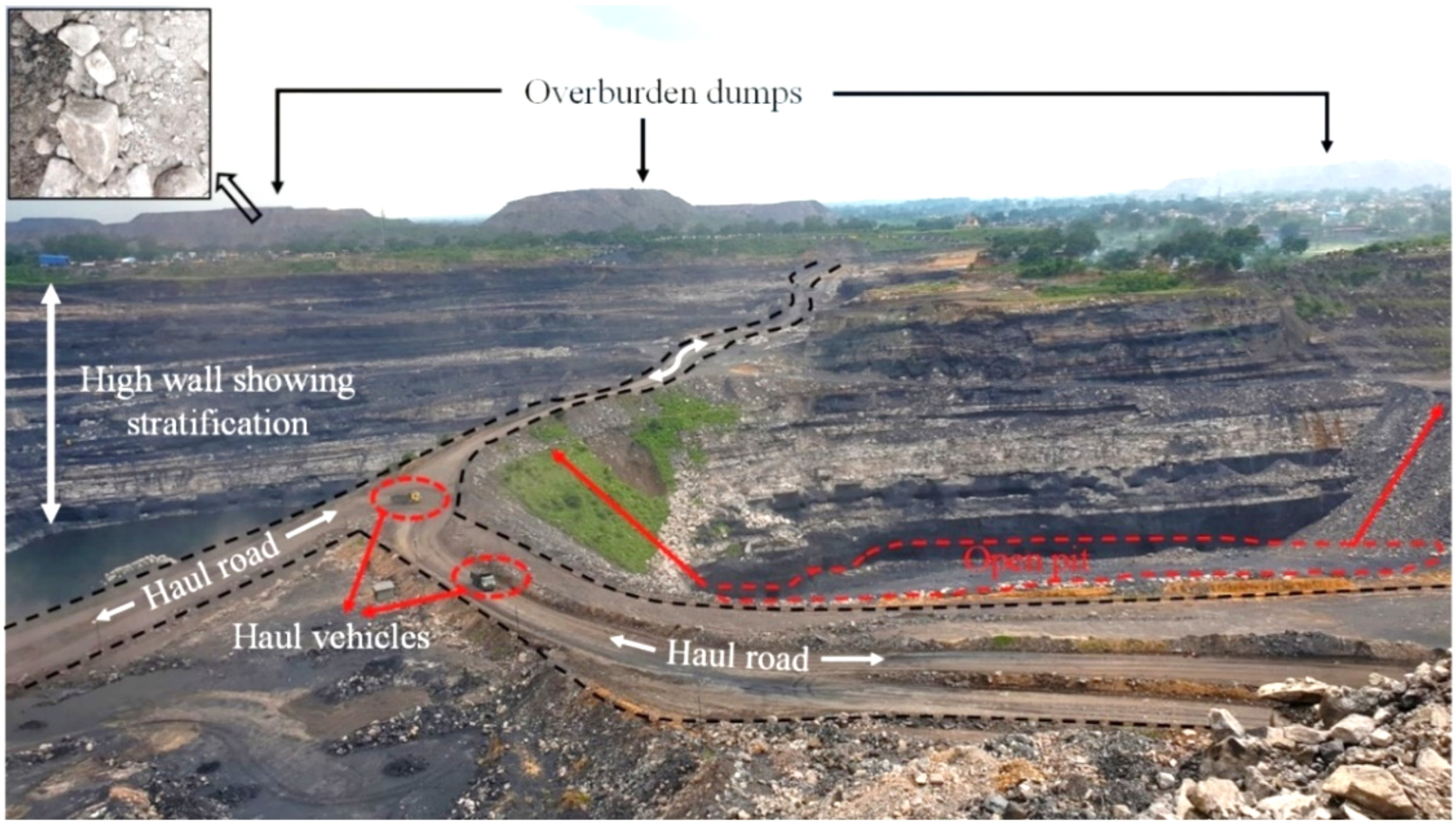



**Figure 1**

Typical view of an open cast coal mine showing open pit, stratification, and OB dumps present in Jharkhand, India

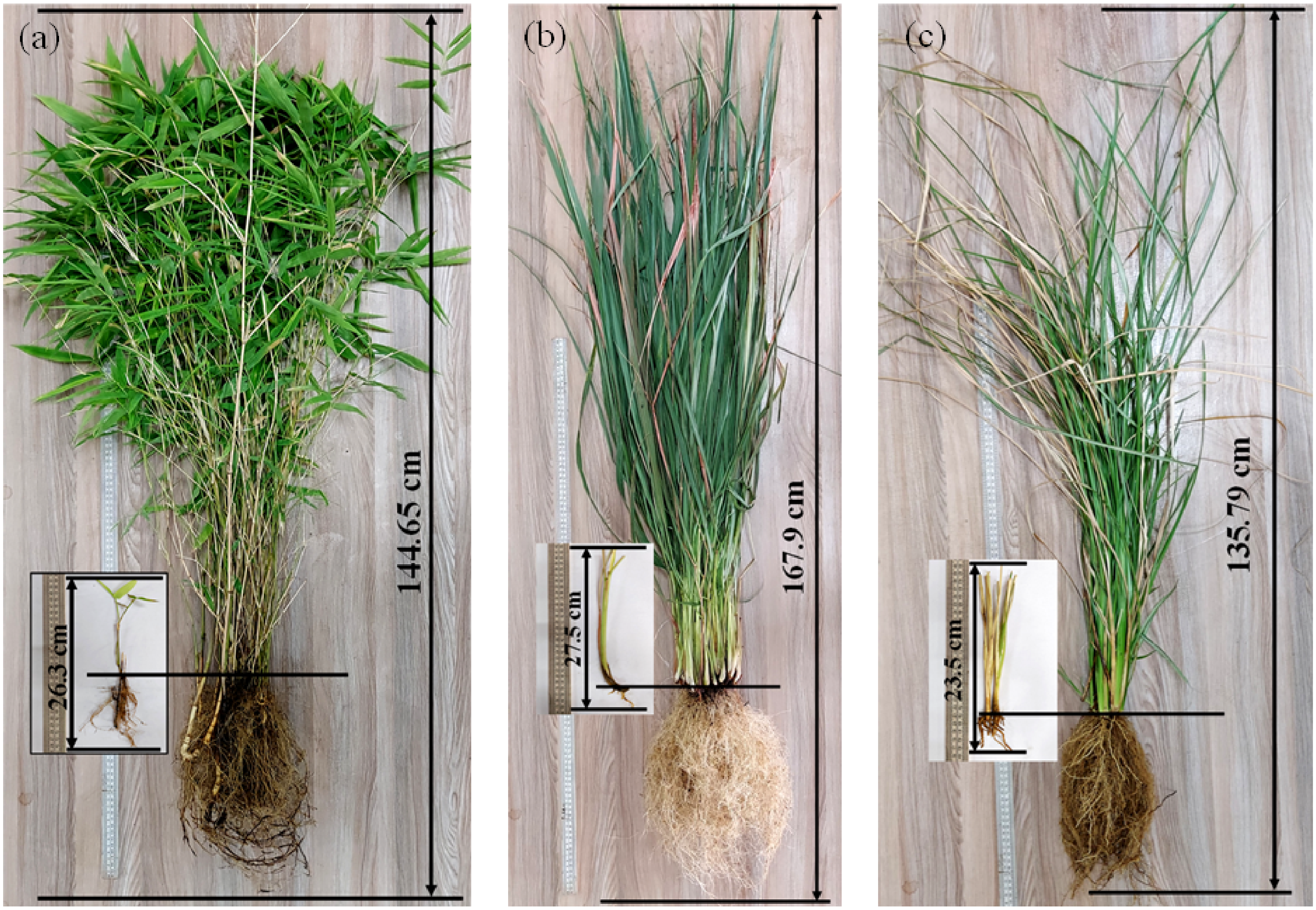
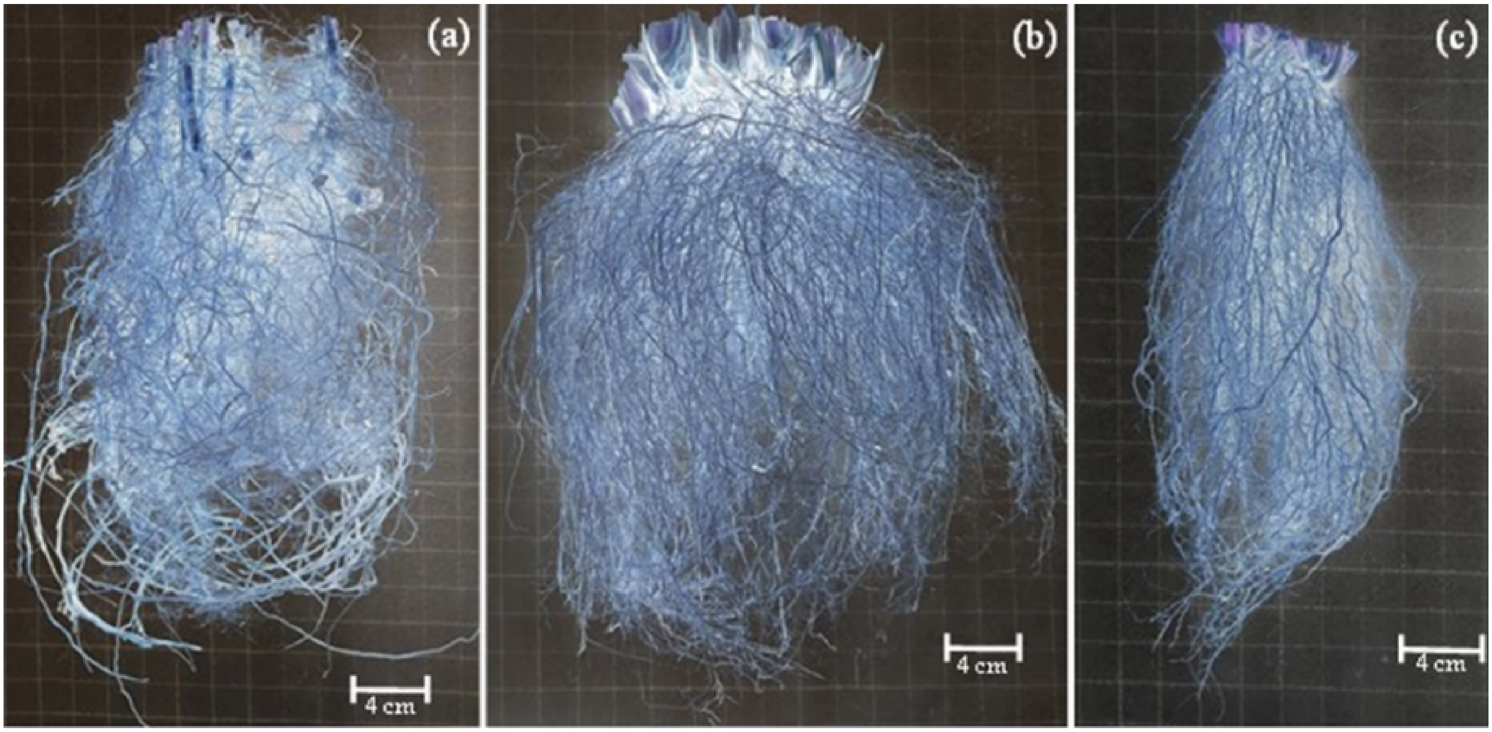


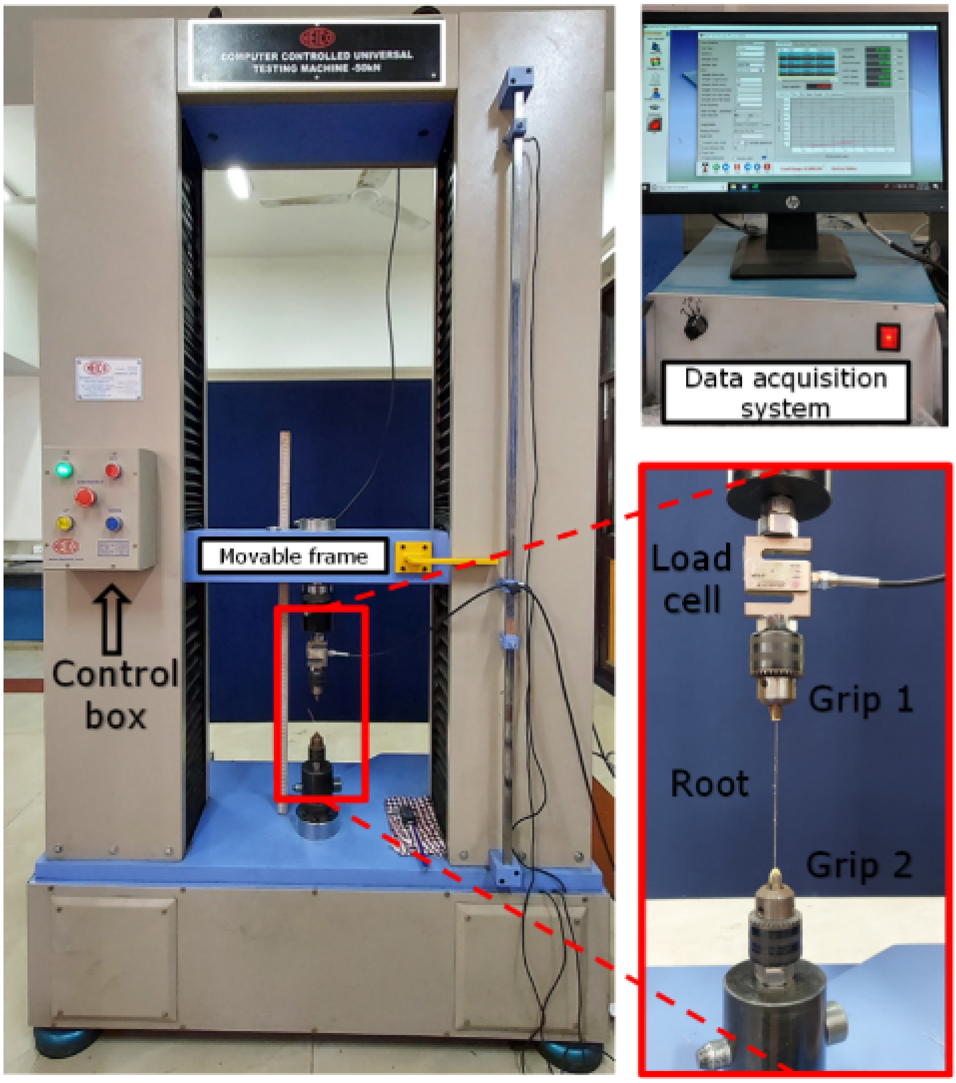

**Figure 2**

Initial and final growth states of: (a) Bamboo grass, (b) Lemon grass, and (c) Vetiver grass




## Figure 3

Root patterns (binary image) showing the spatial distribution of root fibers of: (a) Bamboo grass, (b) Lemon grass, and (c) Vetiver grass




## Figure 4

Laboratory root tensile strength test setup showing the enlarged root clamping assembly connected to 0.5 kN load cell

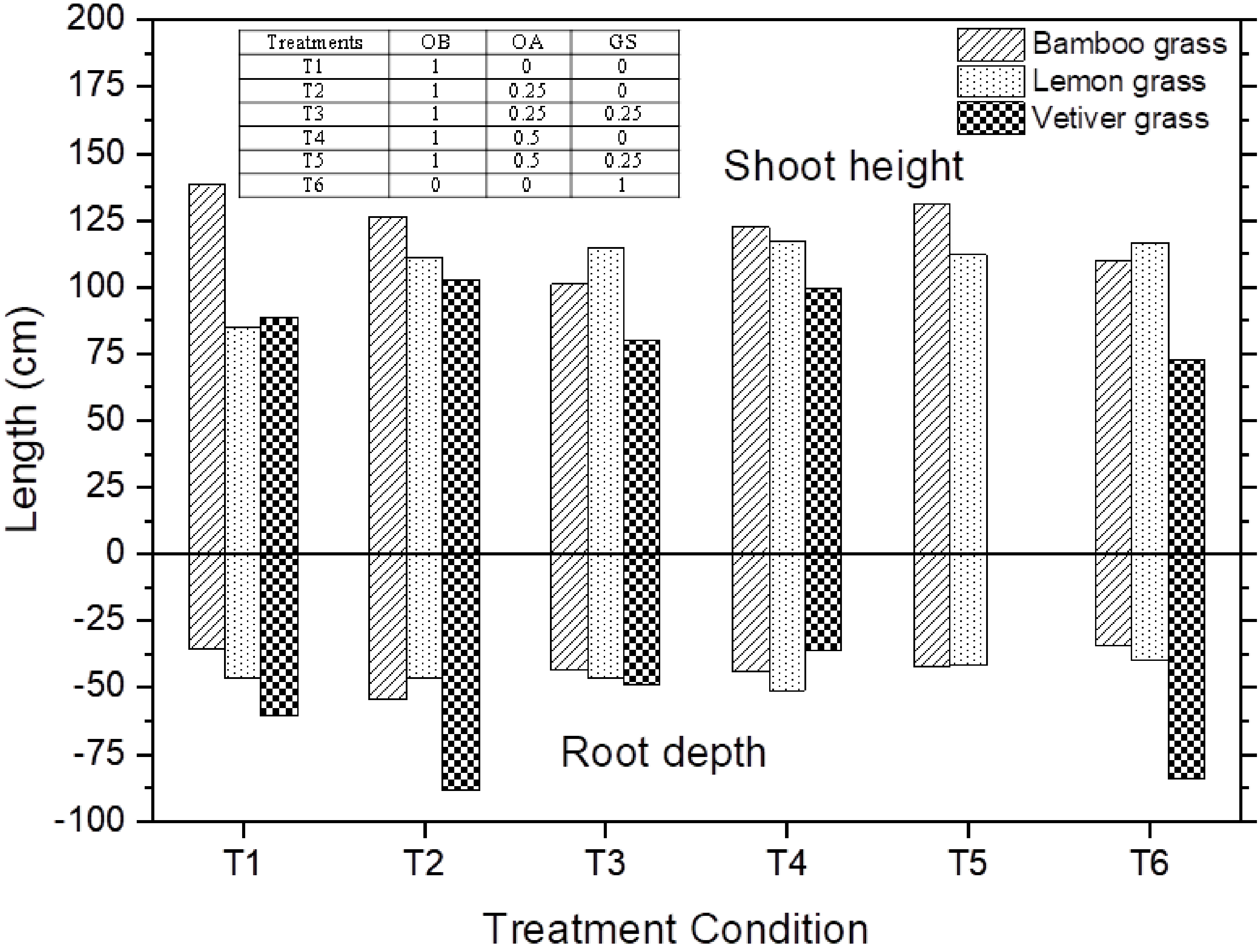



**Figure 5**

Root and shoot lengths of Bamboo, Lemon, and Vetiver grass under different treatment conditions

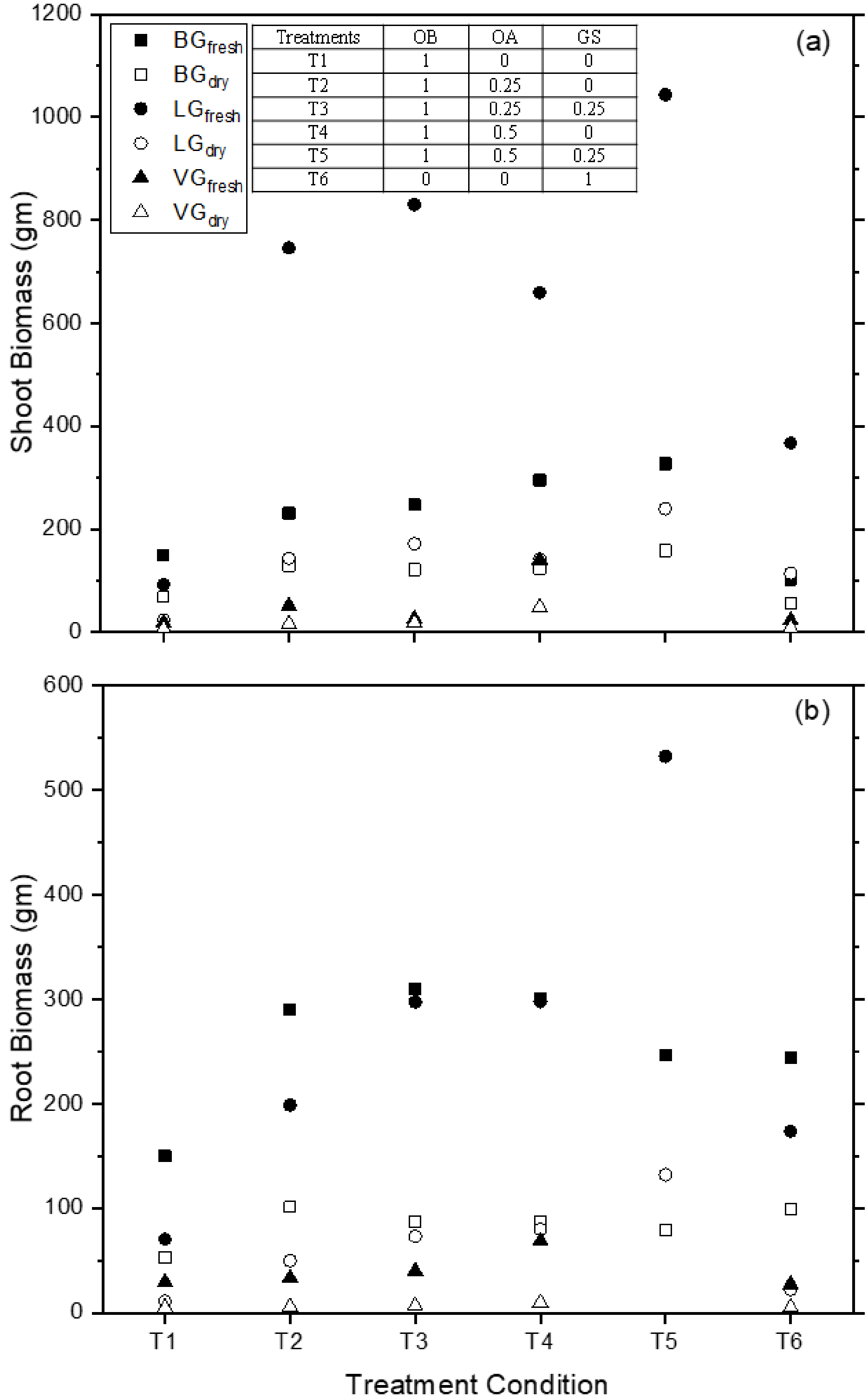
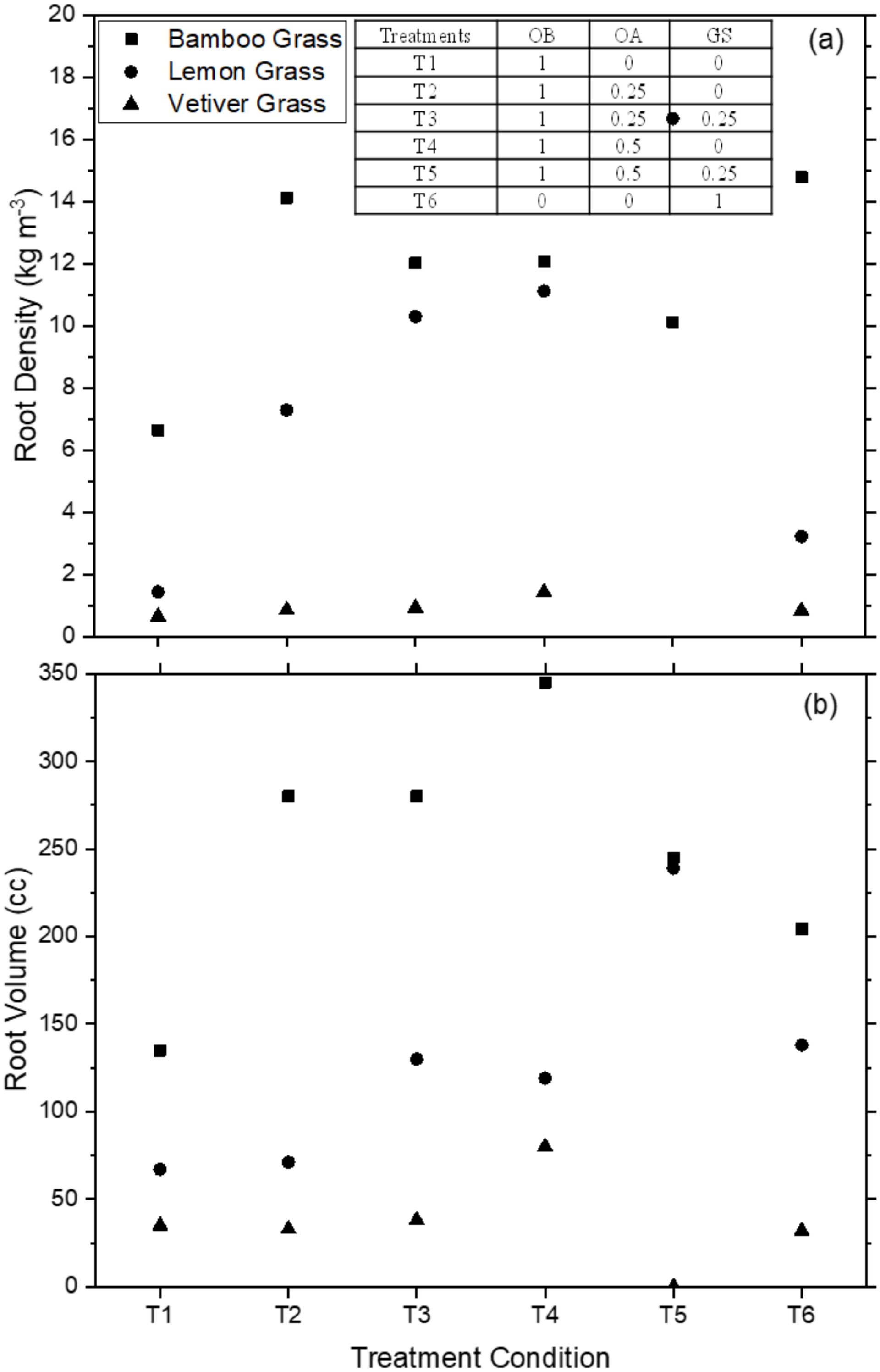


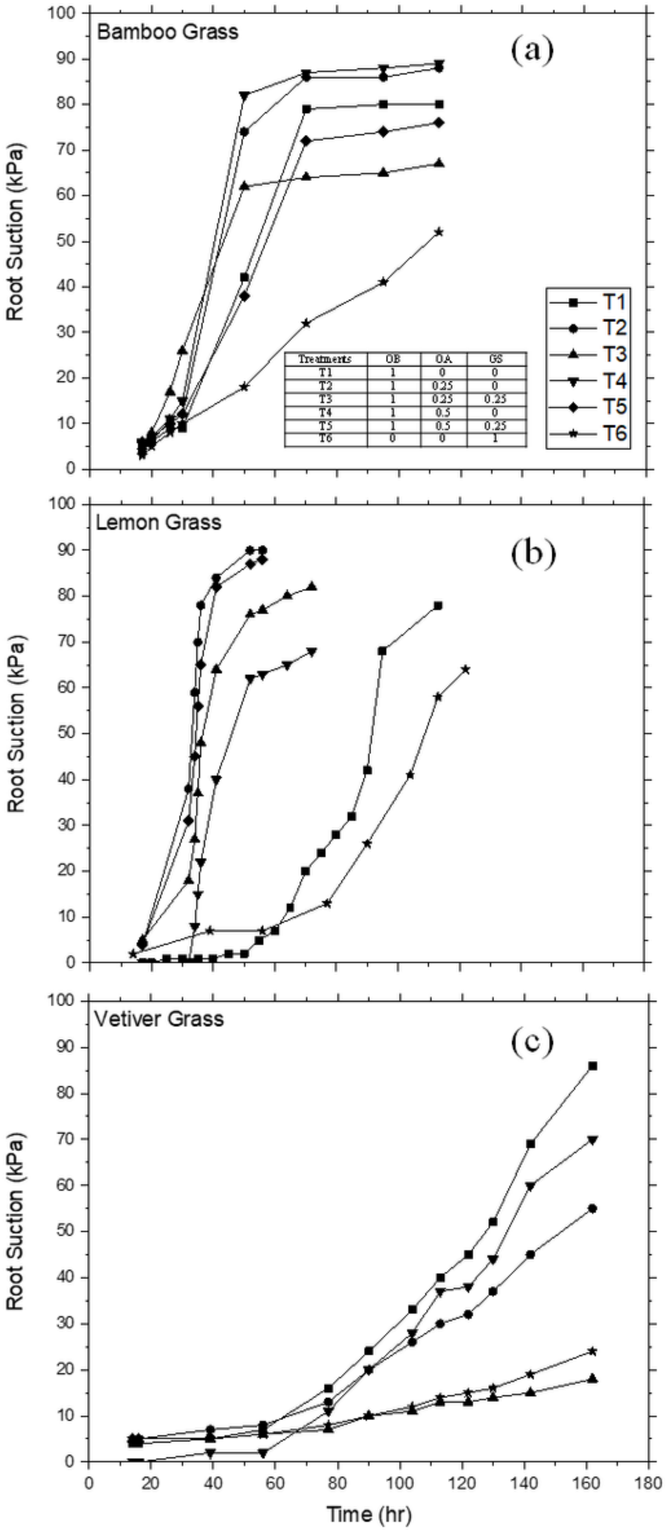

**Figure 6**

The effect of treatment on plants' fresh and dry (a) shoot biomass and (b) root biomass




## Figure 7

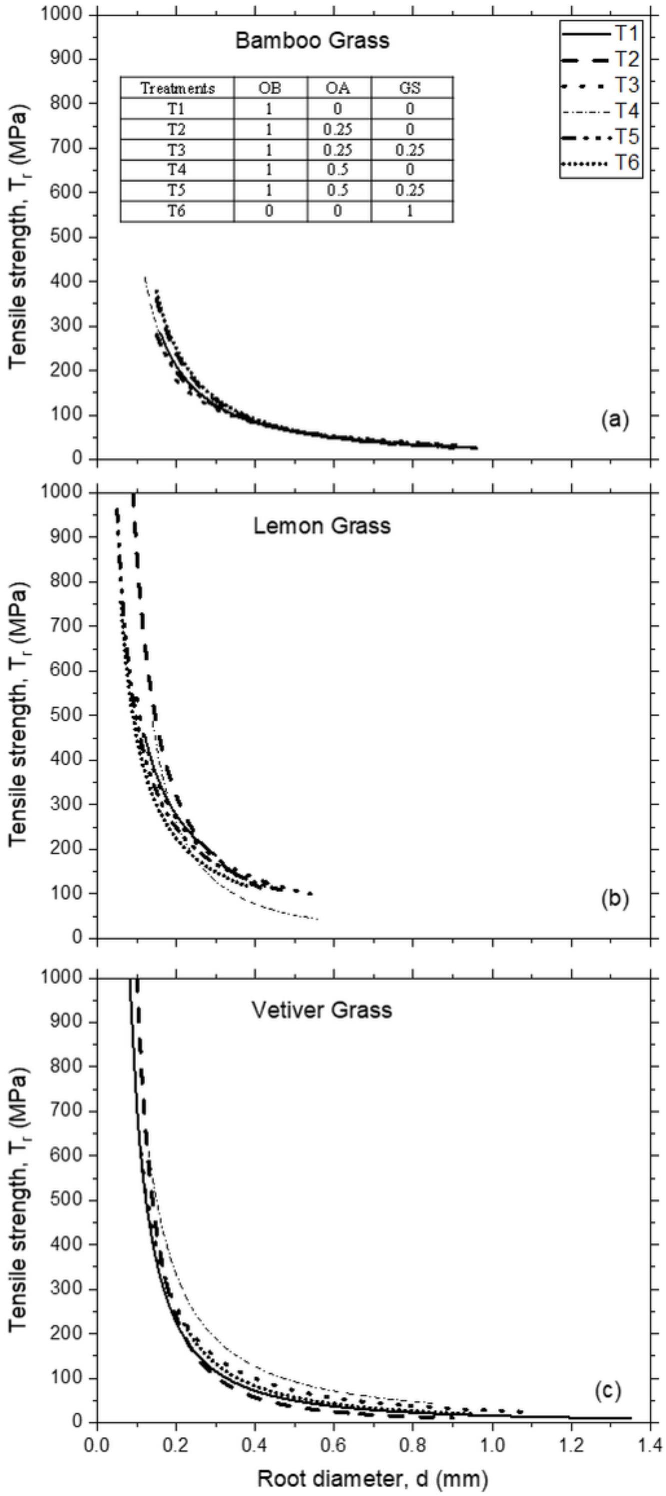
The effect of treatment on (a) root density and (b) root volume of different plant species grown under varying proportions of organic amendment




## Figure 8

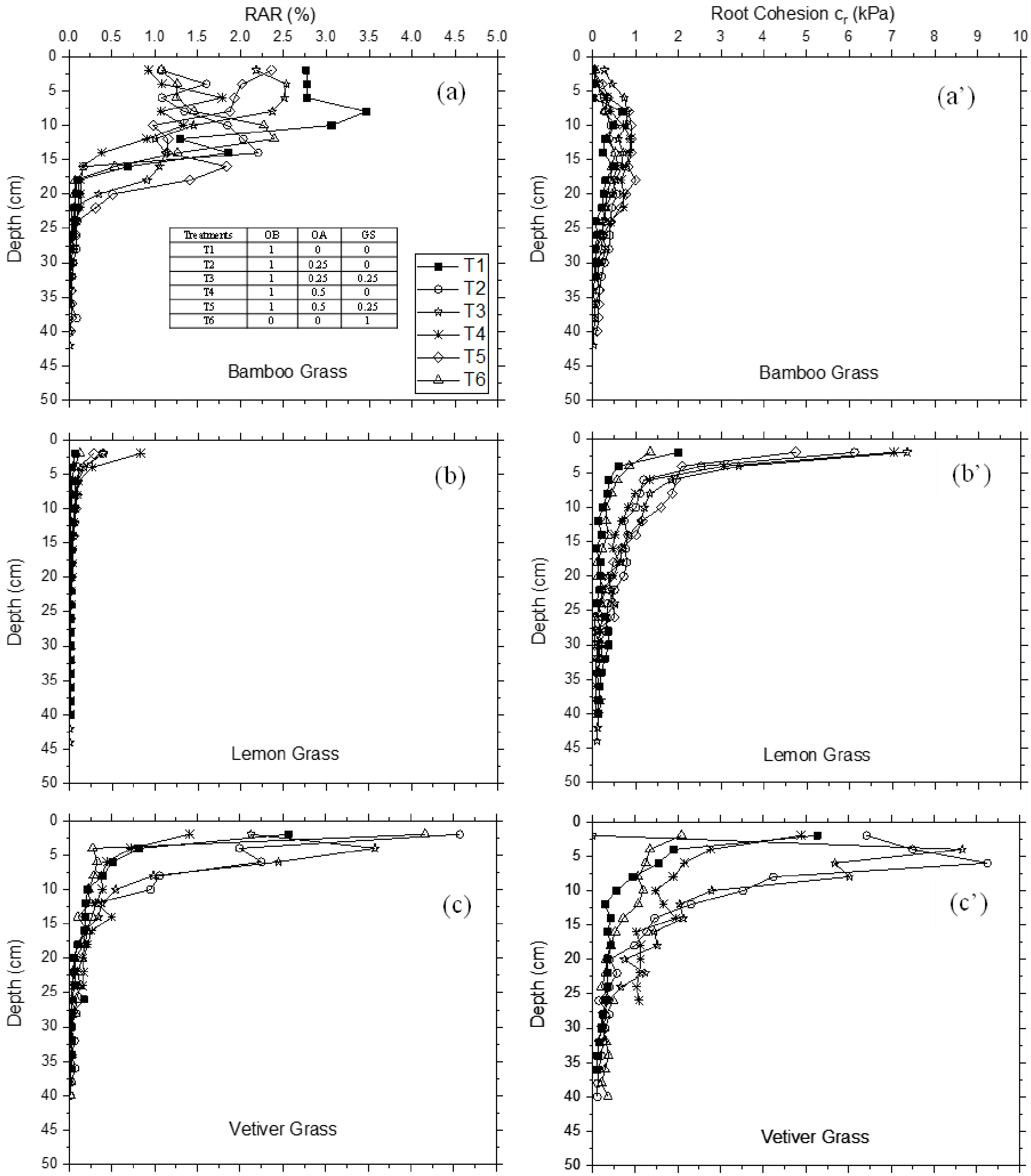
The variation of root suction with time under different treatment conditions for:

(a) Bamboo grass, (b) Lemon grass, and (c) Vetiver grass




## Figure 9

The variation of root tensile strength with root diameter under different treatment conditions for: (a) Bamboo grass, (b) Lemon grass, and (c) Vetiver grass




## Figure 10

The effect of depth on RAR (a, b, and c) and cr (a’, b’, and c’) for plants cultivated under different treatment conditions for Bamboo grass, Lemon grass, and Vetiver grass, respectively