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# Growth Characteristics and Root Tensile Strength's Variability in Selected Potential Shrub Species for Slope Bio-engineering Applications

(Ciri Pertumbuhan dan Kepelbagaian Kekuatan Tegangan Akar Spesies Renek Terpilih yang Berpotensi bagi Aplikasi Bio-Kejuruteraan Cerun)

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ABSTRACT

Malaysia's tropical climate, alternating wet and dry conditions, and high rainfall contribute to soil erosion issues and landslide risk. Soil bioengineering techniques are among the approaches that can be adopted to tackle these issues and reinforce hillslopes. However, selecting appropriate species for bioengineering applications is crucial. Besides the growth of selected plant species, the root tensile strength also plays an important role in soil structure improvement. This research investigated the growth and root characteristics of four potential shrub species namely *Strobilanthes crispa* (SC), *Tabernaemontana divaricata* (TD), *Pseuderanthemum carruthersii* (PC), and *Hibiscus rosa-sinensis* (HR) as a plant bioengineering material by determining their root tensile force and stress after six months of growth. The soil medium for plant propagation was prepared using a 3:1:1:1 ratio of soil, sand, organic materials, and chicken manure and used for planting the shrub species for 6 months of monitoring. The results show that SC and HR species exhibit superior growth performance in most variables. Root diameter influences mechanical properties of tensile force and stress which can be best presented by power-law equation. TD species has the strongest root for tensile stress, followed by species HR, PC, and SC. All the selected species have potential as biological material in terms of growth performance and root tensile strength. However, further study is essential to evaluate the survivability and root tensile strength of the selected shrubs when implemented on real slopes. This would offer genuine insights into the specific characteristics of their root systems under practical conditions.

Keywords: Bio-engineering; growth; shrubs; tensile strength

ABSTRAK

Malaysia yang beriklim tropika dengan silih berganti antara keadaan basah dan kering dan menerima hujan yang tinggi menyumbang kepada isu hakisan tanah dan risiko tanah runtuh. Teknik biokejuruteraan tanah adalah salah satu pendekatan yang boleh membantu mencegah isu ini dan mengukuhkan cerun bukit. Walau bagaimanapun, pemilihan spesies untuk digunakan sebagai bahan biologi dalam teknik biokejuruteraan adalah tugas yang kritikal. Selain pertumbuhan spesies pokok yang dipilih, kekuatan tegangan akar juga memainkan peranan penting dalam memperbaiki struktur tanah. Penyelidikan ini mengkaji ciri pertumbuhan dan akar empat spesies pokok renek yang berpotensi iaitu *Strobilanthes crispa* (SC), *Tabernaemontana divaricata* (TD), *Pseuderanthemum carruthersii* (PC) dan *Hibiscus rosa-sinensis* (HR) dalam menentukan daya tegangan dan tegasan akar selepas enam bulan pertumbuhan. Medium tanah disediakan menggunakan nisbah 3:1:1:1 tanah, pasir, bahan organik dan tinja ayam sebelum menanam spesies pokok renek selama 6 bulan pemantauan. Hasil kajian menunjukkan spesies SC dan HR menunjukkan prestasi pertumbuhan yang lebih baik dalam kebanyakan parameter yang dikaji. Diameter akar mempengaruhi sifat mekanikal daya tegangan dan tegasan, yang boleh dibentangkan dengan persamaan kuasa. Spesies TD mempunyai akar yang paling kuat dengan daya tegasan paling tinggi, diikuti oleh spesies HR, PC dan SC. Kesemua spesies yang terpilih mempunyai potensi sebagai bahan biologi dari segi prestasi pertumbuhan dan kekuatan tegangan akar. Namun, kajian lanjut diperlukan untuk menilai daya tahan hidup dan kekuatan tegangan akar spesies terpilih apabila dilaksanakan di cerun sebenar. Ini akan memberikan gambaran yang lebih jelas tentang ciri khusus sistem akar dalam keadaan yang lebih praktikal.

Kata kunci: Biokejuruteraan; kekuatan regangan; pokok renek; tumbesaran

## INTRODUCTION

Soil erosion poses significant challenges to both natural ecosystems and human structures resulting in reduced soil fertility, landscape degradation, and increased risks of landslide especially 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, Ushiyama & Sayama 2017). According to Abd Majid (2020), there were 49 cases of landslides reported from 1993 to 2019 resulting in extensive loss of life and property in Malaysia. Furthermore, Malaysia's total economic loss from landslides and erosion was estimated at US$1 billion from 1973 to 2007. The collapse of the 14-storey block A of the Highland Tower in Ulu Klang, Selangor was the most tragic landslide in Malaysia with 48 deaths. 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).

Hard engineering approaches for slope stabilisation solutions are frequently used which include the use of non-biological materials such as concrete structures and retaining walls which are costly, environmentally damaging, aesthetically unattractive and ineffective over time as well as inadaptable to the changing slope environment since they are not dynamic while requiring continual repair and maintenance (Aimee & Normaniza 2014). In recent years, there has been increasing interest in using vegetation-based technologies, known as bio-engineering, for slope stabilisation due to their sustainability, ecological advantages, and possible cost-effectiveness (Dorairaj & Osman 2021). In comparison to civil engineering techniques, the bio-engineering approach has lower capital costs and requires less maintenance because the use of vegetation can self-regenerate to adapt to its surroundings, making it highly sustainable and the local can involve with management and maintenance of the slope (Giupponi et al. 2019). However, the selection of plant species as bio-material is crucial depending on the function that plant species can offer. Principally, the indigenous or native plant species is preferrable and better acclimatized to the local condition and environment, thus they are often deemed sturdy and competitive (Ghestem et al. 2014; Gray & Sotir 1996; Stokes et al. 2009).

Various plant species have been studied for biological material in slope erosion control and slope stability (Ettbeb et al. 2020; Saifuddin & Normaniza 2016; Saifuddin, Osman & Khandaker 2022). Grasses are commonly used for slope erosion control due to their ability to provide surface coverage against rainfall and increase soil shear strength through root networking (Ghosh, Poddar & Chatterjee 2012). Vetiver (*Chrysopogon zizanioides*) is a typical grass species used in slope management to improve eroded regions (Ettbeb et al. 2020). However, grass provides short-term mitigation and necessitates regular maintenance, which are time-consuming and expensive (Coppin & Richards 1990; Dorairaj & Osman 2021). Meanwhile, woody tree, despite having deeper root system, may eventually cause slope problems attribute to the surcharge load and slow growth rate of plant which take time to establish on slope (Reubens et al. 2007; Selby 1993). Among the various types of vegetation, shrub species have garnered attention for their potential contribution to slope stabilization (Comino & Marengo 2010; Mulyono et al. 2018; Stokes et al. 2008). Shrubs are small to medium-sized perennial plants and many studies show shrubs effectively reduce surface erosion and improve slope stability. A few shrubs species have been suggested by Department of Irrigation and Drainage Malaysia (2010) for slope protection purpose such as *Cassia biflora*, *Caesalphina pulcherrima*, *Dillenia suffruticosa*, *Dillenia indica*, *Hymenocallis littoralis*, *Heliconia* spp., *Mussaenda eryhrophylla,* and *Melastoma malabathricum.* A high biodiversity of Malaysia shrub plants provide plentiful of plant species to choose from, giving priority to native plant species to be explored as biological materials in slope bio-engineering approaches. Therefore, native species can be value added, multipurpose function, economically cheaper, easily adaptable, and abundantly available.

In order to perform selection of shrub species for slope bio-engineering, the growth characteristic of selected species should be taken into account as it can be important how quick the slope can be protected against surface runoff or rainfall splash erosions (Reubens et al. 2007). As per suggested by Dorairaj and Osman (2021), the plant should be fast-growing and self-sustainable since a fresh cut slope is bare, infertile and eroded. Therefore, understanding the growth and morphological characteristic of shrub species is essential for evaluating their suitability for slope erosion and protection. Besides that, the tensile strength of plant roots is also an important element in determining the effectiveness of vegetation in slope stabilisation (Masi, Segoni & Tofani 2021; Ni, Leung & Ng 2019; Zhang et al. 2021). A study shown that their fibrous and tap roots of shrubs species, *C. microphylla* and comparable in tensile strength to other tree species (Abdi 2018). Root strength, distribution, and morphology all exert their ability to reinforce soil (Abdi 2018; Abdullah, Osman & Ali 2011; Meng, Zhao & Yang 2020). Stronger root tensile and more evenly distributed plants can better reinforce the soil (Stokes 2002; Yang et al. 2016). Numerous studies has been conducted to evaluate the tensile strength of plant root which resulted the variability of tensile strength depending by many factors such as species and environmental conditions (Abdi 2018; Abdi et al. 2018; Ettbeb et al. 2020; Osman, Abdullah & Abdullah 2011; Vergani, Chiaradia & Bischetti 2012). Genet et al. (2005) and Zhang, Chen and Jiang (2014) stated that the chemical composition such as cellulose and lignin content influence the root tensile strength while Yang et al. (2016) examined the relationship of root tensile with the moisture content of the plant's root. They found that slight loss of root moisture could enhance tensile strength, however too much loss of water associated with weaker capacity for root elongation, and consequently reduce tensile strength. Evaluating and contrasting the mechanical attributes, especially tensile strength, of multiple species offers valuable insights for prioritizing their suitability in bioengineering applications (Watson & Marden 2004). Abdi (2018) found that root tensile strength of shrub species higher than some tree species. Moreover, shrubs can reduce rainwater infiltration and matric suction loss which responsible to improve the shear strength of slope materials (Rahardjo et al. 2014).

In this study, four selected shrub species were used in this study consisting of *Strobilanthes crispa* (SC), *Pseuderanthemum carruthersii* (PC), *Tabernaemontana divaricata* (TD), and *Hibiscus rosa-sinensis* (HR) to evaluate their growth and root tensile strength. A preliminary study found that these plants have a potential use based on their growth performance variables (Aznan et al. 2023). Therefore, the objectives of this study were (a) to determine the growth and root characteristic and (b) to determine the tensile strength of root including the root tensile force and stress variable. To the best of our knowledge, there has been no prior research utilizing these specific species of shrubs as bio-materials for slope protection and erosion mitigation. Following a six-month period post-planting, the growth, root characteristics, and root tensile strength of the plants were observed and further examined in the laboratory.

## MATERIALS AND METHODS

### SITES AND SHRUB SPECIES

The research was carried out in a shaded area at Rumah Tumbuhan, Universiti Kebangsaan Malaysia, situated at Bangi, Selangor. This area is gently undulating terrain, varying in elevation from 18 to 110 meters. The area experiences a humid tropical climate influenced by two monsoons, resulting in bimodal patterns: The southwest and north monsoons, contributing to an average annual rainfall of 2197.20 mm. Temperatures typically range from 21 °C to 32 °C, with evaporation rates varying between 500 and 1000 mm according to the Malaysia Meteorological Department (MMD).

Four selected shrub species were used in this study consisting of *Strobilanthes crispa* (SC), *Pseuderanthemum carruthersii* (PC), *Tabernaemontana divaricata* (TD), and *Hibiscus rosa-sinensis* (HR) (Figure 1). *Strobilanthes crispa* plant is locally known as 'pecah beling' or 'bayam karang' or 'pecah kaca' or 'jin batu' in Malaysia (Arifin 2005). This bush-like plant is attaining a maximum height of 0.5-1.0 m (Figure 1(a)). It can be found on riverbanks or abandoned fields (Arifin 2005). The leaves are oblong-lanceolate, fairly obtuse, and shallowly crenate crispate, with a rough surface coated with small hairs. The upper surface of the leaves is darker green and less rough in comparison to the bottom. This plant's flowers are short, thick panicked spikes and the flowers are yellow (Hamzah & Norfarizan-Hanoon 2013). *Tabernaemontana divaricata* is an evergreen medicinal shrub that grows reasonably quickly. It grows as a garden plant and can be found on roadsides, lawns, and in human settlements. The plant is glabrous, 1.5-2.5 m tall, with silvery grey bark, wrinkled latex that flows when damaged, and fragrant snow-white blooms and the leaves are lustrous, deep green in colour (Ghosh, Poddar & Chatterjee 2021) while *Pseuderanthemum carruthersii* is a soft-wooded shrub that grows up to 1.5 m tall and contains cystoliths on its surface. Its leaves are oblong to elliptical, up to 17 cm long, and often variegated (Dave's Garden 2017). Lastly, *Hibiscus rosa-sinensis* is a small evergreen tree found in shrubs, typically 4 m tall. Its flowers are found on long stalks, measuring about 20 cm wide, and consist of five egg-shaped oval petals. The flowers are typically found in single forms on glossy green, oval leaves with pointed tips and pinnate veins (Missoum 2018). All selected shrubs are native species of Malaysia and Southeast Asia.

### MEDIUM PREPARATION AND PLANTING

Prior to planting all the studied species, a soil medium was prepared with a mixture ratios of 3:1:1:1 consisting of soil, sand, organic materials, and chicken manure. The base soil was collected from the nearby soil slope within the study area. The characteristics of the base soil and the soil medium are detailed in Table 1. Seedlings of the studied shrub species were cultivated in polybags measuring 10 inches by 12 inches that contained approximately 20 drainage holes that distributed evenly at the bottom to ensure proper drainage. Each shrub species consisted of 10 polybags of individual plants, arranged in a randomized complete block design (RCBD). Plant shoots were collected randomly from various sites within Universiti Kebangsaan Malaysia, Bangi, and were cut to a length of 15 cm from mature plants. These shoots were initially treated with root-promoting hormone before being sown in a sand-filled propagation chamber. After spending four weeks in the sand chamber, the saplings were carefully transplanted into polybags. Subsequently, the plants were relocated to a greenhouse and positioned on designated platforms for monitoring purposes. The shrubs received approximately 300±1.5 mL of water twice a day.

### PLANT GROWTH AND ROOT CHARACTERISTICS

Collection of the plant growth parameters and root characteristics of the shrub species was carried out after 6 months of planting. The parameters of plant growth measured were the plant height, number of leaves,

a) *Strobilanthes crispa* (SC) | b) *Tabernaemontana divaricata* (TD) | c) *Pseuderanthemum carruthersii* (PC) | d) *Hibiscus rosa-sinensis* (HR)

FIGURE 1. Four selected shrub species used in this study

TABLE 1. Basic physical and chemical characteristics of base and medium soil

| Parameters | Base soil (N=10) | Medium soil (N=10) | Chicken manure (N=3) |
|---|---|---|---|
| pH | 4.62±0.33 | 7.39±0.17 | 8.83±0.08 |
| Organic ct. (%) | 6.14±1.01 | 8.23±0.32 | 24.17±1.14 |
| Moisture ct. (%) | 29.21±12.56 | 20.45±1.03 | n.a |
| Silt (%) | 30.43±15.19 | 43.46±3.50 | n.a |
| Clay (%) | 31.29±9.65 | 30.59±4.10 | n.a |
| Sand (%) | 38.28±7.75 | 25.95±2.36 | n.a |
| Texture | Clay loam, loam | Sandy clay loam | n.a |
| K (μg/g) | 197.18±39.08 | 5959.84±1096.06 | 33740.89±10492.01 |
| P (μg/g) | 0.49±0.18 | 2.56±0.96 | 7.98±0.04 |
| Total Nitrogen, N (%) | 0.23±0.09 | 0.41±0.07 | 2.01±0.35 |
| TOC (%) | 1.85±0.49 | 4.25±0.46 | 7.75±0.43 |

na- not available
TOC- Total organic carbon

TABLE 2. Diameter, tensile force and tensile force-diameter relationship

| Species | Diameter (mm) | | Tensile force, $T_f$ (N) | | $T_f$-D relationship | | |
|---|---|---|---|---|---|---|---|
| | Range | Mean | Range | Mean | $\alpha$ | $\beta$ | $R^2$ |
| *Strobilanthes crispa* | 0.3 - 6.68 | 2.39 ± 1.81 | 1.07-361.72 | 58.07 | 7.56 | 1.49 | 0.8567 |
| *Tabernaemontana divaricata* | 0.28- 3.69 | 1.81 ± 1.11 | 1.94- 152.43 | 46.24 | 12.28 | 1.75 | 0.8380 |
| *Pseuderanthemum carruthersii* | 0.43 - 4.66 | 1.71 ± 1.07 | 1.89 - 112.63 | 29.46 | 9.45 | 1.66 | 0.8522 |
| *Hibiscus rosa-sinensis* | 0.47 - 6.61 | 2.02 ± 1.63 | 1.45 - 165.40 | 43.27 | 13.39 | 1.44 | 0.8729 |

chlorophyll content, root length, and root biomass. 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 is determined using a portable chlorophyll meter (SPAD-502 Minolta Co. Ltd).

In the characterization of root variables, 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 measurement of root length was carried out from the upper part of the primary root until the end of the root cap using a universal measuring tape. The root biomass was determined by placing the root sample in the oven at 60 °C for 48 h. Then, the root samples were repeatedly weighed until the weight became constant.

## ROOT TENSILE TEST

Root tensile strength was determined following the established techniques applied by previous researchers (Ettbeb et al. 2020; Vergani, Chiaradia & Bischetti 2012). Root specimens were collected from the polybags using the same methods applied for root biomass determination. Individual root tensile strength was performed using a Universal Testing Machine (UTM) with a 50 N capacity (Testometric, Model M350-10CT, United Kingdom). A total of 40 root samples for each species were collected and these samples were cut into 10 cm segments and weighed, with a total of 40 samples used per species. The root's diameter was measured at three different points along its length using a digital vernier caliper. To ensure a secure grip on the root's ends and reduce the risk of slippage during testing, sandpaper was applied to wrap the root's tips (approximately 2 cm from the edge) before clamping. The upper and lower wedge grips were carefully fastened to the tips of the root to securely hold during the testing process (ASTM 1975). The root was vertically pulled upwards at the rate of 5 mm/min until the root failed as recorded as maximum extensive or tensile force, $T_f$ (unit in Newton, *N*). Any tests in which the roots broke near or at the point of clamping were deemed invalid. After testing, the root samples were encased in plastic film to preserve their moisture content for subsequent laboratory analysis. The relationship of root tensile force ($T_f$)-diameter (mm) is presented using the power law Equation (1) as shown herewith.

$$T_f = \alpha . d^{\beta} \qquad (1)$$

where $T_f$ is tensile force (N); $\alpha$ is the proportionality constant; $d$ is the average root diameter (mm) and $\beta$ is

The maximum tensile force, $T_f$ at the point of rupture corresponds to tensile stress, $T_s$ (MPa) which is determined by dividing the breaking force to the cross-sectional area of the tested root (mm$^2$), as shown in Equation (2). It is assumed that the diameter of the root at the point of failure has not changed throughout the test.

$$T_s = \frac{4F_{max}}{\pi d^2} \qquad (2)$$

where $T_s$ is tensile strength (MPa); $F_{max}$ is the maximum force at rapture point (N); and $d$ is the average root diameter (mm).

## STATISTICAL ANALYSIS

The data were analyzed using the IBM SPSS version 26.0. To assess and compare root tensile force and resistance values across different species, while considering diameter as a covariate factor, the statistical method employed was ANCOVA (Abdi et al. 2018; Vergani, Chiaradia & Bischetti 2012). The normality of the data was initially determined using the Kolmogorov–Smirnov test before conducting the ANCOVA analysis. Given the non-normal distribution of the data, particularly in terms of force and stress values, a log transformation was applied to achieve homogeneous residual variance and ensure the normality of the data (Abdi et al. 2018). Subsequently, Tukey's test multiple comparison was utilized to compare the mean values of plant growth, root biomass and root length parameters among the studied species.

# RESULTS

## GROWTH AND ROOT CHARACTERISTIC

After 6 months of growth, the plant heights shows that the HR species has the greatest height, followed by SC, PC, and TD, with mean heights of 157.66, 143.18, 95.62, and 82.18 cm, respectively. However, statistical analysis, Tukey's test multiple comparison indicates no significant difference between HR and SC heights, as well as TD and PC heights. In terms of the number of leaves, HR and SC exhibit higher abundance compared to PC, and statistical analysis shows no significant difference ($p>0.05$) between SC, TD, and HR, suggesting robust growth for these three species. Regarding chlorophyll content, no significant differences ($p>0.05$) are found among the selected species, indicating uniformly high chlorophyll levels except for PC which recorded the lowest value. In term of root characteristics, SC stands out with the longest root length (81.5 cm), followed by PC (75.6 cm), HR (73.74 cm), and TD (65.83 cm). The trend is consistent for root biomass, where SC shows the highest mean value at 47.52 g.

## ROOT TENSILE FORCE

High variability in diameter and force was evident both among and within a particular species, as illustrated in Table 2. Root diameters of the SC, TD, PC, and HR species range from 0.30 mm to 6.68 mm, 0.28 mm to 3.69 mm, 0.43 mm to 4.66 mm, and 0.47 mm to 6.61 mm, respectively, after 6 months of growth. The results of root tensile force tests of the studied species are also shown in Table 2. The peak tensile force, $T_f$, and mean value for SC, TD, PC, and HR species were 1.07-361.72 N with a mean of 58.07 N, 1.94 - 152.43 with a mean of 46.24, 1.89 - 112.63 with a mean of 29.46 and 1.45 - 165.40 with mean of 43.27, respectively, where SC recorded the highest value of tensile force followed by TD, HR, and PC. For the $T_f$-D relationship, the root tensile force, $T_f$ increased with increasing root diameter by a power law equation for all species (Figure 2) 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 0.8380 to 0.8567 (Table 2) which indicates as good correlation. Furthermore, there was a rise in root tensile force corresponding to an increase in root diameter, following a power law pattern across the three species (Figure 3). The results of the ANCOVA showed that mean root tensile forces were significantly different among species ($F=10.838$, $p=0.001$) with regards to root diameter as a covariate factor ($F=92.503$, $p=0.000$).

### ROOT TENSILE STRESS

Tensile stress was employed to assess the species with the highest tensile strength, as it provides a clearer trend across all species than tensile force, enabling a more distinct comparison between them. In the examination of four plant species, *Strobilanthes crispa, Tabernaemontana divaricata, Pseuderanthemum carruthersii,* and *Hibiscus rosa-sinensis*—based on their diameter, tensile stress ($T_s$), and the $T_s$-D relationship, distinctive trends and variations are evident. *Strobilanthes crispa* tensile stress ranges from 2.02 to 86.75 MPa, with a mean of 12.42 ± 13.65 MPa. The $T_s$-D relationship is characterized by the parameters $\alpha$ and $\beta$, with values of 9.68 and -0.48, respectively, resulting in an $R^2$ value of 0.5613. *Tabernaemontana divaricata* exhibits a $T_s$ range of 6.67 to 48.26 MPa, with a mean of 16.15 ± 8.53 MPa. The $T_s$-D relationship is defined by the parameters a and b as 15.64 and -0.25, yielding an $R^2$ value of 0.1826. *Pseuderanthemum carruthersii* has recorded $T_s$ range of 2.89 to 39.18 MPa (mean: 12.66 ± 7.59 MPa), with the $T_s$-D relationship characterized by parameters $\alpha$ and $\beta$, as 12.03 and -0.34, resulting in an $R^2$ value of 0.1259. Lastly, *Hibiscus rosa-sinensis* displays a diameter range of 0.47 to 6.61 mm (mean: 2.02 ± 1.63 mm) and a *Ts* range of 3.83 to 31.34 MPa (mean: 15.54 ± 7.54 MPa). The $T_s$-D relationship is defined by parameters $\alpha$ and $\beta$ as 17.05 and -0.56, yielding an $R^2$ value of 0.3569.

These results in notable differences among the species, both in terms of their diameter and tensile stress characteristics. *Strobilanthes crispa* exhibits the highest mean tensile stress at 12.42 ± 13.65 MPa. In contrast, *Pseuderanthemum carruthersii* has the narrowest diameter range (0.43 to 4.66 mm) and the lowest mean tensile stress at 12.66 ± 7.59 MPa. The *Ts*-D relationships also highlight distinctions, with *Strobilanthes crispa* and *Hibiscus rosa-sinensis* showing negative slopes, indicating a decreasing trend in tensile stress with increasing root's diameter. Conversely, *Tabernaemontana divaricata* and *Pseuderanthemum carruthersii* have shallower negative slopes, suggesting less pronounced decreases in tensile stress with increasing diameter. The highest $R^2$ value is observed in *Strobilanthes crispa*, signifying a relatively better fit for the $T_s$-D relationship compared to the other species (Table 3).

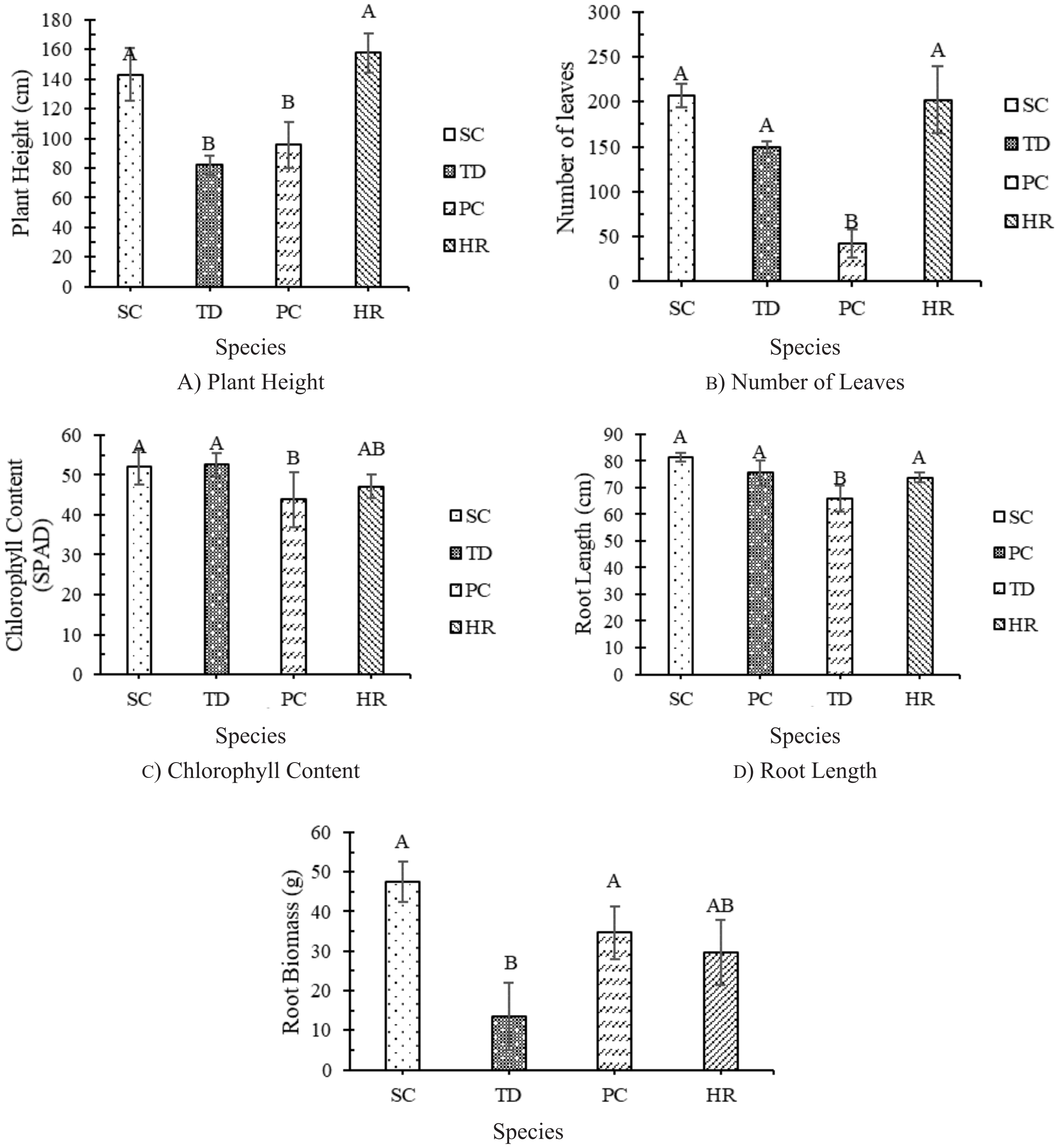
The results of the ANCOVA showed that mean root tensile stress was significantly different among species ($F=2.960$, $p=0.035$) with regards to root diameter as a covariate factor ($F=11.593$, $p=0.000$). Conversely, root tensile strength exhibited a decline with the augmentation of root diameter, also conforming to a power law relationship (Figure 4).

## DISCUSSION

### GROWTH AND ROOT CHARACTERISTICS

Our results show that there are significant differences in growth parameters among species. Most of the parameters such as plant height, number of leaves, and root biomass were significantly higher for SC and HR than PC and TD. However, there is not much difference between all species in leaves chlorophyll content and root length. The growth performance of plant species plays a crucial role in the restoration of landslide-prone areas and slope bioengineering aiming to improve the photosynthetic efficiency of plants (Pang et al. 2018). The height, leaf number, and chlorophyll content are linked to nitrogen availability, known for its positive impact on overall plant growth and height. This, in turn, also leads to the development of more nodes and internodes, ultimately resulting in an increased production of leaves (Rabert et al. 2017). In conjunction with this study, higher production of leaves recorded for SC and HR causes the bigger plant canopy and potentially lower the effective precipitation and erosion effect on a slope's surface by intercepting rainfall (Zhao et al. 2019). According to Seitz and Escobedo (2014), rainfall interception varies with plant type, plant canopy and planting density. In addition, the aboveground biomass including stem and leaves acts as a buffer that reduces the velocity of raindrops hence reducing its kinetic energy and preventing splash erosion by reducing big raindrops into smaller raindrops (Duchemin & Hogue 2009).

Genetic structure and leaf structure plays an important role in differentiating chlorophyll levels of plants (Güney et al. 2020). In this study, there is no significant different of chlorophyll content in SC, TD and HR species while significant different in PC. The higher amount in that species because the leaves of these plants are dark green in color (Tepe et al. 2002) while PC leaves are yellowish green in color that making the chlorophyll content low. Chlorophyll levels encourage




A) Plant Height

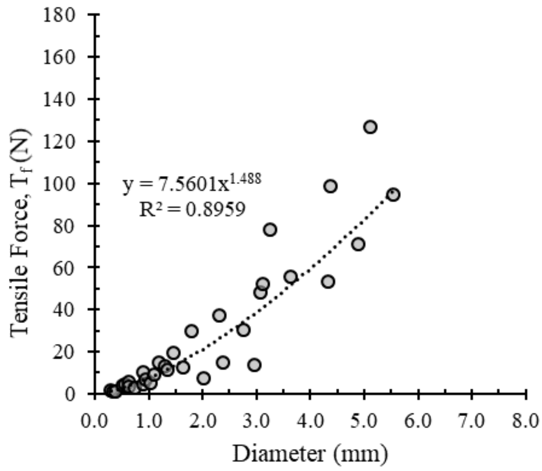
B) Number of Leaves

C) Chlorophyll Content

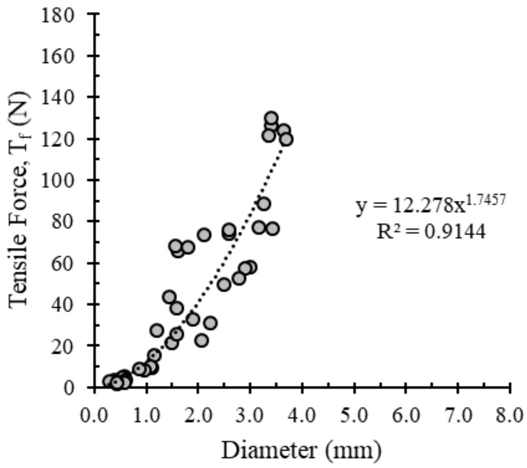
D) Root Length

E) Root Biomass

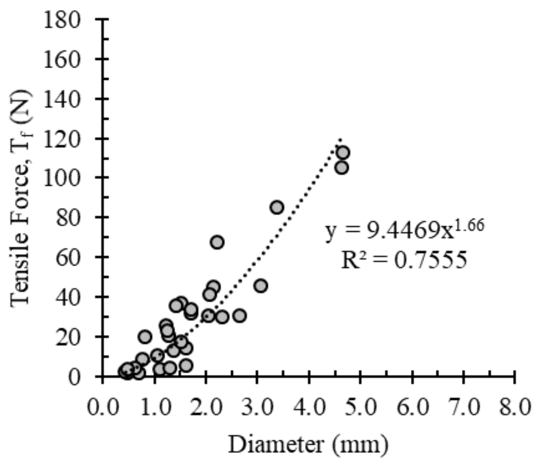
FIGURE 2. Plant growth and root characteristics. Same alphabet is not significant different ($p<0.05$)



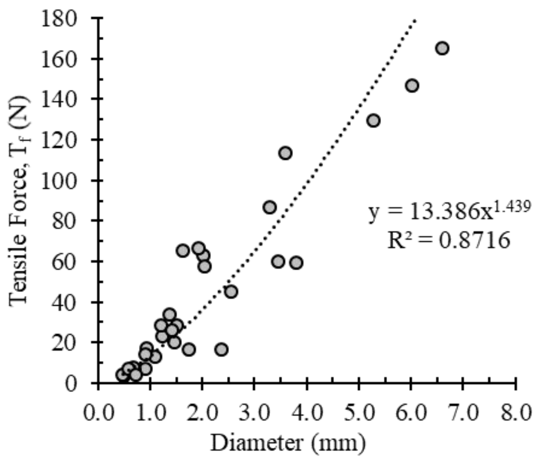

a) Strobilanthes crispa




b) Tabernaemontana divaricata




c) Pseuderanthemum carruthersii




d) Hibiscus rosa-sinensis

FIGURE 3. Tensile force against root diameter

TABLE 3. Diameter, tensile stress and tensile stress-diameter relationship

| Species | Diameter (mm) | | Tensile stress, $T_s$(N) | | $T_sD$ relationship | | |
|---|---|---|---|---|---|---|---|
| | Range | Mean | Range | Mean | $\alpha$ | $\beta$ | $R^2$ |
| *Strobilanthes crispa* | 0.3 - 6.68 | 2.39 ± 1.81 | 2.02 - 86.75 | 12.42 ± 13.65 | 9.68 | -0.48 | 0.5613 |
| *Tabernaemontana divaricata* | 0.28- 3.69 | 1.81 ± 1.11 | 6.67 - 48.26 | 16.15 ± 8.53 | 15.64 | -0.25 | 0.1826 |
| *Pseuderanthemum carruthersii* | 0.43 - 4.66 | 1.71 ± 1.07 | 2.89 - 39.18 | 12.66 ± 7.59 | 12.03 | -0.34 | 0.1259 |
| *Hibiscus rosa-sinensis* | 0.47 - 6.61 | 2.02 ± 1.63 | 3.83 - 31.34 | 15.54 ± 7.54 | 17.05 | -0.56 | 0.3569 |

vigorous root and shoot development, which leads to greater plant establishment and overall slope stabilisation (Li et al. 2018; Razaq et al. 2017).

SC species have significantly greater root biomass than other species, suggested that SC has higher drought tolerance ability (Lee, Shih & Hsu 2023). Grossnickle (2012) indicated that greater root biomass equates to a larger root absorptive surface and greater drought tolerance capability. Moreover, it is well-acknowledged that the movement of water through soil medium toward plant tissues and water absorption are associated with the presence of root biomass in the soil (Cairns et al. 1997; Tognetti et al. 2009). Kang et al. (2002) also reported that more root biomass is attributed to a higher chance of better water uptake by plant roots. The depletion of soil moisture because of root absorption induces the soils to crack (Mulyono et al. 2018) thus the rate of infiltration is increased in presence of vegetation which then reduces run-off as more water is removed by evapotranspiration from the soil (Tamin & Hashim 2008).

Considering these findings, the overall growth performance suggests that SC is exhibiting better growth compared to the other species, particularly in terms of root length and biomass. However, it's important to note that the absence of significant differences in certain parameters, such as plant height and chlorophyll content, indicates that HR and SC have comparable growth in those aspects.

## ROOT TENSILE FORCE AND STRESS

Root tensile force and stress are crucial factors that determine soil reinforcement and tree anchorage, and they give important information on employing living materials in bioengineering techniques (Abdi 2018; Lee et al. 2020). Consistent with prior studies, our research shows substantial variability in root tensile force and resistance, dependent on both species and root diameter (Abdi 2018; Chen et al. 2022; Vergani, Chiaradia & Bischetti 2012). The root tensile force exhibited a strong relationship with root diameter where tensile force increases with increasing of root diameter, as depicted by the power law equation. This observed trend aligns with findings from earlier studies investigating the correlation between root tensile force and root diameter (Ali Rahman et al. 2021; Ettbeb et al. 2020; Osman, Abdullah & Abdullah 2011). While tensile stress decreased with increasing root diameter which is in line with the previous root studies (De Baets et al. 2008; Genet et al. 2005; Tosi 2007). However, the relationship ($T_s$-D) is not significantly strong except for SC species ($R^2$=0.56). Given the number of factors other than root diameter that influence *Ts*, the lack of a relationship between root tensile stress and root diameter for TD, PC, and HR is not surprising. Root tensile stress variability can be attributed to variations in root age and growth rate, which are influenced by variations in soil moisture content, soil texture, and nutrient status (De Baets et al. 2008; Genet et al. 2005). De Baets et al. (2008) also found a poor correlation between tensile stress and root diameter due to the inclusion of root bark which is probably the same reason in this study.

To date, no study has used the same species for tensile test, thus comparison with the current results is difficult. Besides, in comparison with other types of shrub's species and plant also sensitive to the diameter range tested and the number of samples (Zhang, Chen & Jiang 2014). Mean tensile force of shrubs, *Crataegus microphylla* and *Mespilus germanica* recorded by Abdi (2018) was 135.86±100.06 and 143.25±123.94, respectively, in diameter range from 0.4 to 5.9 mm. Meanwhile, mean tensile force recorded for *D. suffruticosa* and *M. malabathricum* were 670.35 and 406.05 N, respectively (Saifuddin, Osman & Khandaker 2022). Based on this comparison, the tensile force value recorded for selected species in this study is considered low. In term of mean tensile stress for selected study (*S. crispa* 12.42 ± 13.65 MPa, *T. divaricata* 16.15 ± 8.53, *P. carruthersii* 12.66 ± 7.59, *H. rosa-sinensis* 15.54 ± 7.54) also indicates the lower result compare to other well-known slope shrubs species, *D. suffruticosa* (47.15±2 MPa) and *M. malabathricum* (29.72±1 MPa) (Saifuddin, Osman & Khandaker 2022), however, almost similar to *L. camara* (<25 MPa) (Saifuddin & Normaniza 2016).

The low values of tensile force and stress are likely due to the species being planted in polybags rather than on an actual slope as the discussions by previous studies that site topography and other environmental site condition

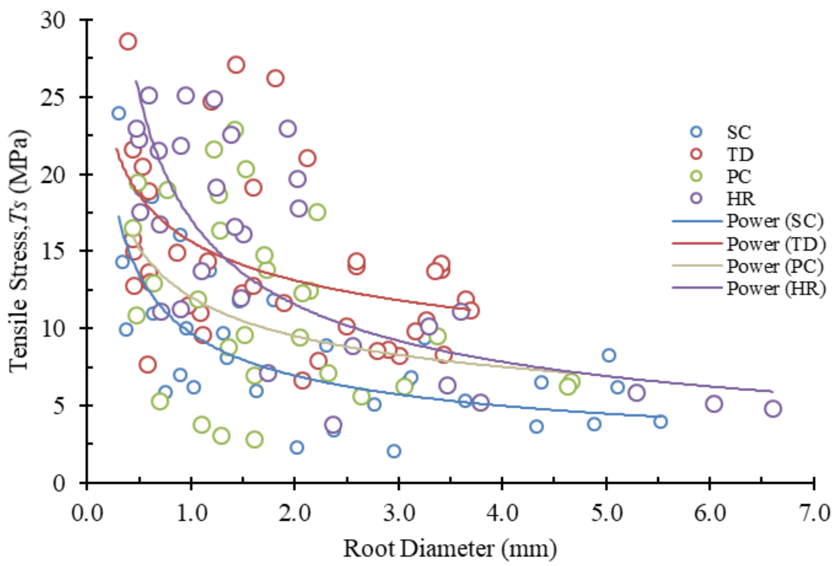



FIGURE 4. Root tensile stress against root diameter

such as soil properties, drainage and external stress, affect strongly the root biomechanical properties (Chen et al. 2022; Genet et al. 2005; Hales et al. 2009). Hales et al. (2009) demonstrated that the plants located on slopes possessed higher roots tensile strength compared to those in low-land area, attributing this difference to alterations in the chemical compositions of the roots while Chen et al. (2022) indicated that slope position significantly affected the tensile properties for *O. bodinier* species. Plant root tissue under greater gravitational or mechanical stress has a lower lignin to cellulose ratio compared to non-stressed plant root tissue. This phenomenon, termed tension wood, generalizes across many angiosperm tree species and results in localized accumulation of cellulose which imparts higher root tensile strengths (Hales et al. 2009). Hence, the observed lower values in tensile force and stress for the selected studied species are likely attributed to the fact that they were planted in polybags. In this setting, their roots were not subjected to mechanical or gravitational stress, which typically influences the root chemical composition and, consequently, results in lower tensile strength. Other than that, the influence of cellulose and lignin contents on tensile strength has been comprehensively studied by Genet et al. (2005) and Zhang, Chen and Jiang (2014) where, they found that the thinner root diameter attributed to stronger tensile strength as a result of the cellulose and lignin contents which subsequently add to slope stability. Ye et al. (2017) attributed this relationship to the chemical composition of root tissues and showed that tensile force was significantly negatively correlated with cellulose and holocellulose and significantly positively correlated with lignin and the lignin: cellulose ratio, while for tensile stress, opposite correlations have been reported.

Comparisons of force–diameter and stress-diameter relationships for different species (ANCOVA) confirmed that there are statistically significant differences in root tensile force and stress between species. Based on the finding, the strongest root was arranged by TD>HR>PC>SC based on tensile stress variables where TD species has a strongest root while SC is the weakest root. Even though the mean tensile stress for SC shows an acceptable high value (Table 3), based on the trend as illustrated in Figure 4, SC indicates as the weakest tensile among the studies species probably due to diameter variation, genetic and environmental factors, as well as the composition of the root system tissue (Chiaradia, Vergani & Bischetti 2016; De Baets et al. 2008; Genet et al. 2005; Ye et al. 2017). Plant species with high tensile strength in roots represent enhanced resilience against tensional forces that occur during slope failure (Stokes et al. 2009). Plant roots play a pivotal role in intercepting potential failure planes by binding the ground/soil surface and the failure plane together (Ghestem et al. 2014). Augmenting the stability of a soil slope involves factors like root density, network, and types, all contributing to improve root anchorage (Dupuy, Fourcaud & Stokes 2005). Furthermore, the presence of heightened root tensile resistance leads to a greater density of plant on the slope, delivering supplementary resistance against overturning (Coppin & Richards 1990; Osman, Abdullah & Abdullah 2011).

## CONCLUSIONS

We investigated the growth and root mechanical behavior of four species of selected shrubs to be applied as biomaterial for bioengineering. Our results show that there are significant differences in growth parameters among species. Most of the parameters such as plant height, number of leaves, and root biomass were significantly higher for SC and HR than PC and TD. The mechanical properties of roots are influenced by their diameter, and power law relationships effectively describe the relationship between root diameter and both force and however only SC species for tensile stress diameter function. Root tensile force and stress differed significantly among species where TD species has a strongest root follow by HR, PC and SC. In comparison, the mean tensile force and stress of all studied species are considered lower than literature. It is important to acknowledge that each species exhibits potential characteristics in terms of growth performance and tensile strength. Further research is essential to evaluate the survivability and root tensile strength of the selected shrubs when implemented on real slopes. The field growth performance of the selected shrubs should be monitored for longer time frames and root sample for tensile strength test should be taken gradually from the field plot. This would offer genuine insights into the specific characteristics of their root systems under practical conditions.

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