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Abstract: In southern Taiwan, mudstone badland accounts for over 1000 km\textsuperscript{2} of the upstream region of watersheds. Rainstorms often induce interrill and surface erosion on the mudstone slopes. Furthermore, the large quantity of soils detached by surface runoff result in severe sedimentation in reservoirs. Thus, soil erosion control of mudstone badlands represents one of the most pressing problems in reservoir watershed management. Cynodon dactylon (L.) Pers. (Bermuda grass) and Eremochloa ophiuroides (Munro) Hack. (Centipedegrass) are two native predominant C\textsubscript{4} grass species appearing on mudstone badlands. They play a key role in erosion control and the revegetation of mudstone slopes. Nevertheless, their root functional traits and water erosion-reducing potential have not been investigated. In this study, the root traits were examined. Vertical pullout and tensile tests were conducted to measure root pullout resistance and root tensile strength. Hydraulic flume tests were also performed to evaluate their water erosion-reducing potentials. The results demonstrated that the root systems of C. dactylon and E. ophiuroides grasses all belonged to the fibrous M-type. C. dactylon had remarkably better root traits compared to those of E. ophiuroides. Furthermore, the root tensile resistance of C. dactylon was remarkably higher than that of E. ophiuroides. In addition, hydraulic flume tests showed that C. dactylon has remarkably smaller soil detachment rates than that of E. ophiuroides. Altogether, our data clearly show that C. dactylon has better root traits, root pullout resistance, root tensile resistance and water erosion-reducing potential than E. ophiuroides and is more suitable for erosion control of mudstone badland. Further studies on large-scale implementation techniques of these species for efficient vegetation restoration are needed.

Keywords: mudstone badland; root functional traits; biomechanical properties; water erosion-reducing potential

1. Introduction

In southwestern Taiwan, mudstone badlands, characterized by gullies and erosion, occupy over 1000 km\textsuperscript{2} of upstream area of eight reservoir watersheds (Figure 1). Badland soils, consisting mainly of CaCO\textsubscript{3}, clay and silt, are poorly congealed and are very prone to rill and interrill erosion [1–4]. The badland soils are also low in mineral nutrients to support plant growth [2]. In recent years, earthquakes and typhoon rainstorms have frequently induced serious landslide, debris flow, and runoff erosion disasters [5]. Large amounts of eroded mudstone soils cause major problems of sedimentation in reservoir and river systems [6,7]. Consequently, erosion control of mudstone badlands has become a major issue of soil and water conservation [8,9]. Ecological restoration has frequently been used for erosion control and bio-reclamation of degraded lands [10–12]. Aridity, low fertility, high erosion rates, and sharp terrain are common features of badlands [8,13]. Generally, native grass species play an important role in soil stabilization of mountainous marly lands [14]. C. dactylon and E. ophiuroides are indigenous warm-season C\textsubscript{4} grasses occurring
on badland soils in Taiwan [15]. Previous studies have demonstrated that C. dactylon and E. ophiuroides, characterized by drought and high salinity tolerance, which are creeping and which propagate easily, are beneficial for revegetation of mudstone badlands [16,17].

![Figure 1. Rugged terrain of mudstone badland in southwestern Taiwan.](image)

Grass roots have remarkable influence on reinforcing slope stability and reducing runoff erosion [18–20]. The root systems of C. dactylon and E. ophiuroides are categorized as fibrous massive M-type [21]. Previous studies have shown that plant root reinforcement is closely correlated with root system architecture, functional traits, root pullout resistance, and root tensile resistance [22–25]. However, the root system architecture, root characteristics, biomechanical characteristics, and water erosion-reducing potential of C. dactylon and E. ophiuroides have not been fully inspected. Hence, this research was focused on: (1) examining the root system and characteristics, biomechanical properties and water erosion-reducing potential of these two indigenous grasses; and (2) comparing the dissimilarities between the two species with respect to erosion control and ecological restoration of mudstone badlands. Since there have been very few studies inspecting the relationships among plant root functional traits, root biomechanical properties and water erosion-reducing potential in vegetation engineering for erosion control of mudstone badlands, there is novelty and originality in this research.

2. Materials and Methods

2.1. Sample Preparation

Seeds were gathered from plants of C. dactylon and E. ophiuroides on the badlands located at Qishan Village, Kaohsiung City, Taiwan (120°23′22″ E, 22°53′13″ N) in September 2018 and stored under natural conditions. In October 2018, 200 seeds of each species were germinated in badland soils collected from the same site. One-month-old seedlings of C. dactylon and E. ophiuroides, getting to a mean height of 3.2 ± 0.5 cm and 2.8 ± 0.3 cm, respectively, were transplanted to high wooden crates (35 cm × 35 cm × 30 cm, l × w × h, 1 plant per crate) and low wooden crates (35 cm × 35 cm × 20 cm, l × w × h, 40 plants per crate), packed with badland soils collected from the same area. The soils were packed utilizing rammer to duplicate the physical properties of mudstone soils [26]. For analyses of root configuration, root trait and root biomechanical characteristics, one seedling of each species was planted to 32 high wooden crates individually. For hydraulic flume test, 40 seedlings of each species were transplanted to 24 short crates, individually. After transplanting, all wooden crates were arrayed at random in the nursery of National Chiayi University (120°29′06.67″ E, 23°01.69″ N) under natural conditions, and watered every four days. Twenty low crates without seedlings served as control for hydraulic flume test. All crates were rotated weekly to decrease shading influence. Collectively, the azimuth of crates was unchanged.
2.2. Growth Traits

A pilot study conducted by the authors revealed that the wooden crate had enough space for root growth. After four months of cultivation, 14 plants of each species were selected arbitrarily for root growth characteristics and architecture investigations. Roots were cautiously extracted from soil with running water. Root configuration was estimated and documented. Root area ratio was calculated according to Bischetti et al. [27]. Root system photos were recorded for root system configuration investigation. Root surface area and length were evaluated utilizing WinRHIZO software (Regent Inc., Quebec, QC, Canada) [28], while root volume was estimated using water displacement technique [29]. Root dry unit weight was also measured [30]. These figures were used to determine root traits. Together, live roots were gathered for subsequent tensile testing.

2.3. Pullout Test

For each species, one plant from each crate was selected arbitrarily for vertical pullout test. The mudstone soils have an average dry mass of 18.5 kN m\(^{-3}\), and water moisture of 12.2 ± 1.2%. Prior to each pullout test, stems were cut off from 10 cm beyond the stem base. Vertical pullout test was executed utilizing a pullout machine (USPA-003, U-Soft Tech Co., Taipei, Taiwan) [31]. The maximum pullout resistance (\(\text{PR}_{\text{max}}, \text{N}\)) was calculated utilizing the following equation:

\[
\text{PR}_{\text{max}} = F_{\text{max}}
\]

where \(F_{\text{ult}}\) is the maximum pullout force at uprooting (N).

2.4. Root Tensile Test

After whole root extraction, live root samples were classified into 0–1-, 1–2-, and 2–5-mm-diameter grades. Only undamaged root sections were selected and cut into 40 mm lengths and stored [27]. Fifty root segments of each species were tested within 20 h of collection. Root tensile test was performed using a tensile testing apparatus (USPT-003, U-Soft Tech Co., Taipei, Taiwan) [31]. Prior to testing, the diameter of the mid-segment was measured. Root segment was fastened with screw grips and the tensile test was subsequently carried out at a consistent speed of 4.5 mm min\(^{-1}\) till fracture. Twenty-seven middle segments of \(C. \text{dactylon}\) and 20 middle segments of \(E. \text{ophiuroides}\) plants were tested. The tensile strength (\(T_{\text{si}}, \text{MPa}\)) was calculated utilizing the following formula [14,31]:

\[
T_{\text{si}} = \frac{4F_{\text{max}}}{\pi d_{i}^{2}}
\]

where \(F_{\text{max}}\) is the maximum tensile force at breakage (N), and \(d_{i}\) is the diameter (mm) of mid-segment measured at the midpoint.

Moreover, the relation between root tensile strength (\(T_{s}\)) and diameter (\(d\)) was computed utilizing the subsequent equation [32]:

\[
T_{s} = \alpha \cdot d^{-\beta}
\]

where \(\alpha\) and \(\beta\) are experimental coefficients contingent on species.

2.5. Hydraulic Flume Experiment

Hydraulic flume tests were performed utilizing a flume resembling Lee et al. [33]. The flume was constructed with steel (5 mL, 0.35 mW) with an opening (0.35 mL, 0.35 mW) at the bottom, equaling the width of the low wooden crate, so that the surface of the crate suits the flume surface (Figure 2). Prior to the test, the aerial parts of plants were severed at the base. Crates were submerged in water for 3 h and drained for 12 h. The rims between the sample crate and the flume were fixed with epoxy sealant to avoid edge effects. The soil surface slope, flow discharge, mean bottom flow discharge, and water temperature were
recorded, and the bottom flow shear stress ($\tau$, Pa) was computed using the subsequent equation [34,35].

$$\tau = \rho_w g RS$$

(4)

where $\rho_w$ is the water density ($\text{kg m}^{-3}$), $g$ is the acceleration caused by gravity ($\text{m s}^{-2}$), $R$ is hydraulic radius (m), and $S$ is the sin $\alpha$ in which $\alpha$ is soil surface slope angle ($^\circ$). Afterwards, samples were exposed to a consistent flow of 0.61 m$^3$ m$^{-1}$ for three minutes. Pilot experiments demonstrated that erosion primarily occurred during the first three minutes of the test. For each species, 10 plant sample boxes were tested at a slope of 15$^\circ$. Ten bare-soil boxes without plants served as control. Water and sediments were collected in 50 L plastic pails every three-minute time interval from the flume outlet. The collected soil sediments were separated by settling for 12 h, dried at 75 $^\circ$C for 60 h before measurements. The relative soil detachment rate (RSD) of each species was calculated as dividing the soil loss amount from plant samples with the mean soil loss amount from control ones. The hydraulic flume tests included two grass species, with one control for each slope and ten replicates.

![Figure 2. Graphic illustration of hydraulic flume test.](image)

2.6. Statistical Analysis

Differences in root characteristics, root biomechanical properties and water erosion-reducing potential between species were analyzed with $t$-test using IBM SPSS V22.0 (SPSS, Chicago, IL, USA). Microsoft Excel Regression analysis (Microsoft Excel 2013, Redmond, WA, USA) was utilized to analyze the relationships between root tensile force, tensile strength, and root diameter.

3. Results

3.1. Root System Configuration

After 4 months of cultivation in the crates, *C. dactylon* grass produced more profuse root systems than *E. ophiuroides* grass (Figure 3). The root architecture for *C. dactylon* and *E. ophiuroides* were categorized as M-type according to Yen [21]. Furthermore, *C. dactylon* distributed most of its roots at 0–15 cm soil depth (Figure 3a), whereas *E. ophiuroides* developed its roots at 0–10 cm deep in soil (Figure 3b). Statistical results of root area ratio (RAR) demonstrated remarkable differences between these two species (Table 1). Altogether, the root area ratio and growth performance of *C. dactylon* were superior to those of *E. ophiuroides*. 
Table 1. Means ± SEs of root area ratios at various soil depths for *C. dactylon* and *E. ophiuroides*.

| Species            | 0–5 cm  | 5–10 cm | 10–15 cm | 15–20 cm | 20–25 cm |
|--------------------|---------|---------|----------|----------|----------|
| *Cynodon dactylon* | 1.34 ± 0.23<sup>a</sup> | 1.64 ± 0.34<sup>a</sup> | 0.63 ± 0.07<sup>a</sup> | 0.12 ± 0.03<sup>a</sup> | 0.02 ± 0.01<sup>a</sup> |
| *Eremochloa ophiuroides* | 0.46 ± 0.14<sup>b</sup> | 0.18 ± 0.03<sup>b</sup> | 0.13 ± 0.02<sup>b</sup> | 0.04 ± 0.01<sup>b</sup> | 0.01 ± 0.01<sup>a</sup> |

Different superscripts in the same column present remarkable dissimilarity (t-test) between species. N = 14.

3.2. Root Characteristics

Statistical data demonstrated significant differences in root characteristics between these two species (Table 2). Essentially, all root traits except for total root length and root length density were remarkably greater for *C. dactylon* than for *E. ophiuroides*. Overall, the root traits, such as root biomass, tip number, volume, root density, total root surface area and root tissue density, of *C. dactylon* were remarkably better than those of *E. ophiuroides*.

Table 2. Means ± SEs of root traits for *C. dactylon* and *E. ophiuroides*.

| Root Traits | *C. Dactylon* | *E. Ophiuroides* | p     |
|-------------|---------------|------------------|-------|
| RB (kg)     | 0.012 ± 0.002<sup>a</sup> | 0.006 ± 0.0004<sup>b</sup> | 0.001<sup>***</sup> |
| RT          | 5111.75 ± 492.3<sup>a</sup> | 3715.63 ± 200.05<sup>b</sup> | 0.020<sup>*</sup> |
| RV (cm<sup>3</sup>) | 46.5 ± 1.48<sup>a</sup> | 36.63 ± 1.24<sup>b</sup> | 0.000<sup>***</sup> |
| TRL (cm)    | 4751.13 ± 408.014<sup>a</sup> | 4195.88 ± 398.57<sup>a</sup> | 0.34<sup>ns</sup> |
| RD (kg m<sup>−3</sup>) | 0.22 ± 0.02<sup>a</sup> | 0.1 ± 0.01<sup>b</sup> | 0.001<sup>***</sup> |
| RLD (km m<sup>−3</sup>) | 0.88 ± 0.08<sup>a</sup> | 0.78 ± 0.07<sup>a</sup> | 0.32<sup>ns</sup> |
| RSA (cm<sup>2</sup>) | 4830.85 ± 513.94<sup>a</sup> | 3297.77 ± 230.35<sup>b</sup> | 0.017<sup>*</sup> |
| RTD (g cm<sup>−3</sup>) | 0.26 ± 0.06<sup>a</sup> | 0.15 ± 0.01<sup>b</sup> | 0.001<sup>***</sup> |

RB, root biomass; RT, root tips; RV, root volume; TRL, total root length; RD, root density; RLD, root length density; RSA, total root surface area; RTD, root tissue density. Different superscripts in the same row represent notable dissimilarities (t-test) between species. N = 14. Significance levels: ns, non-significant, *p < 0.05, **p < 0.001.

3.3. Root Pullout Resistance

Vertical pullout test measures the pullout force for raising the plant until it drops as the root breaks. The maximal pullout resistance of *C. dactylon* (0.31 ± 0.03 kN) was about
twofold that of *E. ophiuroides* (0.16 ± 0.52 kN) (Table 3), indicating that *C. dactylon* plants have higher anchorage ability than *E. ophiuroides* plants.

**Table 3.** Means ± SEs of maximal pullout resistance for the two species.

| Biomechanical Properties | C. Dactylon  | E. Ophiuroides | t-Value |
|--------------------------|--------------|----------------|---------|
| Maximal pullout resistance (kN) | 0.31 ± 0.03 \(^a\) | 0.16 ± 0.02 \(^b\) | 5.301 ** |

Different superscripts in the same row specify remarkable dissimilarities (t-test) between species. N = 14. Level of significance: ** \(p < 0.01\).

### 3.4. Root Tensile Strength

Statistical results showed remarkable dissimilarities in root diameter and tensile force between these two species. The average root diameter of *C. dactylon* (0.42 ± 0.02 mm) was notably larger than that of *E. ophiuroides* (0.34 ± 0.01 mm). The average root tensile resistance of *C. dactylon* (13.21 ± 0.65 N) was also remarkably higher than that of *E. ophiuroides* (9.0 ± 0.46 N). However, there was no notable dissimilarity in average root tensile strength between these two species (Table 4). Furthermore, for both species, root tensile resistance decreased with decreasing root diameter (Figure 4), although root tensile strength increased with decreasing root diameter (Figure 5). Taken together, the root diameter and tensile resistance of *C. dactylon* were notably higher than those of *E. ophiuroides*.

**Table 4.** Means ± SEs of root diameter, root tensile resistance force and root tensile strength for *C. dactylon* and *E. ophiuroides*.

| Parameters                  | C. Dactylon | E. Ophiuroides | \(p\)     |
|-----------------------------|-------------|----------------|-----------|
| Root diameters (mm)         | 0.42 ± 0.02 \(^a\) | 0.34 ± 0.01 \(^b\) | 0.001 *** |
| Tensile resistance force (N) | 13.21 ± 0.65 \(^a\) | 9.0 ± 0.46 \(^b\) | 0.000 *** |
| Tensile strength (MPa)      | 104.705 ± 6.56 \(^a\) | 104.54 ± 4.24 \(^a\) | 0.978 ns   |

Different superscripts in the same row represent notable dissimilarities (t-test) between species. Level of significance: *** \(p < 0.001\).

**Figure 4.** Relationship between root tensile resistance and root diameter for *C. dactylon* and *E. ophiuroides*. Level of significance: *** \(p < 0.001\).
Figure 5. Relationship between root tensile strength and root diameter for *C. dactylon* and *E. ophiuroides*. Significance level: *** $p < 0.001$.

3.5. Water Erosion-Reducing Potential

A soil surface slope of 15° was applied to assess the water erosion-reducing potential for *C. dactylon* and *E. ophiuroides*. Since this experiment was focused on the implementation of revegetation for water erosion control of mudstone badlands, the surface slope was set at 15°, according to the guideline of vegetation engineering (18). At this slope, the average flow velocity, flow discharge, and bottom flow shear stress were 49.72 cm s$^{-1}$, 0.95 L s$^{-1}$, and 0.0035 Pa, respectively. The analytical data showed that the average soil loss amount was remarkably differed among root-permeated soil samples and control sample. At the slope of 15°, the average soil loss amount for bare soil (411.11 ± 30.13 g min$^{-1}$) was much greater than that of root-permeated soil samples of *C. dactylon* (44.74 ± 6.62 g min$^{-1}$) and *E. ophiuroides* (72.8 ± 9.81 g min$^{-1}$) (Table 5). Furthermore, the average relative soil detachment rate of *E. ophiuroides* (27.36 ± 3.82%) was about 1.7 times higher than that of *C. dactylon* (16.15 ± 2.26%) (Table 6). Regression analysis showed a positive relation between relative soil detachment rate and root density for the two species (Table 7, Figure 6). Taken together, these results clearly demonstrate that *C. dactylon* possesses a higher water erosion-reducing potential than *E. ophiuroides*.

Table 5. Means ± SEs of soil loss amount for *C. dactylon* and *E. ophiuroides* and bare soil.

| Slope (°) | *C. Dactylon* | *E. Ophiuroides* | Bare Soil | ANOVA ($p$) |
|-----------|---------------|-----------------|-----------|-------------|
| 15        | 44.74 ± 6.62  | 72.8 ± 9.81     | 411.11 ± 30.13 | 0.000 *** |

Superscripts in the same row signify notable dissimilarities (ANOVA and Tukey’s HSD test) among species. N = 10. Level of significance: *** $p < 0.001$.

Table 6. Means ± SEs of relative soil detachment rates between *C. dactylon* and *E. ophiuroides*.

| Slope (°) | Relative Soil Detachment Rate (%) | $p$ |
|-----------|----------------------------------|-----|
| 15        | *C. Dactylon* 16.15 ± 2.26   | 0.031 * |
|           | *E. Ophiuroides* 27.36 ± 3.82  |     |

Superscripts in the same row represent notable dissimilarity (T-test) between species. N = 10. Level of significance: * $p < 0.05$. 

Table 7. Relationship between root density and relative soil detachment rate at slope 15° for the two species.

| Root Functional Traits | Species          | Regression Equation       | R²      | F     |
|------------------------|------------------|----------------------------|---------|-------|
| RD (kg m⁻³)            | C. dactylon      | RSD = −80.14RD + 32.805    | 0.573 * | 6.452 |
|                        | E. ophiuroides   | RSD = −219.95RD + 47.063   | 0.607 * | 7.713 |

RD, root density; RLD, root length density. Level of significance: * p < 0.05.

Figure 6. Relationship between root density (RD) and relative soil detachment rate (RSD) at slope 15°. Significance level: * p < 0.05.

4. Discussion

4.1. Root System Architecture

_C. dactylon_ and _E. ophiuroides_ are the main indigenous pioneer grass species growing in the mudstone badlands in Taiwan. They are perennial C₄ grasses belonging to the Poaceae family, and are less sensitive to drought and low soil fertility than C₃ plants [15,36,37]. In addition, being C₄ plants, they exhibit superior photosynthetic performance at warm temperatures to boost their growth. Our results showed that the root systems of _C. dactylon_ and _E. ophiuroides_ resemble fibrous M-type root system with stolons. Earlier studies have demonstrated that M-type root systems are more suitable for soil and water conservation, as well as erosion and sediment control [22,38]. Thus, _C. dactylon_ and _E. ophiuroides_ with massive root systems are favorable for erosion control of mudstone badlands. Moreover, the RAR distribution demonstrated that _C. dactylon_ has more profuse roots in soil depths 0–20 cm than _E. ophiuroides_, suggesting that _C. dactylon_ is superior to _E. ophiuroides_ for erosion control.

4.2. Root Traits

Our results showed that all root characteristics, except for total root length and root length density, differed significantly between these two species. The root traits were notably greater for _C. dactylon_ than for _E. ophiuroides_. Earlier investigations have demonstrated that root biomass, root density and root tissue density have remarkable effects on root pullout resistance and erosion-reducing potential [38–42]. On the mudstone badlands, native vegetation rehabilitation is critical for erosion control and badland reclamation. _C. dactylon_ and _E. ophiuroides_ are indigenous dominant C₄ grasses able to resist adverse environments in badlands and are advantageous for ecological reclamation. Taken together, our findings indicate that _C. dactylon_ plants have better root traits and can grow better in mudstone badlands than _E. ophiuroides_ plants.
4.3. Root Pullout Resistance

Statistical data demonstrated that the maximal root pullout resistance of *C. dactylon* is remarkably higher than that of *E. ophiuroides*. Earlier studies also demonstrated positive relations between pullout resistance, root biomass, architecture, and root surface area [30,39,43]. Clearly, *C. dactylon* with more profuse fibrous roots, root biomass and total root surface has higher pullout resistance than *E. ophiuroides*. Altogether, *C. dactylon* has better anchorage capability than *E. ophiuroides* and is more advantageous for erosion control of mudstone badlands.

4.4. Root Tensile Strength

Root tensile resistance and root distribution play a critical role in soil conservation and slope stability [44–46]. Our results demonstrated that root tensile resistance and root configuration varied notably between these two species. Root tensile force of *C. dactylon* was remarkably higher than that of *E. ophiuroides*, although there was no notable dissimilarity in root tensile strength between the two species. Furthermore, root tensile resistance and tensile strength were highly related to root diameter, congruent with earlier investigations [14,33,47–49]. Evidently, *C. dactylon* possesses higher root tensile resistance force than *E. ophiuroides* and is more advantageous for soil reinforcement of mudstone badlands.

4.5. Water Erosion-Reducing Potential

In Taiwan, gully erosion and interrill erosion are responsible for soil detachment on mudstone badlands [5,50]. In general, grass root functional traits have notable influence on slope stabilization and gully erosion control [51,52]. *C. dactylon* and *E. ophiuroides* are indigenous pioneer C₄ plants and are able to adapt to the adverse environmental conditions of mudstone badlands, such as drought, salinity and low soil fertility [16]. Their roots can increase soil erosion resistance, and reduce soil detachment rates [53]. However, our results demonstrate the remarkable dissimilarity between the two grass species with respect to soil loss amounts and soil detachment rates at slope 15.0°. The bare soil has the highest soil loss amount, the root-permeated soil of *E. ophiuroides* ranks second, and *C. dactylon* the lowest. Moreover, the average soil detachment rate of *E. ophiuroides* is significantly greater than that of *C. dactylon*. Our analytical data also highlight that the root density of *C. dactylon* was remarkably higher than that of *E. ophiuroides*, and the relative soil detachment rates declined with increasing root density. Earlier studies have indicated that higher root density and root mass density have a positive effect on reducing soil erosion [18,25,51,52]. Overall, our results clearly display that the water erosion-reducing potential of *C. dactylon* is notably higher than that of *E. ophiuroides*.

In southern Taiwan, rainstorms often cause severe surface runoff and gully erosion as well as interrill erosion on mudstone badlands [6,50]. Vegetation engineering has become an efficient technique for soil conservation and restoration of degraded lands [1,50,52,54]. *C. dactylon* and *E. ophiuroides* are indigenous pioneer grass species on mudstone badlands. They have important influences on erosion control, soil reinforcement and ecosystem sustainability. Taken together, our results demonstrate that there are notable dissimilarities in root traits, pullout resistance, tensile resistance, and water erosion-reducing potential between these two grass species, and that *C. dactylon* is better than *E. ophiuroides* for erosion control of mudstone badlands. However, there are limitations, such as large-scale practical application techniques and costs. Further studies are needed to enhance revegetation and erosion control of mudstone badlands.

5. Conclusions

The results revealed that *C. dactylon* had remarkably greater root biomass, larger root surface area, larger root volume, higher root tip number, higher root density, and a higher root tissue density than those of *E. ophiuroides*. Furthermore, the root tensile resistance of *C. dactylon* was remarkably higher than that of *E. ophiuroides*. In addition, hydraulic flume tests showed that *C. dactylon* has remarkably smaller soil detachment...
rates than those of *E. ophiuroides*. Our findings highlight that *C. dactylon* has notably better root functional traits, pullout resistance, and root tensile resistance than *E. ophiuroides*. Importantly, hydraulic flume experiments showed that *C. dactylon* plants possess a higher water erosion-reducing potential than *E. ophiuroides* plants. Thus, our results contribute to enhancing ecoengineering technology of mudstone badlands by integrating the information of plant root functional traits, root biomechanical properties and water erosion-reducing potential. Furthermore, we suggest that companion planting with other indigenous C₄ grasses, such as Formosan arundo (*Arundo formosana*), Pacific Island silvergrass (*Miscanthus floridulus*), Sour grass (*Paspalum conjugatum*), and Wild sugarcane (*Saccharum spontaneum*), can be applied to reduce water erosion and enhance biodiversity of mudstone badlands.

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