JUATIKA
JURNAL AGRONOMI TANAMAN TROPIKA
VOL. 8 No. 1 January 2026

DOI :https://doi.org/10.36378/juatika.v8i1.5005
eissn 2656-1727
pissn 2684-785X
pages : 240 – 248

RESEARCH ARTICLE **Open Access**

Architecture System Root and the Tensile Strength *of Piper sarmentosum* and Pandanus *amaryllifolius* for Application in Biotechnology on Land Slope Tropical

Yahya Rizki Abdillah[1,]*, Taufiq Caesar Hidayat[1], Intan Nadhirah Masri[2]

Abstract

Erosion and slope instability are major causes of land degradation in tropical areas. This research aims to evaluate the root architecture and tensile strength of *Piper sarmentosum* (Kaduk) and Pandanus amaryllifolius (Pandan) as candidate vegetation for slope stabilization using biotechnology. Root samples were analyzed using the WinRHIZO software to characterize root morphology, while tensile strength was tested with a digital push-pull meter (AMF-300) using the equation $\sigma = 4F/\pi d^2$. The results show significant differences between the two species. Kaduk has a fibrous root system (type H) with an average fine root diameter of 0.65 ± 0.02 mm and a length-to-volume ratio of 600.38 ± 384.87 cm/m^3, which effectively increases soil surface cohesion. Pandan has a very thick adventitious root system (type VH) with an average root diameter of 3.74 ± 0.53 mm and a large surface area of 155.75 ± 0.22 cm^2, functioning as a strong anchor to stabilize lower soil layers. Both species exhibit a strong correlation between root diameter and tensile strength, with Kaduk showing higher tensile stress (R^2 = 0.8652) and Pandan demonstrating greater total withdrawal force. The excellent results indicate that combining these two species can double slope stability compared to using either species alone, making this an effective and sustainable vegetative solution for tropical land management. It is recommended to plant Kaduk on the upper slope to strengthen the soil surface and Pandan in the middle to lower slope sections to serve as a structural anchor, thereby optimizing the natural erosion-retention system.

Keywords: Anchorage Roots, Biotechnology Soil, Cohesion Surface, Conservation Land, Control Erosion

1. Introduction

Soil erosion is the process of loosening, detaching, and transporting soil particles, primarily from the surface layer. This process is driven by external forces such as rainfall, surface runoff, wind, ice or glaciers, and gravity. Erosion can be classified into two main types based on its causes: natural erosion, which occurs as part of the soil formation process, and anthropogenic erosion, which results from human activities. Anthropogenic erosion is generally more severe, often stemming from unsustainable land development or poor agricultural practices that neglect soil conservation principles (Model & Eisenberg, 2020).

Erosion is one of the biggest challenges in land management because it can damage soil structure and reduce fertility. Erosion removes the topsoil layer, which contains the dominant nutrients and influences the soil's physical and chemical characteristics. This process reduces infiltration capacity, organic material content, and nutrient availability. Consequently, land productivity declines significantly, negatively affecting the long-term sustainability of agricultural systems. In addition to its biophysical impacts, erosion also has social and economic consequences. In severe cases, when erosion leads to landslides, the damage can extend to infrastructure, agricultural land, and even pose a threat to human life, especially for communities living nearby (Nurhayati & Nugraha, 2012). From this, an effective conservation strategy is needed to reduce erosion's impact. One of them, with an approach vegetative, has proven capable of increasing land stability and strengthening slope structure

---

*Correspondence: yahyarizky270@gmail.com
1) Universitas Sumatera Utara - Jl. Dr. A. Sofyan No. 3, Padang Bulan, Kec. Medan Baru, Medan, 20155, Sumatera Utara, Indonesia
2) Soil Science, Water and Fertilizer Research Centre - Malaysian Agricultural Research and Development Institute, Malaysia

(Stokes et al., 2009). With this, choose the right plants as a step toward providing a solution based on sustainable practices.

Selecting appropriate plant species for land conservation requires careful consideration of several key factors, including root system strength, the capacity of the leaf canopy to absorb rain energy, and tolerance to local environmental conditions such as slope gradient, soil type, and rainfall intensity. Native species are often preferred because they are better adapted to local conditions and can offer dual benefits: production and conservation. Utilizing local vegetation that not only supports farmers' livelihoods but also stabilizes the soil ensures a balance between community income generation and ecosystem sustainability. By reducing erosion, maintaining soil fertility, and strengthening root systems, these plants play a vital role in stabilizing and protecting the land environment (Revika, 2022).

Among species with potential native status, *Piper sarmentosum* (locally known as kaduk) offers significant economic and ecological value. Kaduk can be applied commercially in the food, functional, and pharmaceutical industries. In Malaysia, kaduk Lots Are used in traditional treatments and health supplements because of their bioactive compounds and distinctive aroma (Ibrahim & Azman, 2019). Likewise, Pandanus amaryllifolius (pandan) has significant cultural and economic value. In general, the food industry uses pandan leaves as natural colorings and flavorings, with green pigments derived from chlorophyll and a distinctive aroma that enriches the product's sensory quality (Rachmawati & Ramdanawati, 2020). Several studies have previously examined potential plants for stabilizing slopes, such as Baets et al. (2008), who assessed the contribution of root pull strength of Mediterranean plants to improve land cohesion, and Aznan et al. (2025), who evaluated root pull strength variability in shrub species for bioengineering applications. However, research focused on woody or shrubby plants, not on herbaceous plants local to the area that have marked economic value. This research presents novelty by analyzing the architectural system's roots and strength, and by identifying tree species worth commercializing — kaduk and pandan that have not been previously evaluated in the context of biotechnology in the tropics. This approach can be an understanding of local utilization, a solution-based approach that not only supports conservation but also provides economic benefits for the farmer.

However, beyond their economic role, *Piper sarmentosum* and Pandanus amaryllifolius have distinctive root morphologies that can provide valuable functions in biotechnology and slope stabilization. Vegetative or biotechnological approaches use plant roots as natural reinforcing materials that improve slope stability, restore degraded areas, and reduce reliance on conventional civil engineering structures. The mechanical effectiveness of these systems depends on the architecture, distribution, and tensile strength of plant roots (Zhang et al., 2014). Fine fibrous roots increase surface cohesion, while coarse, vertically oriented roots provide deeper anchorage and shear resistance (Baets et al., 2008).

Root system architecture (RSA) integrates morphological, geometric, and topological characteristics that determine how plants explore the soil and interact with hydrological and mechanical processes. Root architectures vary, including taproot (type A), heart-shaped (type B), horizontal or fibrous (type H), and mixed vertical-horizontal (type VH) forms, each contributing uniquely to soil reinforcement. Combining species with complementary root systems enhances surface cohesion and deep anchorage, resulting in an effective nature-based slope stabilization strategy (Stokes et al., 2009).

Therefore, this study aims to (i) characterize the morphology and architecture of the roots of *Piper sarmentosum* and Pandanus amaryllifolius using image-based analysis, (ii) determine root tensile strength and its relationship to root diameter, and (iii) evaluate their potential as native herbaceous species for biotechnology and slope stabilization applications.

2. Material and Methods

2.1. Place and Time

Study This was carried out in the laboratory, Steel Technology, Research Center, Soil, Water, and Steel Science at the Institute of Research and Progress, Malaysian Agriculture (MARDI), Serdang, Selangor, Malaysia (2.983392.101.700652), and is at an altitude of ± 36 meters above sea level (masl). The activities study takes place from September 23, 2025, to October 3, 2025.

2.2. Root Sample Preparation and WinRHIZ O Analysis

Root samples of *Piper sarmentosum* (Kaduk) and Pandanus amaryllifolius (Pandan) were obtained from MARDIBB Shop, Serdang, Selangor, Malaysia. Three Kaduk plants and two Pandan plants, each grown in polybags for approximately 2–3 months, were transported to Block A8, Research Center for Soil, Water, and Fertilizer Sciences, MARDI, for sample preparation. All root systems were carefully removed from the polybags, and the potting media was gently removed by washing with tap water, then rinsing with distilled water to ensure complete removal of adhering soil particles. All intact root systems were kept moist and immediately transported to the Bioprocess Laboratory (Block A15) for image analysis.

WinRHIZO software Arabidopsis 2022a (Regent Instruments Inc., Canada), combined with an EPSON Expression 12000XL optical scanner operated through EPSON Scan 2 software (version 6.5.29.31650). Scanning and analysis followed the protocol recommended by Bouma et al . (2000) and Regent Instruments (2024), which specifies (i) a scanning resolution of 400 dpi, (ii) a sample density below 0.5 mm root (mm^{-2}), and (iii) the use of an automatic threshold option to optimize contrast and minimize errors caused by overlapping roots. The roots were arranged in a single layer on a waterproof scanning tray with a thin layer of water to prevent ghosting and ensure perfect contact with the glass surface. No background objects were present between the roots and the exposure cover.

Images were acquired in black-and-white mode, and WinRHIZO automatically skeletonized all visible roots. The software quantified total and fine root parameters, including total length, projected area, surface area, average diameter, root volume, number of tips, branching, and intersections. The resulting data were exported as ASCII text files and processed in Microsoft Excel for descriptive statistics (mean ± standard deviation). Representative scans of both species are shown in Figures 1 and 2.

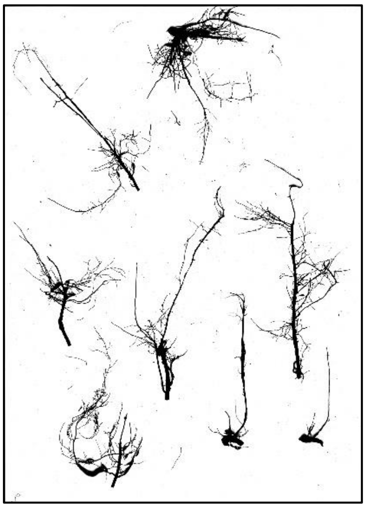


Figure 1. Results scanning Stir

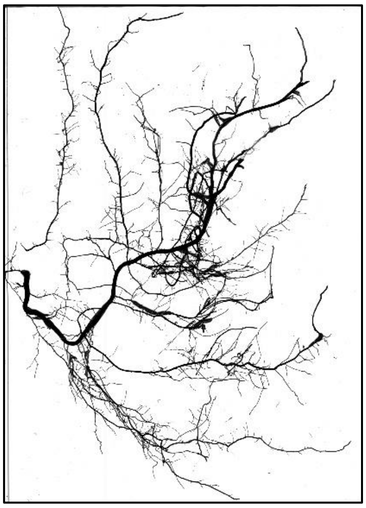


Figure 2. Pandan scan results

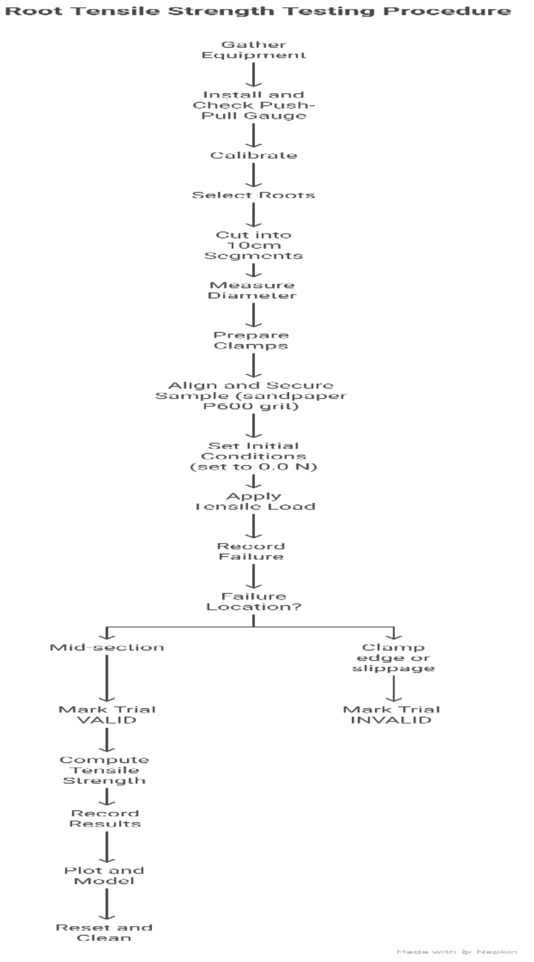
2.3. Determination of Root Tensile Strength

Root tensile tests were conducted in the Soil Chemistry Laboratory (Block A8) using a digital push-pull meter (AMF-300, China) mounted on a manual test stand (Figure X). The AMF-300 has a measuring range of 0–300 N (≈30 kg), with an accuracy of ±1% and a load resolution of 0.1 N. The instrument is powered by two 1.5 V AAA batteries and is zero-calibrated before each experiment. The test configuration and procedure were adapted from Wang et al. (2020), who used a similar handheld tensile instrument to assess the mechanical behavior of straight roots under axial loading.

Figure 3. Settings push -pull tester for strength pull root

Figure 4. The sample root is broken in the middle

Pieces of root *Piper sarmentosum* (Kaduk) and Pandanus amaryllifolius (Pandan), straight and undamaged, were chosen from system roots that had been washed and cut, and the segments were 10 cm long. Root diameter was measured at three points (base, middle, and end) using a digital vernier caliper (precision ±0.01 mm), and the average was used for subsequent calculations. Every sample root is installed horizontally between two clamp metals, equipped with fine sandpaper (P600) to prevent slip. The clamp tightened evenly to ensure axial alignment and minimize local concentration voltage. Tensile load is applied gradually, with the handle rotated at a uniform speed until the root breaks. The implementation diagram study is as follows:



For control quality, samples broken at the edge clamp are not included; only broken samples at the middle section are considered valid for data analysis. Maximum pull force (F, N) at break, noted directly from the digital meter. Power tensile (σ, MPa) each root, then counted based on the equality materials mechanics (Wang et al., 2020) :

$$=\frac{4F}{\pi d^2}$$

where F is the style break (N), and d is the average root diameter (mm).

Strength value: The calculated tensile strength (in MPa) is plotted against root diameter. For the regression law rank, which describes the correlation between voltage, common tensile, and diameter, the root fiber occurs. All data were processed in Microsoft Excel 2013, Version 15.0.5603.1000, to determine the mean value and standard deviation (mean ± SD).

3. Results and Discussion

3.1. Architecture System Root

Architecture system root (RSA) refers to configuration spatial roots within land, determined by morphology, topology, geometry, and distribution (Kinhal, 2023; Lynch, 1995). Morphological characteristics, such as diameter, length, and surface area, can be used to characterize individual roots. Characteristics include geometric coverage, corner branching, branch spacing, and root distribution. On the other hand, characteristic topology describes the hierarchical root of the system (Fitter & Stickland, 1991). Attributes. In a way, the collective determines how plants obtain their energy, interact with the soil, and contribute to mechanical stabilization. Therefore, the variation architecture root is characteristic of functional bridging physiology, plant performance engineering, and ecological ecology (Ghestem et al., 2011; Stokes et al., 2009).

Architectural patterns differ significantly between *Piper sarmentosum* (Kaduk) and Pandanus amaryllifolius (Pandan), which reflect different ecological and mechanical strategies. Based on the typology proposed by Fitter & Stickland (1991), Kaduk exhibits the characteristics of an H-type or fibrous root system, with densely branched, fine roots that are horizontally oriented and concentrated in the topsoil. This configuration maximizes contact with the soil, resulting in a high root density per unit volume and thereby increasing near-surface cohesion and erosion resistance. In contrast, Pandan is more aligned with a VH-type (vertical-horizontal) system, which is characterized by strong, downward-extending adventitious roots for anchorage, while supporting lateral branches for stability and facilitating nutrient exchange. This VH-type architecture is related to shear resistance and slope reinforcement in cohesive soils. (Ghestem et al., 2011) .

Factors in the environment, such as density, mass, aeration, and soil water content, also affect form. Roots. Kinhal (2023) notes that system roots adapt in a way that is plastic to the environment: solid ground or flooded, pushing deeper roots, thicker and more slowly elongated, while well-aerated soil Provides Good support, more systems, smoother and branched, higher. Plasticity: This explains differences observed in Pandan and Kaduk — roots: rough adventitious roots on Pandan are a characteristic of adapted species with more land, heavy or more wet conditions, whereas root fibrous, smooth on Kaduk, is suitable for an environment with a shallow land layer, well-drained top, and better conditions. The contrasting architecture of Pandan and Kaduk thus reflects an exchange of ecological functions between anchorage structures and surface cohesion, both of which are important for slope stabilization and land reinforcement.

3.2. Morphology System Root

Analysis using WinRHIZO reveals clear differences in root system architecture between *Piper sarmentosum* (Kaduk) and Pandanus amaryllifolius (Pandan) (Table 1).

(a) (b)

Figure 5. Kaduk roots during sample preparation (a) and illustration produced by AI (b) showing H-type or fibrous root system according to Yen's (1987) root architecture system.

(a) (b)

Figure 6. Pandanus roots during sample preparation (a) and illustration produced by AI (b) showing a VH or fibrous type root system according to Yen's (1987) root architecture system.

Table 1. Root Parameters Species Obtained Kaduk and Pandan from WinRHIZO

Root Parameters	Stir (n=3)	Pandanus (n=2)
Total length (cm)	762.95 ± 558.46	4,341.56 ± 0.02
Total Projected Area (cm^2)	21.43 ± 11.20	111.65 ± 0.07
Total Surface Area (cm^2)	30.56 ± 14.43	155.75 ± 0.22
Average diameter (mm)	0.65 ± 0.02	3.74 ± 0.53
Length per Volume (cm/m^3)	600.38 ± 384.87	7,722.02 ± 1212.58
Root Volume (cm^3)	1.93 ± 1.18	42.74 ± 7.38
Tips	755.00 ± 488.69	7,447.75 ± 476.94
Forks	1,627.66 ± 978.49	21,542.25 ± 8227.54
Crossings	236.67 ± 141.16	2,296.25 ± 971.21

In Table 1 above is the Analysis WhinRHIZO for determining Tensile strength (root), Root length(cm^3), Root Volume(cm), Root Diameter(cm), Root Structure, Root area(cm^2), Tensile Force(N) using 60 Pandan root samples and 26 root samples

Stir show long root more cumulative short (762.95 ± 558.46 cm) and the total area of the projection and the area more surface small (21.43 ± 11.20 cm² and 30.56 ± 14.43 cm² respectively) compared to Pandan (4,341.56 ± 0.02 cm; 111.65 ± 0.07 cm²; and 155.75 ± 0.22 cm²). In analysis-based WinRHIZO, the total area of the projection (2D) represents wide system planar roots or horizontal footprint, while the wide total surface (3D) estimates the interface physique place root interacts with the matrix, the surrounding land, for nutrient and water exchange (Rose & Jourdan, 2017; Willigen et al., 2017). These parameters together describe the distribution, spatial, and efficiency contact interface soil-roots, key influencing factors absorption source power, and potential strengthening land (Willigen et al., 2017)

A larger projection area and surface area on Pandan show a network with deeper roots, rougher and thicker enough to anchor in a way that is extensive and binding, more mechanical, strong with the land. On the other hand, the area surface and projection are more compact roots of the small reflect system. However, greater smoothness is likely to increase the top of the binding layer and the cohesion scale slightly. Differences in geometric interaction roots-soil, in turn, directly influence hydrological and mechanical behavior, because partial root contact and irregular spatial distribution affect nutrient transport and distribution, and stress within the rhizosphere (Willigen et al., 2017).

The average root diameter shows a significant difference between types, with root Stir having an average diameter of 0.65 ± 0.02 mm and Pandan roots having an average diameter of 3.74 ± 0.53 mm. Contrast morphology. This finding shows two different biomechanical strategies : root smooth and slender, for example, in Kaduk, increase soil interlocking and resistance to friction, whereas deeper roots , thick as in Pandan, give greater pull and more anchorage (Ettbeb et al., 2020; Me et al., 2025) If compared with research on species from the same family, such as Piper aduncum and Piper betle, both species show a generally small root diameter (< 1 mm), which contributes to improved cohesion of the land layer (Zhang et al., 2014). This pattern, consistent with results on Kaduk, explained that species in the family Piperaceae tend to develop fine root fibers with high strength per unit area. In contrast, the findings on Pandan are in line with those of a previous study on the family Pandanaceae, such as Pandanus tectorius, which was reported to have root adventitious diameters of 2 to 6 mm and to function as a vertical support structure capable of withstanding greater total weight. With this, the study's results strengthen the case that differences in root morphology between families reflect adaptation to specific ecologies: Piperaceae, superior at strengthening the surface through root smoothness, whereas Pandanaceae, with utility in stabilizing structure through root roughness and adventitious roots.

Geometry of contact roots-soil is a determinant of mechanical efficiency; Willigen et al. (2017) emphasize that thinner roots maintain more effective contact with the soil at a given height per unit of width, thereby increasing nutrient absorption and mechanical stabilization. Root diameter More Kaduk small with thus support his role in strengthening the layer of land above, while root more adventitious Pandan thick contribute to anchoring vertically and resistance to deformation shear. Root volume of the more differentiated species. Pandan shows a much higher average volume (42.74 ± 7.38 cm³) than Kaduk (1.93 ± 1.18 cm³), and a greater investment in biomass, with thicker, more resistant root burrows. However, as warned by Rose & Jourdan (2017), analysis of digital roots can exaggerate volume and properties at the surface when inner-diameter variability is ignored. Thus, the trend observed here is still clear — structured roots with more Kaduk fine offer higher resilience at higher voltage, superior per unit wide, while more pandan roots rough contribute more substantially to anchoring and distribution load. The properties that are mutually complete. This result explains the role of those that are different, however, synergistic in reinforcement soil: Kaduk for cohesion near the surface and Pandan for deep stabilization.

The ratio length to volume (LenPerVol) increasingly highlights the functional difference between the second species, as said. Kaduk recorded 600.38 ± 384.87 cm/m³, indicating a system with fibrous roots, long and smooth, occupying a relatively small tissue volume. Configuring the capacity binding to more land, larger, and more efficient surfaces (Baets et al., 2008). On the contrary, Pandan shows a LenPerVol of 7,722.02 ± 1,212.58 cm/m³, driven by its extensive total root length and larger root volume. Although this reflects high total root development, with a higher average rough diameter (3.74 ± 0.53 mm), the Pandan root system prioritizes anchorage and structural support over cohesion at the land scale. Together, the attributes morphology are in harmony with the behavior observed drag, where Kaduk shows strength, pulling more height per unit width, and Pandan shows style, withdrawing more total consistent with the role structural.

Characteristics: branching is also very different between species. Pandan produces more Lots shoots (7,448 ± 477), branches (21,542 ± 8,228), and crosses (2,296 ± 971) compared to Kaduk (shoots = 755 ± 489; branches = 1,628 ± 978; crosses = 237 ± 141). These parameters represent the number of growth nodes and branches active at each system root, which determine the complexity of the spatial interface between roots and soil. A higher amount in Pandan, related to its large, branched architecture in an extensive manner, while Stir balances it out through a matrix root, finer per unit volume, which increases the surface-to-volume ratio and increases capacity for binding land near the surface. Branching and crossing also increase soil interlocking and anchorage. mechanical, which describes how each species contributes in a way different from reinforcement slope — Kaduk with push cohesion scale smooth on the layer land top, and Pandan with give stabilization more structural through branching rough roots.

The morphological differences observed in the WinRHIZO analysis indicate variation in the performance of the second root species. Size root Small and architectural Kaduk fiber fine produce strength pull per unit more area high, in line with findings on members of Other Piperaceae such as *Piper aduncum* and *Piper betle*, which have a small root diameter with high lignin content, so that effective mechanical withhold voltage (Zhang et al., 2014). On the other hand, Pandan roots are thicker, with wider surfaces and more projections , showing a big, showy style, reaching a higher total height, consistent with the characteristics of the family Pandanaceae, for example, Pandanus tectorius, which has a root adventitious diameter that is big and functional as a buffer structure on slopes and coastal areas. This explains more in pattern biomechanics typical of both families — Piperaceae superior in strengthening the surface through root smooth, while Pandanaceae contribute to structural stability through root adventitious thick (Ettbeb et al., 2020; Me et al., 2025).

3.3. Root Tensile Strength

The connection between strength pull and root diameter of *Pandanus amaryllifolius* shows a pattern of the following improvements in law exponent, where the root with a larger diameter has its own ability to withstand higher voltage , in line with the pattern biomechanics reported in various plant species (Baets et al., 2008; Zhang et al., 2014). With R² value = 0.6812, approximately 68% of the variation in the strength pull is influenced by root diameter. Strength pull-ups to ±55 MPa in pandan roots with a diameter of 0.5–2.5 mm, aligned with findings in members of the family Pandanaceae and others, such as Pandanus tectorius, which also shows that the root adventitious diameter contributes significantly to the total pull and anchorage slope. This pattern is also consistent with the study by Ettbeb et al. (2020), which found that root diameter thickness tends to produce taller styles, even though voltage per unit width is not always increased. In terms of overall results, this confirms the character biomechanics typical of Pandanaceae as species with strong, functional root adventitious structures as the main support for land stability.

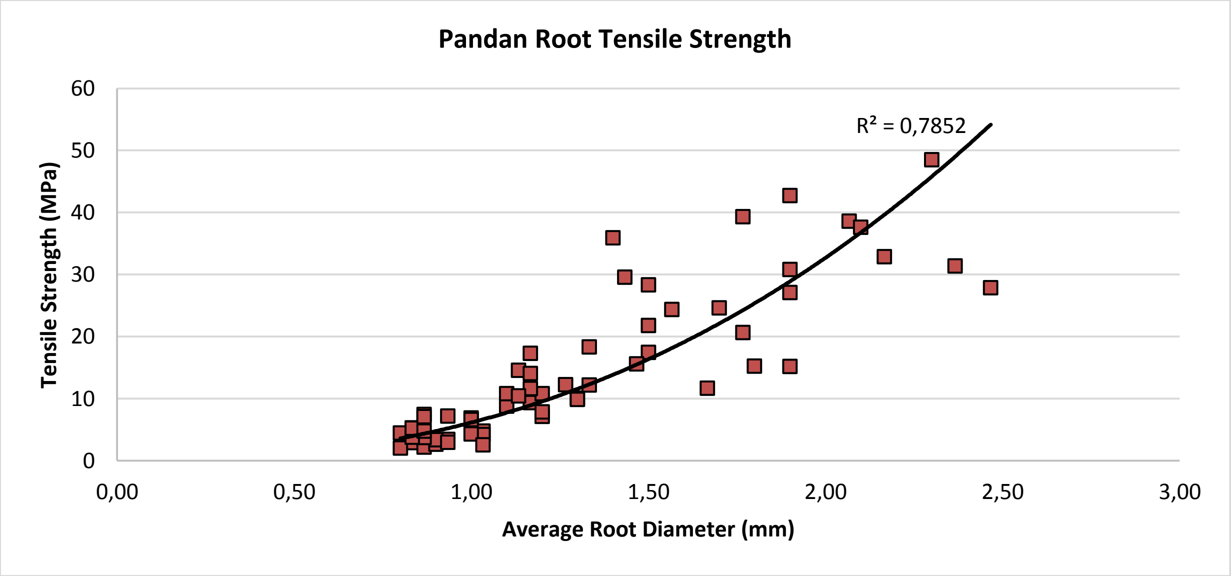


Figure 7. Strength pull pandan root (MPa)

Figure 7 illustrates the connection between the average root diameter and tensile strength for *Piper sarmentosum* (Kaduk). Data follow an exponential, strong positive relationship (R² = 0.8652), which indicates that almost 87% of the variation in pull strength is explained by changes in root diameter. Strength measurable pull range from < 1 MPa at the root fine (~ 0.4 mm) to > 40 MPa in larger root thick (~ 2.0 mm). Grouping more points meeting relatively against Pandan shows a composition more structural, more uniform and consistent, big in behavior and mechanical properties, possibly related to lignin-to-fiber ratio, more cellulose, and height, which are characteristics typical of root smooth and durable stress (Zhang et al., 2014).

Figure 8 shows that the connection style pull-diameter on Pandanus amaryllifolius and *Piper sarmentosum* follows the legal model power ($T = a\ d^b$), a common pattern found in species stabilizer slope (Baets et al., 2008). On the second species, style pull increases with increasing root diameter; however, the correlation is stronger in Kaduk (R² = 0.8652) than in Pandan (R² = 0.6812), indicating a more mechanical uniformity. This result is consistent with research on members of Other Piperaceae, such as Piper aduncum, which also shows roots with fine strength per unit width, tall consequence, and a higher proportion of lignin in roots with small diameters (Zhang et al., 2014). In contrast, the trend on Pandan is in line with the character family Pandanaceae, for example, Pandanus tectorius, which has a thick, adventitious root, with a style pull absolute tall but voltage pull per unit wide more low, so that it is more effective as an anchor structure on slopes and soil. A reverse pattern between voltage pull and root diameter was found in the study; this is also consistent with findings by Ettbeb et al. (2020) on species with large roots, such as Pennisetum, which show that the diameter increases with increased voltage pull. However, voltage pull does not always increase. Overall, findings confirm different biomechanics, but each complements the other: Stir, like species in Piperaceae, strengthens the land layer through fine roots with high voltage, while Pandan follows a typical Pandanaceae pattern as a species with anchor roots and adventitious root thickness that increases land stability.

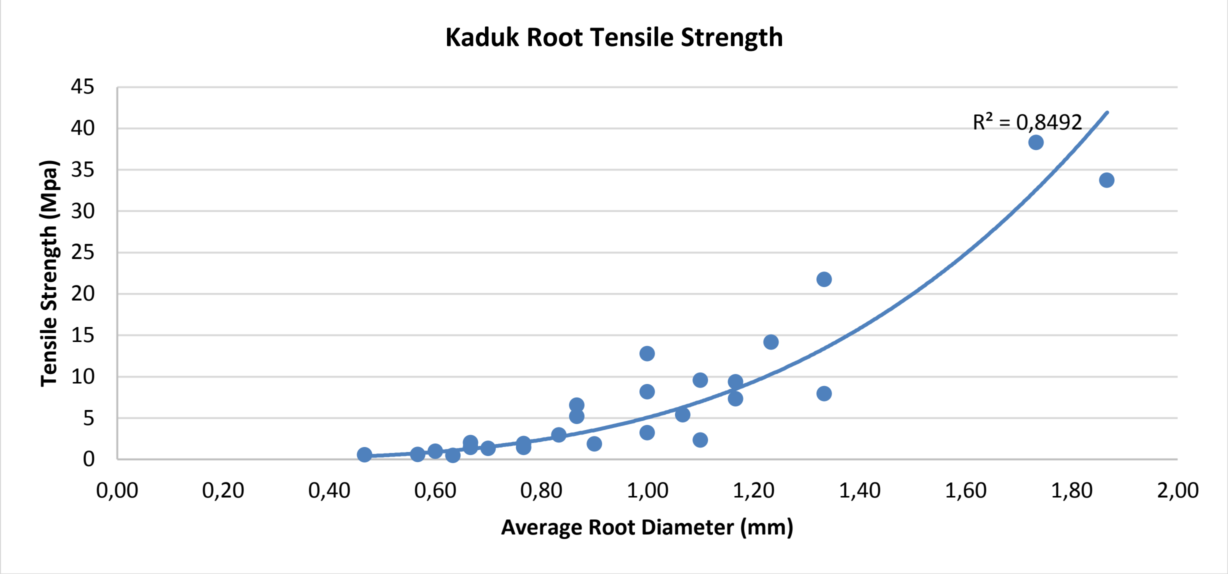


Figure 8. Strength pull root stir (Mpa)

Physiological and biochemical properties also influence the observed differences. Below the pressure slope, roots can form wood pull with high cellulose content, thereby increasing their capacity to pull (Hales et al., 2009). Although this study was conducted in condition-controlled polybags, in situ pressure can further enhance the adaptation mechanism. Roots are fine; lignin-rich roots usually show strength, pull more height, and greater elasticity. Okay, meanwhile, species herbs like Stir often outperform species woody in distributing pressure mechanically in a way efficient for an overall network of deeper roots . Fine.

In a way, overall, the results of this study confirm that behavior pulls root-nature-specific species and, depending on the diameter, are consistent with global findings across various types of vegetation (Baets et al., 2008). Kaduk provides cohesion, a root, a smooth stabilizing layer, and land above, while Pandan strengthens additional layers through anchorage and strong fibrous roots. Together, species. This shows functionally interacts with mutually interacting mechanisms, completing the appropriate application for bioengineering in the tropical environment.

4. Conclusion

The study indicates that the water quality in MARDI is generally good, with most observation points classified as Class II, making it suitable for clean water treatment. However, several ponits that fall into Class III show a decline in water quality that requires further attention. Overall, this study reflects the increase in COD and TSS values at several locations suggests pollution pressure from agricultural activities. Therefore, regular water quality monitoring and the implementation of sustainable agricultural practices are strongly recommended to maintain water quality within acceptable standards and to support long-term agricultural productivity.

This study demonstrates that *Piper sarmentosum* (Kaduk) and Pandanus amaryllifolius (Pandan) possess interconnected root systems that are complete and effective for biotechnological applications on tropical slopes. Kaduk has smooth, strong fibrous roots that enhance the cohesion and stability of the upper soil layers, while Pandan has thick adventitious roots that provide strong anchorage in deeper soil layers. The combination of these two species forms a natural vegetative system capable of preventing erosion and comprehensively reinforcing slopes. These qualities make these two local species excellent alternatives as environmentally friendly, economically viable vegetation options with significant potential for use in nature-based slope engineering.

For practical implementation, Kaduk is recommended for planting on slope sections to strengthen the land surface, while Pandan is more effective in the middle to lower slope areas as an anchoring structure. Both species can be utilized in projects involving the rehabilitation of degraded land, riverbank conservation, and landslide control. Besides their ecological roles, Kaduk and Pandan also have economic value and can support the empowerment of local communities. Therefore, integrating these two species into tropical conservation and bioengineering policies is recommended as a natural and sustainable solution for slope management in tropical regions.

Acknowledgments

The writers would like to express sincere gratitude and appreciation to the Institute of Research and Development, Malaysian Agriculture Association (MARDI), for their support and guidance during the internship. The writers also wish to extend heartfelt thanks to Mr. Mohamad Nasrol Rabidi and Mr. Amirul Mukmin Khairul Anuar for their assistance and guidance during sampling and data recording.

References

Baets, S. de, Poesen, J., Reubens, B., & Wemans, K. (2008). Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil, 305*, 207–226. https://doi.org/10.1007/s11104-008-9553-0

Ettbeb, A. E., Rahman, Z. A., Idris, M. R., Rahim, S. A., Tarmidzi, S. N. A., & Lihan, T. (2020). Ketahanan tarik akar beberapa spesies *Pennisetum* dan kontribusinya terhadap kekuatan geser tanah. *Jurnal Penelitian*, 1–9.

Fitter, A. H., & Stickland, T. R. (1991). Architectural analysis of plant root systems: Influence of nutrient supply on architecture in contrasting plant species. *New Phytologist, 118*, 375–382.

Ghestem, M., Sidle, R. C., & Stokes, A. (2011). The influence of plant root systems on subsurface flow: Implications for slope stability. *BioScience, 61*(11), 869–879. https://doi.org/10.1525/bio.2011.61.11.6

Hales, T. C., Ford, C. R., Hwang, T., Vose, J. M., & Band, L. E. (2009). Topographic and ecologic controls on root reinforcement. *Journal of Geophysical Research: Earth Surface, 114*, 1–17. https://doi.org/10.1029/2008JF001168

Ibrahim, M. A., & Azman, S. N. (2019). Effects of leaf maturity of *Piper sarmentosum* (kaduk) on its antioxidant level. *Journal*, 3(2), 15-17.

Kinhal, V. (2023). Root systems' role in ecosystems. https://cid-inc.com/blog/root-systems-role-in-ecosystems/

Lynch, J. (1995). Root architecture and plant productivity. *Plant Physiology, 109*, 7–13.

Me, A., Z, A. R., Sna, T., Wmr, I., Lihan, T., Aa, K., Naa, J., & Jasni, Z. (2025). Kinerja pertumbuhan, kekuatan tarik akar, dan kekuatan geser tanah pada spesies semak terpilih. *Jurnal*, April.

Model, R. U., & Eisenberg, J. (2020). Quantification of erosion in selected catchment areas of the Ruzizi River (DRC). *Journal*, 1-10.

Nurhayati, L., & Nugraha, S. (2012). Analisis daerah aliran sungai (DAS) Walikan Kabupaten Karanganyar dan Wonogiri. *Jurnal*, 2012.

Rachmawati, W., & Ramdanawati, L. (2020). Pengembangan klorofil dari daun singkong sebagai pewarna makanan alami. *Jurnal*, 2(2).

Revika, S. (2022). Budidaya tanaman pala (*Myristica fragrans*) oleh masyarakat pemegang IUPHKm di Desa Air Lanang Kecamatan Curup Selatan Kabupaten Rejang Lebong. *Jurnal*, 2(1), 69–88.

Rose, L., & Jourdan, C. (2017). Pitfalls in root trait calculations: How ignoring diameter heterogeneity can lead to overestimation of functional traits. *Frontiers in Plant Science, 8*, 1–5. https://doi.org/10.3389/fpls.2017.00898

Stokes, A., Atger, C., Bengough, A. G., & Fourcaud, T. (2009). Desirable plant root traits for protecting natural and engineered slopes against landslides. *Plant and Soil, 324*, 1–30. https://doi.org/10.1007/s11104-009-0159-y

Wang, C., Zhang, X., Liu, J., Wang, B., Li, Y., & Li, Q. (2020). The profiles and tensile strength of straight roots after self-repair following transient tensile injury. *Scientific Reports, 10*, 1-10. https://doi.org/10.1038/s41598-020-68358-8

Willigen, P. de, Heinen, M., & van Noordwijk, M. (2017). Roots partially in contact with soil: Analytical solutions and approximation in models of nutrient and water uptake. *Vadose Zone Journal, 16*(5). https://doi.org/10.2136/vzj2017.03.0060

Zhang, C., Chen, L., & Jiang, J. (2014). Why fine tree roots are stronger than thicker roots: The role of cellulose and lignin. *Annals of Botany, 113*, 1–34.