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GROWTH PERFORMANCE, ROOT TENSILE RESISTANCE, AND SHEAR STRENGTH CHARACTERISTICS OF ROOT-PERMEATED SOIL OF SELECTED SHRUB SPECIES

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Vegetation plays a substantial role in reducing slope instability through root reinforcement. Different species of plants have different characteristics that can contribute to the soil's shear strength. The objectives of this study were to determine the growth performance of selected shrub species, namely *Strobilanthes crispa* (SC) and *Tabernaemontana divaricata* (TD), to determine the tensile strength of root and relationship with cellulose content, and to examine the shear strength of root-permeated soils. The soil medium was prepared before planting the selected species of SC and TD based on the ratio 3:1:1:1 representing the soil, sand, organic materials, and chicken manure. The result of growth performance shows that SC species have better growth than TD in most variables. The result of root tensile force increasing with increasing diameter for both species and months. The tensile force of both species varies slightly in the month of 3, possibly due to root diameter variation. However, in month 6, TD species show higher tensile force than SC, suggesting root age influences root mechanical behaviour. The result of cellulose content indicates that it increases with increasing diameter and tensile force. TD displayed higher values of shear strength than SC. Overall, it was suggested that SC species are better to be applied as ground cover for surface erosion protection based on their growth performance. Meanwhile, TD species are better for slope failure prevention due to their higher root tensile and soil shear strength.

Keywords: Shrubs, plant growth, root tensile, cellulose, shear strength

INTRODUCTION

Soil erosion is a common feature naturally occurring on a very gentle slope. Erosive components responsible for detachment, dissolution, and wear of soil particles lead to further transportation and deposition (Ellison 1948). In tropical regions such as Malaysia, which has a year-round climate that alternates between wet and dry conditions, a high volume of rainfall of over 2,000 mm annually is received (Ahmad et al. 2017). Erosion and landslides commonly occur mainly during the wet season. Human interceptions have exacerbated the process by changing the natural environment through deforestation for agricultural, mining, and urbanisation activities. Erosion has caused a reduction in soil fertility and severe sedimentation in river flows (Stokes et al. 2014, Chen et al. 2018). Several attempts have been adopted to tackle this issue, ranging from hard engineering to more sustainable measures such as bio-engineering (Koerner 2000, Vianna et al. 2020).

The soil bio-engineering combines multiple mechanical, hydrological, and ecological approaches and adopts environmentally friendly solutions for slope erosion and slope instability. This technique has significant advantages, associated with lower environmental impact compared to conventional stabilisation methods that rely on rigid structures, such as the application of retaining walls (Simon & Steinemann 2000). It has been well acknowledged that vegetation successfully stabilises problematic slope areas and becomes an economic alternative in civil engineering (Ettbeb et al. 2020a, Mohamed et al. 2022). In a bio-engineering technique, plants and their components with or without inert components (e.g., rocks, wood, metal and geosynthetics) have been used as biological materials (Gray & Sotir 1996, Lewis et al. 2001, Vianna et al. 2020) and their growth performance as biological materials. Different species might respond and adapt in different ways to new environments. Therefore, the best plant species choice is to use local species of plants as they are already adapted to growing conditions, more likely resistant, readily available, and likely at lower cost (Osman et al. 2011, Chestem et al. 2014). Plants that need much maintenance are not recommended, especially on slopes where watering may form a slipping plane for slope failure. Selected plants should resist drought and poor soil in terms of nutrients available. The selected plants should be able to reinforce soil, prevent and stabilise the erosion process, decrease surface runoff, increase water infiltration, and promote ecosystem restoration (Gray & Sotir 1996, Stokes et al. 2014).

Plants serve two primary functions in reducing soil erosion and slope instability. The plant canopy acts as a physical barrier against the impact of rainfall, reducing the energy received by soil particles at ground level. Plant roots bind soil particles together at the subsurface level, forming a fibrous network that increases the shear strength of the soil (Stokes et al. 2009, Affaf et al.2020). Dense-rooted plants easily drain surface water from the slope, increasing the soil shear strength and slope stability (Shrestha et al. 2008). Root tensile strength as a function of resistance against slope movement. The root reinforcement can be evaluated via root tensile strength (De Baets et al. 2008, Ni et al. 2019).In comparison, soil particles are strong in resisting compression force (limited tensile resistance), while plant root systems are vital in resisting tensile resistance (De Baets et al. 2008, Gray & Barker 2013). Any shear stress the soil matrix receives is transferred to the tensile resistance of the root systems. The combined effect has a favourable impact on soil shear strength (Li et al. 2016). Roots with different orientations, e.g., perpendicular to the soil surface, reinforce the soil on the sheared plane while growing parallel in-plane tensile strength (Zhou et al. 1998, Stokes et al. 2009)

The distinct traits of different plant species determine their suitability as crop covers on specific slopes (Asima et al. 2022). Grasses and ferns, among plant species, form rhizome mats that effectively bind the soil particles and provide physical barriers to erosion (Truong 2000, Ghosh et al. 2012). Grass has a spreading fibrous root system that can hold soil in place; however, its capability is limited to surface erosion rather than deep landslides. It provides short-term mitigation but necessitates regular maintenance, which is time-consuming and expensive (Coppin & Richards 1990, Dorairaj & Osman 2021). Herbaceous plants have high root length density, and fine root content is vital to soil strength (Saifuddin & Osman 2014, Hamidifar et al. 2018). Woody plants, despite having deeper roots to prevent slope failure (Reubens et al. 2007), may eventually cause problems for the slope due to the surcharge load associated with the size of the plant. Meanwhile, shrubs with low-growing woody plants, multi-stems, and growing up to 6 m can potentially be used for slope protection and stability improvement (Dorairaj & Osman 2021). Shrubs are small to medium-sized perennial plants, making them easy to care for and maintain (Stokes et al. 2008). All these traits should be assessed for their effectiveness in practical applications, such as suitability for local environments, ease of planting, and maintenance requirements.

Numerous studies have proven the effectiveness of shrubs in reducing surface erosion and slope instability. Shrub species managed to reduce the runoff and surface erosion compared to grass, which had relatively shallow roots (Liu et al. 2014). Fibrous and tap roots of pioneering shrub plants were also found to have comparable tensile strength to tree species (Tosi 2007, Leung et al. 2015). Rahardjo et al. (2014) discovered that shrubs reduce rainwater infiltration and matric suction loss, contributing to slope materials' shear strength. The assessment of different plants revealed that shrub species, *Juniper chinensis* and *J. horizontalis*, had lower runoff volumes than vetiver and fescue grasses (Asima et al. 2022). In this study, *Strobilanthes crispa* (SC) and *Tabernaemontana divaricata* (TD) were selected to examine their suitability as biological materials for erosion prevention in a bio-engineering approach. These shrubs are native to the region of Southeast Asia. A preliminary study has shown a potential use of these plants based on their growth performance variables (Aznan et al. 2023). To our knowledge, no single study has used these species as bio-materials for slope protection and erosion mitigation. Research on *S. crispa* (SC) and *T. devirata* (TD) has primarily focused on the possibility of using the leaves as a source of medicine (Dantu et al. 2012, Ghasemzadeh et al. 2015, Tan et al. 2019). The objectives of this study were (a) to determine the suitability of these selected shrub plants by monitoring their growth performance, (b) to characterise and determine the tensile strength of root systems and influence of cellulose, and (c) to investigate the influence of roots on the shear strength of root-permeated soils. The plants' growth performance and root tensile strength were monitored for three and six months, respectively, and the soil shear strength was measured at the end of the observation period.

MATERIALS AND METHODS

Shrub species, medium preparation and planting

The selected shrub species used in this study were *Strobilanthes crispa* (SC) and *Tabernaemontana divaricata* (TD). SC is a woody spreading shrub with glossy dark green, opposite, elliptical-shaped leaves (Ghasemzadeh et al. 2015). Meanwhile, TD is a round, evergreen, well-branched shrub with large, glossy, dark green leaves and waxy white, ruffle-edged flowers that are incredibly fragrant at night (Edward 1999). Its flower petals curve like a pinwheel and are prominent throughout the year's warm months.

The soil medium was prepared before planting the selected species of SC and TD based on the ratio 3:1:1:1 representing the soil, sand, organic materials, and chicken manure. The base soil was obtained from the site where the plots were later constructed for slope erosion study. The properties of the soil, chicken manure, and prepared soil medium are shown in Table 1.

Table 1 Basic characteristics of coil medium

Parameters	Base Soil (N=10)	Medium Soil (N=10)	Chicken Manure (N=3)	NPK (N=3)
pH	4.62±0.33	7.39±0.17	8.83±0.08	3.63±0.01
Organic ct. (%)	6.14±1.01	8.23±0.32	24.17±1.14	78.45±0.19
Moisture ct. (%)	29.21±12.56	20.45±1.03	n.a	n.a
Silt (%)	30.43±15.19	43.46±3.50	n.a	n.a
Clay (%)	31.29±9.65	30.59±4.10	n.a	n.a
Sand (%)	38.28±7.75	25.95±2.36	n.a	n.a
Texture	Clay Loam, Loam	Sandy Clay Loam	n.a	n.a
Na (μg/g)	231.53±74.35	1104.46±167.93	4750.18±944.93	14147.04±356.84
Mg (μg/g)	41.69±22.68	1233.09±200.99	4356.51±1339.30	3963.64±114.82
K (μg/g)	197.18±39.08	5959.84±1096.06	33740.89±10492.01	46325.02±134.15
Ca (μg/g)	343.46±98.83	3487.48±579.99	4653.64±1233.48	5924.31±141.90
P (μg/g)	0.49±0.18	2.56±0.96	7.98±0.04	12.18±0.92
TOC* (%)	1.85±0.49	4.25±0.46	7.75±0.43	20.46±0.5
Total Nitrogen (%)	0.23±0.09	0.41±0.07	2.01±0.35	8.82 0.64

* = Total organic carbon, n.a = not available, N = total sample

A polybag with a 10-inch by 12-inch dimension was used for seedlings of the studied shrub species. Each shrub species comprised ten individual plants (replication) and was arranged in a randomised complete block design (RCBD). The plant shoots of each species were randomly collected from the various sites in Universiti Kebangsaan Malaysia, Bangi, Selangor, and cut into 15 cm long from the matured plants. The shoot was initially dipped into root-promoting hormone before sowing into the propagation chamber filled with sand. After four weeks in the sand chamber, the saplings were carefully removed and transferred into the polybags. The plants were moved to the greenhouse and placed on the designated platforms for further monitoring. The plants were watered approximately 300±1.5 ml twice a day. Each polybag received 10 g of NPK (Table 1) after two weeks, twice a month, for the duration of the monitoring period in order to ensure that the soil medium had enough nutrients to support the plants' optimal growth.

Plant growth performance

The monitoring of the shrub species' plant growth performance was carried out for six months. The growth performances measure the plant height, number of leaves, stem diameter, chlorophyll content, and leaf area. The plant height was measured from the ground surface to the highest point of the plant using a universal measuring tape, and the number of leaves was counted manually. The chlorophyll content and leaf area were determined using a portable chlorophyll meter (SPAD-502 Minolta Co. Ltd) and a portable leaf area meter (LI-3000C Instrument, Osaka, Japan), respectively. Before measuring chlorophyll content and leaf area, five individual leaves per plant were tagged and monitored continuously during six months of monitoring stages.

Root characteristics

The characterisation of root variables involved the measurement of root length, diameter, and biomass, which were determined at the third and sixth months of their growth. The polybag was torn off, and the soil medium was carefully rinsed with tap water to remove all soil particles from the plant's roots. The root length measurement was carried out from the primary root's upper part until the root cap's end using a universal measuring tape. The approach to investigate the root architecture and order was the technique adopted by Yen (1972). The root biomass was determined by placing the sample in the oven for 48 hours at 60°C. Then, the root samples were repeatedly weighed with a balance until the weight became constant.

Root tensile test

The tensile strength of the plant's root is a complex attribute affected by various circumstances, and no one equation can precisely predict it for all plant species. However, the tensile strength of the root is usually described in terms of resistance or stress as the resistance or root area ratio (Vergani et al. 2012). The relationship between tensile stress and root diameter, which an inverse power law equation can describe, has been the subject of numerous studies (De Baets et al. 2008, Vergani et al. 2012, Ni et al. 2019, Zhang et al. 2019). Tensile stress is calculated by dividing the applied force by the root's cross-sectional area at the rupture point, as adopted by many researchers:

$$T_r = \frac{4F_{max}}{\pi d^2}$$

Where T_r is tensile strength (MPa), F_{max} is the maximum force at rapture point (N), and d is the average root diameter (mm)

The tensile force, T_f is preferred over tensile stress, T_r, because the accuracy issue of the measurement of the root diameter at breaking force is difficult to determine, and the precise point of rupture cannot be ascertained prior to the test (Vergani et al. 2012). The point of rupture is commonly determined after the test, and tensile strain causes a reduction in the root diameter. The rupture process is associated with a small proportion of the root rather than a single infinitesimal section. Therefore, this study used the tensile force, which refers to the maximum force at failure, F_{max}. The power law equation was adopted to present the relationship of root resistance (T_f)-diameter (mm). The equation of power law is shown below.

$$T_f = \alpha . d^{\beta}$$

Where T_f is tensile force (N), and d is the average root diameter (mm)

Root tensile tests were conducted, as previously reported by (Affaff et al. 2020). Root sampling was performed after three and six months of growing to examine the effect of different root ages on the tensile resistance. Root samples were collected from polybags using the same procedures to determine root biomass. Individual root tensile testing was performed using the Universal Testing Machine (UTM) with a capacity of 50 N (Testometric, Model M350-10CT, United Kingdom). The samples were cut into 10 cm lengths before being weighed. The diameter of the root was measured at three different points along its length with a digital vernier calliper. A sandpaper was used to wrap the end tips of the root (around 2 cm from the edge) to secure a better grip between the root's end before clamping was applied. The two ends of the root sample were carefully fastened into the upper and lower wedge grip to ensure a better grip with a low possibility of slippage during testing (ASTM 1975). The root was vertically pulled up at the rate of 5 mm/min. The occurrence of extension until failure and force reading, F were recorded and generated automatically using the software linked to the UTM. The tensile force at the point of rupture was taken as the peak load, F_{max}. Tests in which the roots broke near or at the point of clamping were considered invalid. Tensile force, F_{max}, was measured in Newton (N). The tested root samples were wrapped in a plastic film to preserve their moisture content for further laboratory analysis.

Root cellulose contents

The root sample first tested for its tensile strength would be used to determine cellulose contents. Based on this method, the initial weight of the root sample was too small (less than 0.1 g) and insufficient to determine the cellulose content, particularly for fine root samples. It is commonly acceptable for the case of a limited supply of root samples between 0.1 and 0.2 g (Leavitt & Danzer 1993). Therefore, the root sample of each species was divided into different classes of root diameter with three replicates for each species (Table 2). The cellulose content of the root was determined using the method described by Genet et al. (2005), with some modifications involving removing non-cellulosic materials from the root. The roots were initially divided into corresponding diameter classes. Then, they were weighed until the mass of each root was constant under conditions of natural ventilation and temperature (25 °C) to obtain the initial fresh weight. Then, the roots were dried at 60 °C for 24 hours before being weighed with a balance with a precision of 0.0001 g. Then, each root was ground into a fine powder, poured into a non-woven sachet, and labelled with a corresponding identification code. This non-woven sachet was then transferred into a soxhlet extractor with a flask containing a 250 ml mixture of toluene 99 % and ethanol 96 % at a ratio of 2:1. The flask was later heated up to the boiling point for 24 hours. After 24 hours, the toluene-ethanol mixture was replaced with 250 ml of ethanol and heated at a similar temperature for another 24 hours. Then, the sample was taken from the soxhlet extractor after 24 hours and submerged in distilled water heated to 100 °C for 6 hours.

In order to remove the lignin content of the roots, the root sample was soaked in a beaker of 500 mL of distilled water added with 5 g of sodium chlorite, $NaClO_2$, and 1.0 mL of acetic acid, $C_2H_4O_2$. A magnetic agitator was used to stir and heat the solution at temperatures ranging between 60 °C and 70 °C for 2 hours. This procedure was repeated thrice, with the solution becoming 100% concentrated each time. The samples were then removed and cleaned in distilled water before being dried, placed into an oven at 40 °C for 12 hours, and re-weighed. The percentage of cellulose was determined

Table 2 Root diameter range D and sample number, N

Range of root dia., mm		0.0-0.4	0.5-0.9	1.0-1.4	1.5-1.9	2.0-2.4	2.5-2.9	3.0-3.4	3.5-3.9	4.0-4.4	4.5-4.9	5.0-5.4	5.5-5.9	6.0-6.4	6.5-6.9
Classes of root dia., mm		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample number, N	SC	60	45	36	34	21	19	18	4	14	12	10	8	6	5
	TD	55	50	36	32	9	18	14	25	14	na	na	na	na	na

n.a = not available

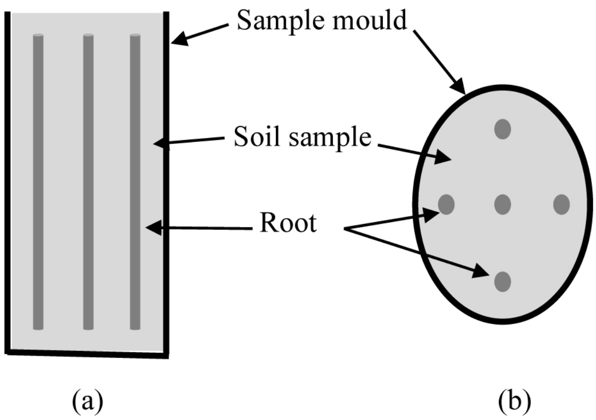


Figure 1 The vertical arrangement of root samples in the remoulded soil (a) side and (b) top views

from the difference between the initial weight, m_1, and the final weight, m_2, of each sample.

Shear strength test

Soil and root preparation

The root's effect on soil shear strength was performed using the conventional triaxial test under undrained unconsolidated conditions (UU test). A bulk sample of 20 kg soil was collected from the plot study to prepare the remoulded samples. Initially, soil samples were dried at room temperature for several days and manually crushed to break down soil aggregates. The soil sample was then thoroughly mixed with 20% water content and left overnight in an air-tight container to become completely homogeneous. For consistency, five root samples with diameters ranging from 1.5 mm to 2.0 mm were selected, and the ratio of root/soil mass was kept close to 0.5 %.

Preparation of remolded sample

The remoulded sample of root-permeated soil was prepared in the cylinder mould with a 45 mm diameter and 90 mm height. Five root samples were vertically (90°) arranged in the mould where this degree of arrangement of the roots had the strongest effect on the shear strength and was most suitable to resist the axial pressure of the root-soil composite (Li et al. 2022). The position of the root in the soil sample is shown in Figure 1. Then, the soil sample was carefully filled and evenly tamped up to three layers. Each layer received the same amount of tamping effort of 30 blows using a tamping rod. The final layer was levelled off to the top of the mould. The control remoulded sample was also prepared in the same manner as the preparation of the root-permeated soil sample. Three remoulded samples were prepared and replicated for each species, ending with 18 and 9 samples of the root-permeated and control soil samples, respectively.

Sample preparation for soil shear strength test

The shear strength of the sample was determined using a conventional compression triaxial instrument. A soil sample was extracted from the cylinder mould using a jacking device, and a rubber membrane was inserted around the sample. Then, the sample was placed on the pedestal, and O-rings were placed on top and base of the sample. The cell was set up and filled with water, and the confining stress, σ_3 was applied to the sample. This study's applied confining stresses were 50, 100, and 200 kPa. Once the confining stress was applied, the sample was sheared at a 1 mm/min rate until 20% of axial strain (Zhang et al. 2010). After shearing, the sample was removed from the cell, and the representative samples were collected to determine the moisture content, w. The root biomass was also determined for each sample for reference.

The Mohr Coulumb's shear strength was applied to determine the strength parameters of friction angle, θ, and cohesion, c. In root-permeated soil, the failure of soil, c_s should consider the failure of root, c_r within the soil.

Therefore, the soil shear strength has also been contributed by the reinforcement of the root, c_r, which the following equation can represent:

$$\tau = c_s + c_r + \sigma \tan\theta$$

Where c_s is the soil cohesion, c_r is the root reinforcement, θ is the friction angle, σ is the normal load, and τ is the soil shear strength.

Statistical analysis

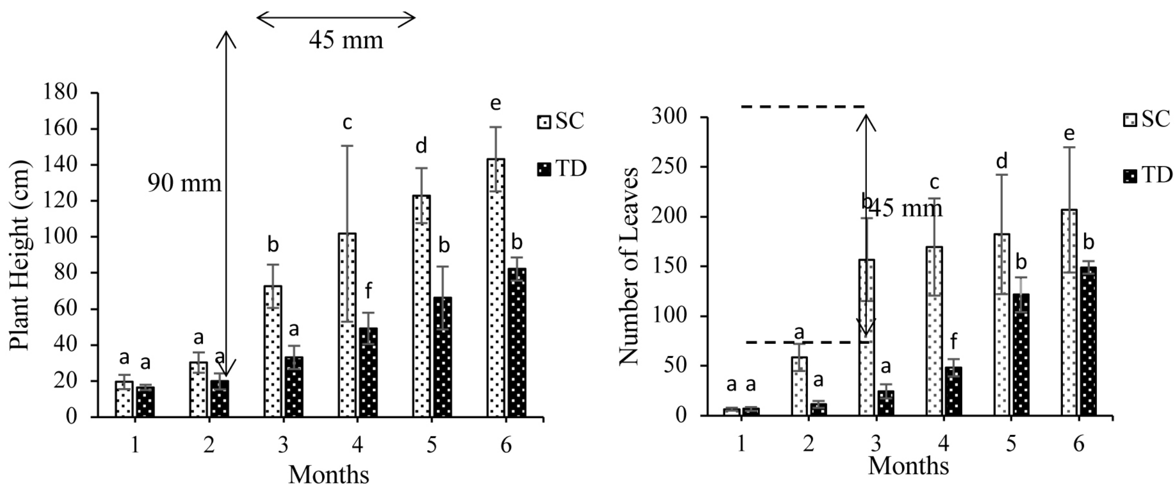
The data were analysed using IBM SPSS version 26.0. One-way ANOVA (analysis of variance) and multiple comparisons (Turkey post hoc test) were used to compare the growth parameters between species and months and moisture and cellulose content. Differences among the tensile strength of each root diameter group were also evaluated using ANOVA. Regression was used to model the cellulose and moisture composition relationships against root diameter and tensile resistance.

RESULTS

Growth performance

The first two months of growth for both species, a negligible increase in height, can be seen in Figure 2a. However, from month 3 through the end of the observation period, a significant difference (*p>0.05*) was seen in SC. A significant increase in TD can be seen only between month 4 and month 5, but the height of TD remains insignificant during that observation period. At the end of the observation periods, SC had a higher mean height than TD, with mean values of 143.19 cm and 82.18 cm, respectively. Similar patterns were also found for the number of leaves. Every month, both species showed a gradual increase. However, statistical analysis reveals no significant increase in the number of leaves for SC species between months 1 and 2. Significant changes in the number of leaves were observed for SC species from months 3 to 6. Nonetheless, TD showed an insignificant increase in the number of leaves from months 1 to 3 but a significant increase to month 4 before remaining equivalent in months 5 and 6. SC had the highest value, with a mean of 165.9 individual leaves (Figure 2b).

A similar trend was also revealed for the leaf area, as SC is always higher than TD. For TD species, the insignificant increase in leaf area can be seen in the first four months before increasing to the maximum value of 57.94 cm^2 at the end of month 6. SC showed the highest leaf area value compared to TD every month, with a maximum value of 132.25 cm^2 in month 6. The change in chlorophyll content showed a gradual increase for both species. However, SC species achieved peak value starting at the third month of the observation period while TD at month 4. The statistical analysis of variance shows no significant difference between both species regarding chlorophyll content at the end of the observation period. TD recorded the highest chlorophyll content of 52.56 at month 6, while SC at month 6 was 51.9 (Figure 2d). SC recorded higher values for stem diameter than TD (Figure 2e). The stem diameter for SC gradually increased and achieved a peak value



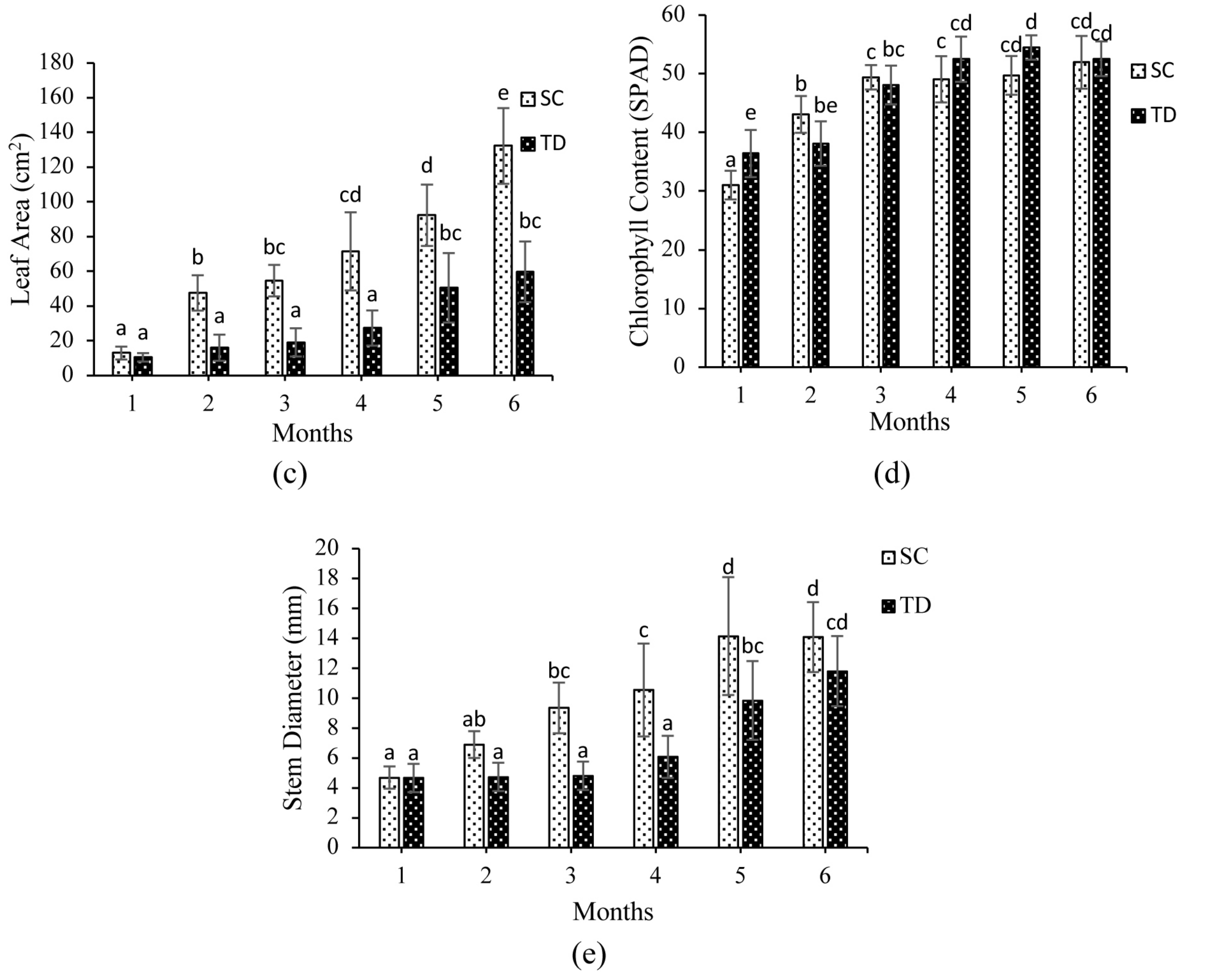


Figure 2 Comparison of plant growth performances (a) Plant height (b) Number of leaves (c) Leaf area (d) Chlorophyll content and (e) Stem diameter. The same alphabet is not significantly different ($p<0.05$)

starting in month 5. Besides, no significant change was displayed by TD between month 1 and month 4 before increasing gradually at months 5 and 6.

Root characteristics

The root length of both species showed an increasing trend from month 3 to month 6 (Figure 3a). The mean root lengths of SC and TD were 37.06 cm and 22.03 cm, respectively, at month 3. At month 6, the mean root length increased significantly to 81.5 cm and 61.83 cm, respectively. In comparison, SC recorded a higher root length than TD. However, the values of root length for both species were acceptably high. The root biomass displayed a similar pattern, with SC recording a higher mean value than TD. Both species' roots displayed shallow and dense root systems (Figure 3b). It was determined that its root architecture was of the M type (Figure 4).

Root tensile for, cellulose and moisture contents

Relationship between root tensile force and diameter

Relationship between root tensile force and diameter. Thirty-five root samples from both species were collected after three and six months and analysed for the tensile strength test. Root diameters of the SC and TD species range from 0.4 mm to 2.06 mm and 0.34 mm to 1.83 mm, respectively, for month 3. Meanwhile, 0.30 mm to 6.60 mm and 0.28 mm to 3.69 mm for month 6, respectively. The results of root tensile strength

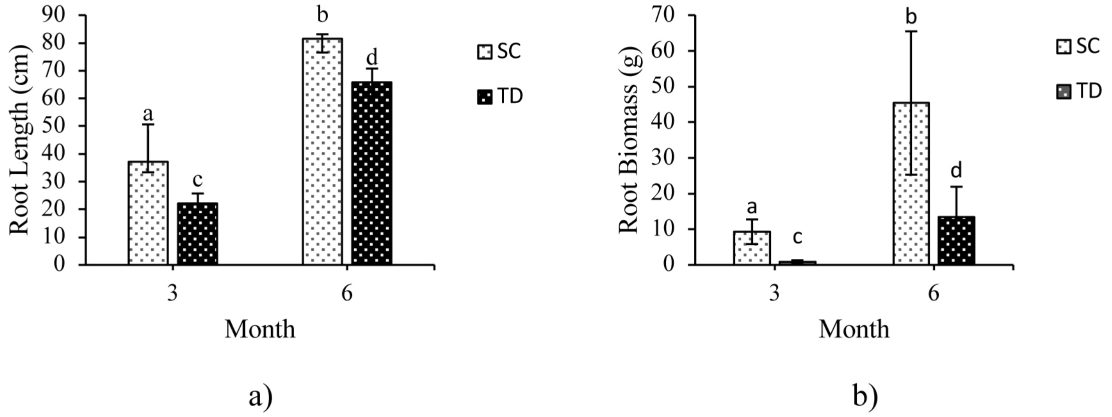


Figure 3 Root characteristics of SC and TD for months 3 and month 6 (a) Root length and (b) Root biomass. The same alphabet is not significantly different ($p<0.05$)

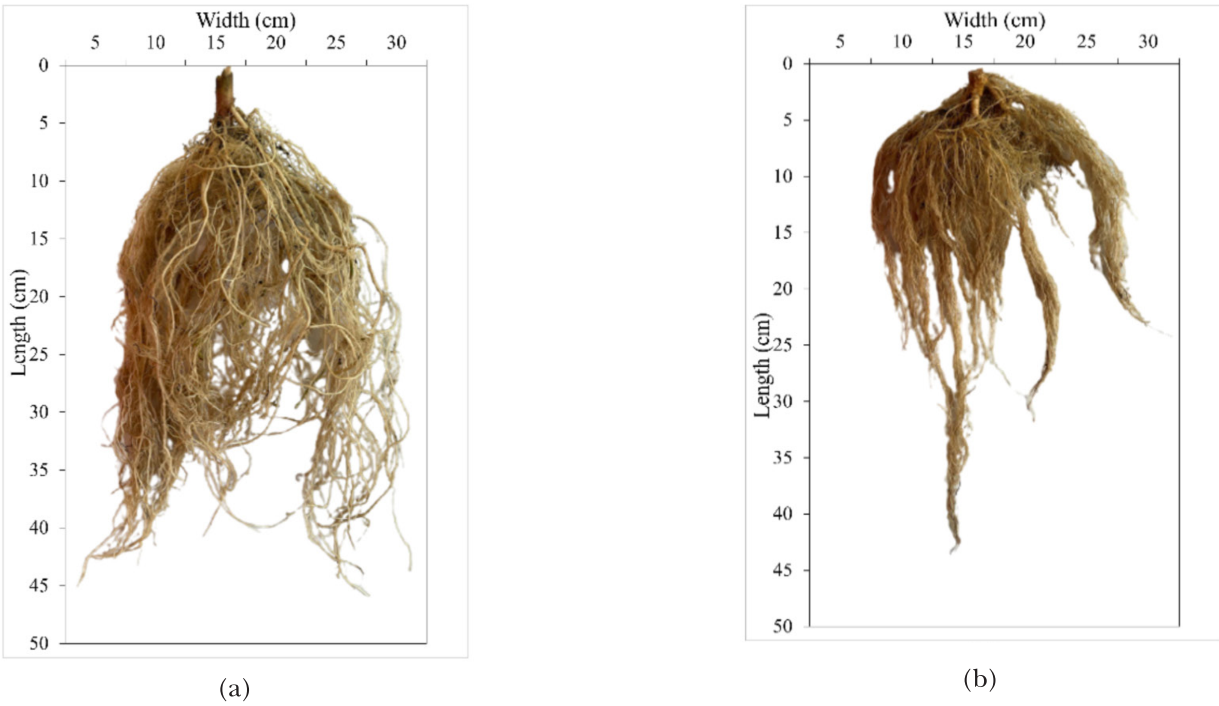


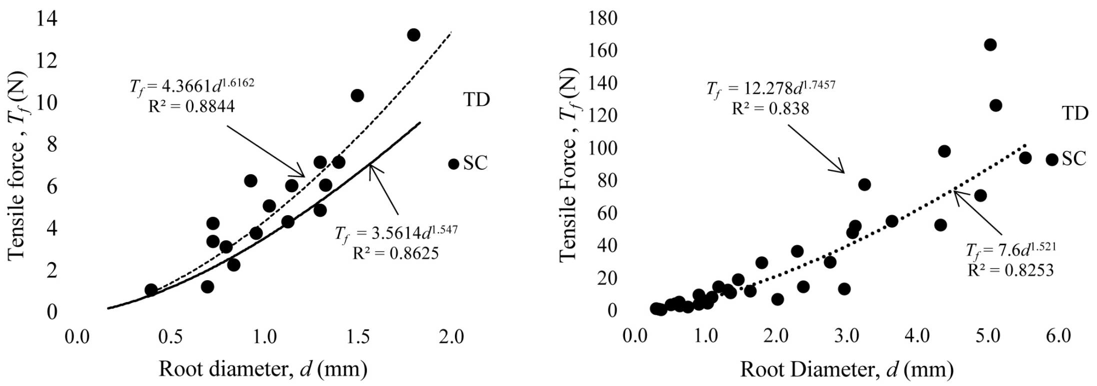
Figure 4 Root architecture (a) SC- *Strobilanthes crispa* (b) TD- *Tabernaemontana divaricata* (Yen 1972)

tests of the studied species are also shown in Table 3. At month 3, the peak tensile force, F_{max}, and mean value for SC species were 1.06-13.34 N and 6.58 N, respectively. In the case of TD, the F_{max} range was 0.28-11.90 N, with a mean value of 5.33 N. In month 6, the F_{max} and mean values for SC were 1.07-361.71 N and 58.07 N, respectively. On the other hand, the F_{max} range for TD species was 1.94-152.43 N, with a mean value of 46.24 N (Table 3). The findings showed that at month 3, SC species had slightly higher root tensile strength than TD species. The mean value for SC at month 6 was still higher than the TD species if all the data ranges were considered as the ranges of root diameter for TD were limited up to 3.69 mm while SC extended to 6.60 mm (Figure 5b). If the range of data for both species were considered up to 3.69 mm (TD) and 3.64 mm (SC), the mean values of tensile force for TD (46.24 N) become higher than SC (24.83 N) species. The root tensile force increased with increasing root diameter by a power law equation for both species and month (Figure 5) and indicated a stronger positive relationship between diameter and tensile force for the based on the highest R^2 recorded by power law equation ranging from 0.8253 to 0.8844 (Table 4).

Table 3 Diameter range and tensile forces of the studied species

Months	Species	Diameter (mm)	Tensile Force, T_f (N)	
		Range	Range	Mean
3	SC	0.40 - 2.06	1.06 - 13.34	6.58
	TD	0.34 -1.83	0.28 -11.90	5.33
6	SC	0.30 - 6.60	1.07 - 361.71	58.07
	TD	0.28 - 3.69	1.94 -152.43	46.24

SC = *Strobilanthes crispa* TD = *Tabernaemontana divaricata*



a) Month 3 (b) Month 6

Figure 5 Relationships between root tensile force (N) and root diameter (mm) (a) Month 3; (b) Month 6

Table 4 Summary of the power law equations and R^2 for SC and TD species of tensile force against root diameter at different growth ages

Months	Species	Power Law Equation	
		T_f	R^2
3	SC	$4.3661d^{1.6162}$	0.8844
	TD	$3.35614d^{1.547}$	0.8625
6	SC	$7.6321d^{1.521}$	0.8253
	TD	$12.278d^{1.7457}$	0.8380

SC = *Strobilanthes crispa* TD = *Tabernaemontana divaricata*

Relationship between cellulose against root diameter

Only roots at month 6 were considered for determining root cellulose content because they had a larger root diameter range for both species, 0.1-7.0 mm, compared to 0.1-3.5 mm in months 3. Considering all root diameters, the mean cellulose content for SC and TD were 34.99 ±1.25 and 42.56 ±1.23, respectively. The largest root diameters for SC and TD species were 7.0 mm and 3.5 mm, respectively. The cellulose content of SC did not change significantly with diameter classes 1 to 3 (0.25-1.5 mm), 5 to 7 (2.0-3.0 mm), 8 to 9 (3.5-4.5 mm), and 12 to 14 (5.0-6.5 mm) (Figure 5). In contrast, the cellulose content of TD species did not change significantly, from diameter class 1 to 3 (0.5 to 1.5 mm), 4 to 6 (1.60 to 3.25 mm), and 7 to 9 (3.0-4.5 mm). However, there is a statistically significant difference ($p<0.05$) in cellulose content of all root diameters for SC and TD species ranging from 3.5-4.5 mm. TD species had higher cellulose content than SC species across all diameter classes (Figure 6).

The relationships between root cellulose

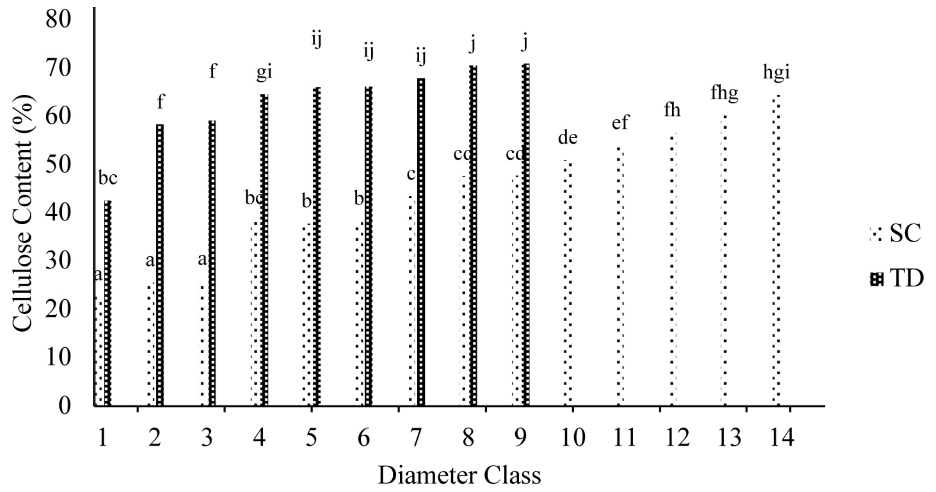


Figure 6 Comparison between root cellulose content in different diameter ranges in studied species. The same alphabet is not significantly different (p<0.0)

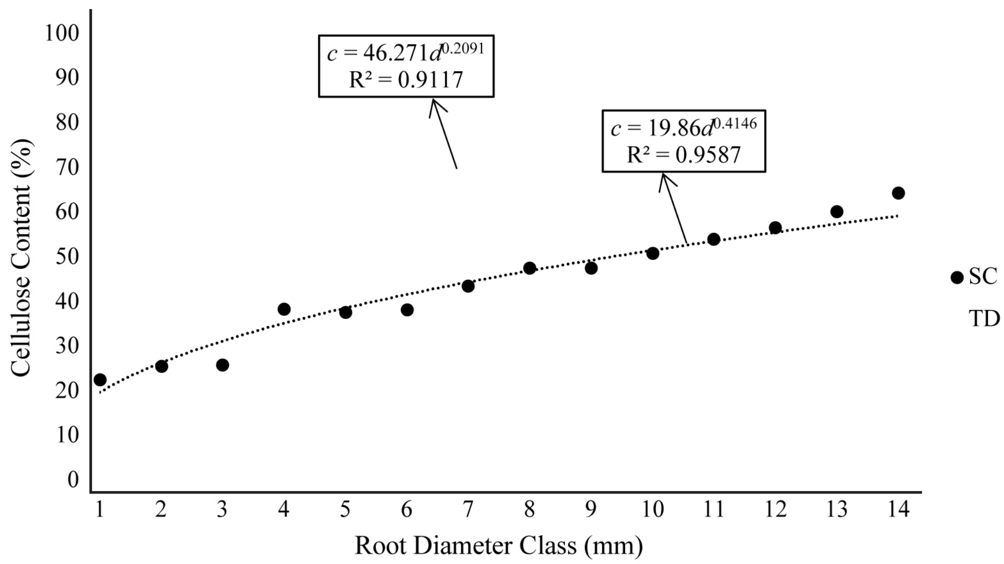


Figure 7 Significant positive relationships of the cellulose content across root diameter class of SC and TD species

against root diameter are shown in Figure 7. The cellulose content increased from 22.72% to 64.54 %, with the root diameter increasing from 0.1 to 7.0 mm for SC species, while 42.61% to 70.97%, with the root diameter increasing from 0.1 to 4.5 mm for species of TD. The results showed that the increase in the root's diameter resulted in increasing cellulose content.. This study also reveals a significant positive power relationship between root cellulose with root diameter for both species (Figure 7).

Relationship between tensile force against root cellulose

The relationship of the content of cellulose with the mean tensile force of SC and TD species is summarized in Figure 8 where the regression analysis reveal that the root tensile force increase significantly with increasing cellulose content for SC ($y = 18.285x^{0.2159}$, $R^2 = 0.9396$, $p = 0.000$) and TD species ($y = 43.183x^{0.1019}$, $R^2 = 0.8594$, $p = 0.001$).

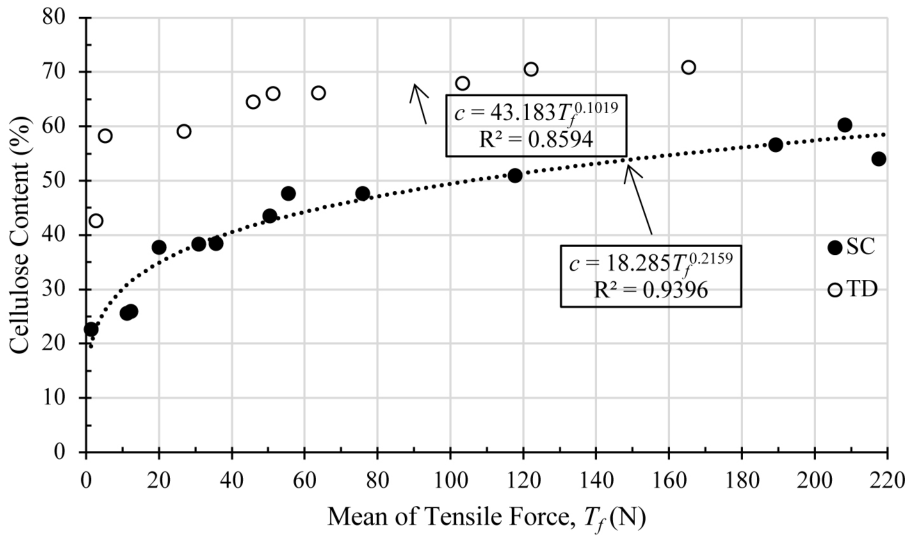


Figure 8 Significant positive relationships of the mean root tensile force with the cellulose content of SC and TD species

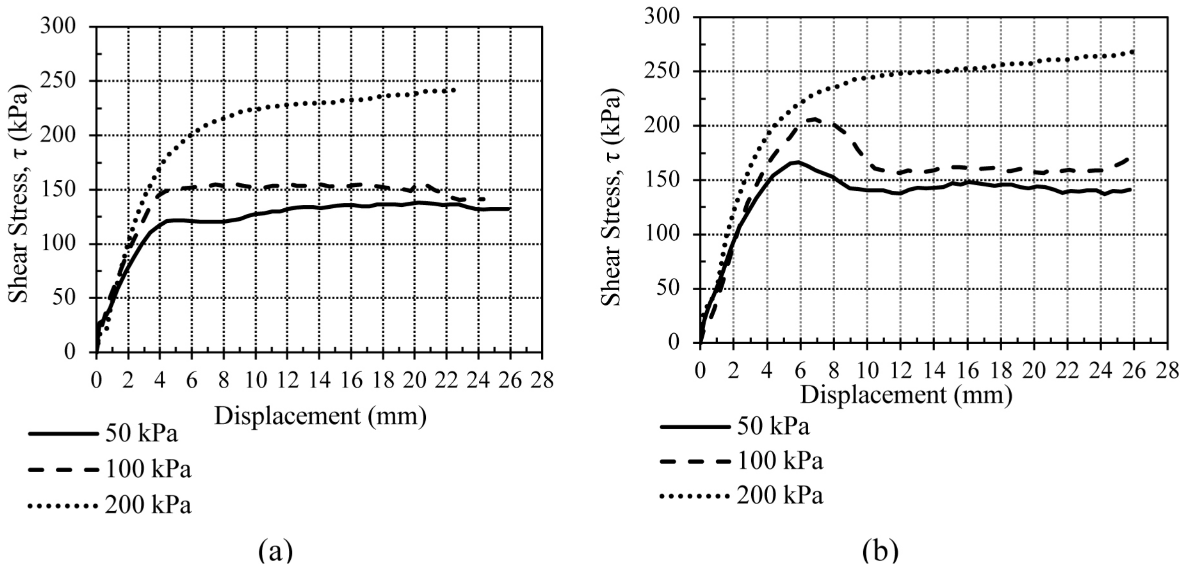


Figure 9 Shear stress against displacement curves for triaxial shear test on three different confining stresses of (a) SC and (b) TD species

Triaxial shear test

The overview of the shear strength parameters and available biomass for each test is shown in Table 5. Figure 9 displays the shear stress against displacement curves from the triaxial shear test for both examined species. The linear increment was seen at early displacement up to 4 mm before reaching their maximum shear stress value. The value of maximum stress increases as the confining stress increases. At particular confining stresses of 50, 100 and 200 kPa, the maximum shear stresses were recorded by TD species at 166.4, 206 and 268.9 kPa, respectively. Meanwhile, the maximum shear stresses of 138.0, 156.5 and 248.9 kPa were recorded for SC species. Both species displayed higher soil shear strength values than control (Table 5). In comparison, TD species demonstrated a higher value of soil shear strength than SC species.

Furthermore, the TD species' cohesion, c value was 134.95 kPa, while the SC species was 102.75 kPa, where both species were higher than the cohesion value of control. Because the weight and ratio of root were predetermined, there was no significant difference in root

Table 5 Summary of the shear strength parameters and biomass of different planted soils at different values of confining pressure

Species	Confining Stress (kPa)	Max. Shear Stress (kPa)	Root Biomass (g)	Cohesive value *c* (kPa)	Friction angle θ (°)	Moisture Content, *w* (%)
	50	138.0	0.51			19.39 ± 0.27
SC	100	156.5	0.54	102.75	35.86	19.29 ± 0.34
	200	248.9	0.50			19.91 ± 0.12
	50	166.4	0.51			19.79 ± 0.64
TD	100	206	0.53	134.95	34.04	19.39 ± 0.14
	200	268.9	0.53			19.45 ± 0.49
	50	111.1	na			19.38 ± 0.27
Control	100	153.2	na	80.3	34.24	19.42 ± 0.31
	200	214.8	na			19.36 ± 0.34

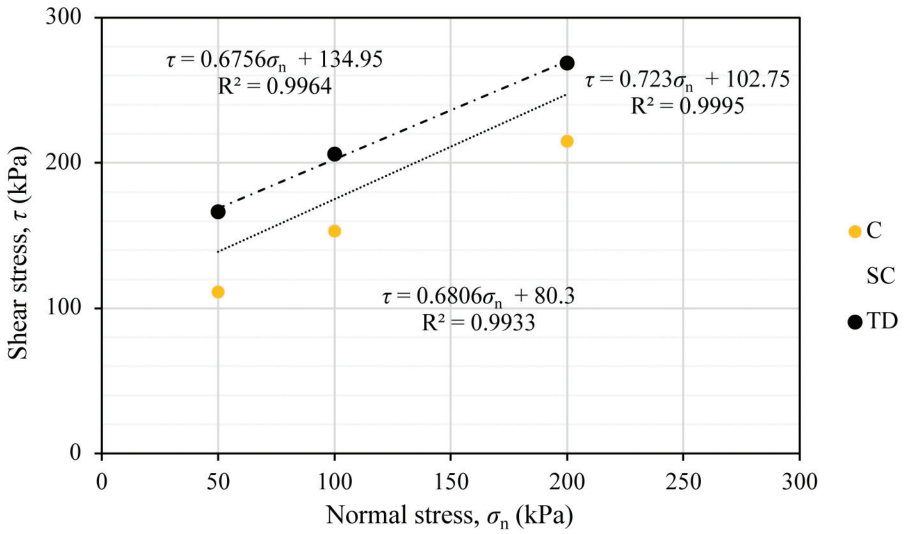


Figure 10 Relationship between shear stress and applied confining stress of control (bare soil) and root-permeated soil samples

biomass between the two species. The range of root biomass for SC and TD species was 0.50-0.54 g and 0.51-0.53g, respectively (Table 5). The internal friction angle, θ for SC species› root-permeated soil, was higher than the control sample. However, the friction angle, θ for TD species, showed a slightly lower value than the control sample. The friction angle for SC was 35.86°, while TD's was 34.04°. The relationship between shear stress and applied confining stress of control (bare soil) and root-permeated soil samples is shown in Figure 10.

DISCUSSION

Plant growth performance

The initial growth characteristic has long been suggested as a good indicator to determine suitable plants for slope bio-engineering (Dorairaj & Osman 2021, Abu Osman et al. 2022). The results demonstrated significant differences in plant growth between the two selected species, with SC surpassing TD in the plant height, leaf number, and leaf area. At the same time, there is no significant difference in chlorophyll content. These variables are critical in the bio-engineering slope application to enhance the plant's photosynthetic efficiency (Dorairaj & Osman 2021). Increased height, leaf number, and chlorophyll content can be attributed to nitrogen, which improves plant growth and height, resulting in more nodes and internodes and, thus, increased leaf production (Hokmalipour & Darbandi 2011, Rabert et al. 2017). Even though the height for both species increased linearly throughout 6 months, there was a significant difference between the two selected species. The variance in height increment across various shrub species during a month can be related to various variables, including genetic variations (Buckley et al. 2019). Different shrub species have unique genetic characteristics that affect how they grow, including responsiveness to environmental signals, maximum height that may be attained, and pace of growth. Due to their genetic makeup, certain species may naturally grow taller and quicker than others (Hamrick 1982, Zu & Schiestl 2017).

This study also showed a significant difference in leaf area between both species. Large leaf area or leaf size results from the interactions of multiple genetic and environmental factors (Gonzalez et al. 2012). According to Ayalew (2014), soil with high nutrient composition and water-holding capacity promoted the development of leaf area, while Gutierrez-Boem & Thomas (2001) indicate that low leaf area was the result of nutrient deficiency, particularly in phosphorus (P). Plant morphology that can provide extensive canopy coverage through leaf area has benefited the hydrology of slope and surface runoff (Liu & Zhao 2020). Plant components of leaves intercept rainwater, stems, and barks, which evaporate into the atmosphere (David et al. 2005, Guevara-Escobar et al. 2007). Subsequently, SC, with a larger leaf area than TD, probably has the potential to prevent soil from being displaced and minimise soil erosion on the ground surface.

Both species were predicted to grow well on the slope because they had high chlorophyll contents in the final months of observation. The amount of chlorophyll in a leaf is one of the key factors influencing plant growth (Ettbeb et al. 2020a). Macro elements, particularly nitrogen, significantly increase the chlorophyll content in plants (Kolodziej 2006, Hokmalipour & Darbandi 2011). Through photosynthesis, chlorophyll captures sunlight and converts it into chemical energy. Plants utilise this energy to synthesise organic substances such as sugars and other nutrients necessary for their development and survival. Plants' chlorophyll concentration directly impacts their growth and establishment on the slope (Li et al. 2018). Healthy chlorophyll levels encourage vigorous root and shoot development, which leads to higher plant establishment and overall slope stabilisation (Razaq et al. 2017). There is no significant difference between the stem diameter purposes. Both have the potential to intercept more rainfall, reducing the kinetic energy of the running water and increasing the surface roughness (Du et al. 2013).

Root characteristics

Root biomass can benefit soil conditions in terms of moisture and structure. The root biomass of SC species is higher than TD species. Thus, SC can withstand better drought conditions and enhance the shear strength of soil. High root biomass increases soil-root contact and absorbs significant water, reducing soil water content (Sainju et al. 2017). Root biomass can also enhance the preferential path of subsurface runoff, improving soil shear strength and reducing slope failure (Osman et al. 2008, Grossnicke 2012). Dense root systems strengthen the soil structure, link particles together, and withstand shear pressures, making slopes less susceptible to landslides and erosion (Lann et al. 2024). Plants with substantial root biomass are highly preferred in bioengineering applications for slope stabilization, as their roots effectively reinforce the soil, enhancing its strength and stability (Punetha et al. 2019, Francini et al. 2021).

The M-shaped root architecture is present in both species. Even though both species had extensive roots at the month of 6 (Figure 3), most of the root matrices were restricted to a depth of 30 cm of soil. Other shrub species that possess an M-shaped type are *M. malabathricum*, *D. suffruticosa* and *L. camara* (Saifuddin & Osman 2016). Even though M-shape has shallow roots, its root system is dense, with outstanding potential as an erosion control plant (Ali 2010). Most M-type roots branch and grow in different directions, mostly in herb species (Li et al. 2017).

Root tensile force and cellulose content

Relationship between root tensile force and cellulose content against diameter

The root tensile force, T_f increased with increasing root diameter following a power law equation. A similar trend has been achieved by previous researchers studying the relationship between root tensile force and root diameter (Vergani et al. 2012, Affaf et al. 2020). Both species had well-distributed data at the lower range of root diameter, but the data scattered away at the higher range of root diameter. At month 3, the species and their maturity constrained the root diameter ranges. Based on species and root diameter, there is a significant variation in root tensile resistance, consistent with other studies (Abdi et al. 2010, Vergani et al. 2012, Schwarz et al. 2013). A power law equation was adopted to represent the scattered tensile force values against root diameter for SC and TD species in months 3 and 6. It suggests that the tensile force is also subjected to the maturity of the root (Genet et al. 2005). Moreover, the growth phase can affect the mechanical properties of root components and the variability of root architecture (Zhang et al. 2018). An excellent root tensile strength, root density, network, and type of root provide better root anchorage against slope instability (Dupuy et al. 2005, Ghestem et al. 2014). It was proposed that TD species with higher root tensile forces could provide more effective slope failure plane interceptions.

The cellulose content of the root also increased with the increase in root diameter. This is consistent with previous research (Lū & Chen 2013, Chao-Bo 2014, Ghestem et al. 2014) however, it contradicts Genet et al. (2005) and Kamchoom et al. (2022). The results' contradiction may be due to different species used, diameter range and root age. This study employed a root age of six months and a root diameter range of 0.1 to 7.5 mm. In addition, even though the same age of root and root diameter have been used, the chemical composition and cellulose content significantly differ (Chao-Bo 2014).

Relationship between root tensile force against cellulose content

Differences in root cellulose is among the primary determinants of root tensile strength (Genet et al. 2005, Alam et al. 2018,). To the best of our knowledge, no study compares the relationship between tensile force and cellulose content. Most researchers applied tensile stress instead of tensile force against the cellulose content (Genet et al. 2005, Chao-Bo 2014, Abdi et al. 2018). The difference between the tensile force and tensile stress is the use of area A (in mm^2) at the failure of and the negative relationship between root tensile stress against cellulose, which is a positive relationship for root tensile force. In our study, the cellulose contents increase with tensile force, coinciding with other researchers (Lū & Chen 2013, Chao-Bo 2014). They found that the root chemical components affecting the tensile strength can differ between plant species. As a result, the size effect of root diameter on tensile strength cannot be explained entirely by changes in root chemical components, probably because of the variety of genetics in plants. Perhaps the root's other inner factors, such as its microstructure, also impact the tensile force (Lū & Chen 2013). TD species recorded higher cellulose content content than SC, resulting in higher tensile force.

Shear strength of the root-permeated soil

The shear strength of the root-permeated soil was higher than that of the unreinforced soil (control), which is consistent with many previous studies (Abdullah et al. 2011, Affaf et al. 2020, Guo et al. 2020, Li et al. 2022). The presence of roots, which interact with the soil at approximately balanced increases in cohesion values and internal friction angles, causes the increase in shear strength. However, roots greatly impacted the cohesiveness parameter (Maffra et al. 2019). Both species showed higher cohesive values in this study than the control sample. However, the friction angle of the TD species is slightly lower than that of the control. Previous studies have shown that fine roots, such as those of most of the root from herb species, can enhance the soil's cohesion but not the soil's friction angle (Liu et al. 2021a, Liu et al. 2021b).

The fact that TD has a higher cohesive value and soil shear strength than SC species suggests that TD species has a potential role in stabilising slopes and slope reinforcement. The root system penetrates the soil mass, reinforcing it, increasing cohesion and, hence, soil shear strength (Ali & Osman 2008). The higher soil strength of the root-permeated soil of TD species than SC species can be attributed to the trends of root tensile force of each species. Several studies also conclude a relationship between root tensile strength and the increase in soil shear strength (De Baets et al. 2008, Mali & Singh 2014).

CONCLUSION

This study assessed the growth performance of roots' physical and chemical composition, including root length, biomass, tensile resistance, cellulose, moisture content, and soil shear strength of remoulded root-permeated soils of two selected species, SC and TD. The result of growth performance shows that SC species have better growth than TD in most variables and are higher in terms of root characteristics, including root length and biomass. The result of root tensile force increasing with increasing diameter for both species and months. The tensile force of both species varies slightly in month 3, possibly due to root diameter variation. However, in month 6, TD species show higher tensile force than SC, suggesting root age influences root mechanical behaviour. The result of cellulose content indicates an increase with increasing diameter. Regression statistical analysis reveals a strong relationship between cellulose content with tensile force. TD species recorded higher cellulose content SC, resulting in higher tensile force. This study also demonstrated that roots could considerably impact soil shear strength. Compared to control samples, which had no plants, the soils with roots displayed higher shear strength. The findings of this investigation were in keeping with the existence of root systems that can mechanically reinforce soil slope. Again, TD displayed higher values of shear strength than SC. Overall, it was suggested that SC species are better to be applied as ground cover for surface erosion protection based on their growth performance. Meanwhile, TD species are better for slope failure prevention due to their higher root tensile force and soil shear strength. It was also suggested that both species have the potential to be applied as bio-material in slope bio-engineering.

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