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Creeper legume, in conjunction with biochar, is a potential tool to minimize soil erosion

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Abstract

Accelerated soil erosion and landslides are destructive consequences of road development and intensive agriculture in the central highlands of Sri Lanka. Properly designed vegetation covers can play a vital role in erosion control. Identifying a plant that can adapt to eroded land with a low-nutrient supply is critical for natural erosion management. A perennial creeper legume, *Vigna marina*, adaptable for marginal lands and used to control soil erosion in Australia, was introduced to Sri Lanka via the 2004 tsunami. The objective of this study was to assess *V. marina* under five different soil substrates, including a reference treatment (RT) recommended for optimal legume growth and subsoil (SS) and decomposing parent materials (DPM) without or with 20% *Pinus* wood biochar (SSb, DPMb). The growth parameters of *V. marina* were in the order RT > SSb = DPMb > SS = DPM. Following *V. marina* growth, nitrogen (N) content in DPM and DPMb increased from non-detectable to 1.83 and 0.99 mg g^{-1}, respectively. The SSb and SS recorded an increase in N by 1.38 and 0.77 mg g^{-1}, respectively. The RT lost soil N by 3.31 mg g^{-1}. Compared to the RT, root nodules were 3× in SSb and DPMb, 2× in SS, and >2× in DPM. Amending SS and DPM with biochar enhanced the growth of *V. marina*. The *V. marina*, in conjunction with biochar, can be an effective tool to provide vegetative cover to exposed soils and, thus, minimize soil erosion on road cuts and other land resources.

1 | INTRODUCTION

Sustainable management of natural disaster-driven consequences like landslides is vital for the environment and ecosystem. A landslide is a mass transfer process of soil or rocks with a sloping direction from its original position due to gravity, rotation, and translational movement generated from the disturbance in the natural soil structure. Increased human activities, such as road cuts in mountainous regions with increased slope dip angles, have aggravated soil erosion and caused frequent landslides. Conventional management of landslides is resource-intensive and relies on unsustainable and expensive approaches, such as slope geometry modification, chemical reinforcement of slope materials, and installation of physical reinforcement structures. Erosion control using vegetation and nature-based techniques is considered more sustainable than conventional methods (Francini et al., 2021). Vegetation can stabilize the slope

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Abbreviation: DPM, decomposing parent material; DPMb, decomposing parent material with biochar; mg g^{-1}, milligram per gram; RT, reference treatment; SS, subsoil; SSb, subsoil with biochar.

with mechanical reinforcement of soil through roots and reduce the hydrological impact on soil through transpiration, interception of precipitation, and active root water uptake (Greenway, 1987; Ziemer, 1981). Implementing a nature-based method as a hybrid engineering approach with the conventional approach can provide a better aesthetic outlook, allowing them to blend with the surrounding environment. The success of this method relies on selecting the right plant with greater root cohesive forces and adaptability on eroded land with marginal nutrient requirements. Some of the plant selection criteria listed by Ghestem et al. (2014) for slope failure remediation in China include greater adaptability, higher root density, root tensile strength, high root nitrogen (N) content, and greater stem density. Ganepola et al. (2021) proposed plant selection criteria for Sri Lanka based on plant root strength characteristics and hydrological, socioeconomical, and ecological significance. Identified potential plant species for soil erosion management in Sri Lanka include native and non-native grasses, shrubs, and tree species but do not include creepers (Ganepola et al., 2021).

Vigna marina, an Australian native perennial creeper legume plant, gained scientific attention due to its adaptability in marginal and extreme saline lands. It is one of the five naturally occurring *Vigna* species (Lawn & Cottrell, 1988), mostly known as dune bean and beach bean (Hacker, 1990). *V. marina* mainly grows in the margins of sandy or gravelly beaches, spread up to 4–6 m (Lawn & Cottrell, 2016). It has potential genes for drought and salt tolerance. *V. marina* seedlings could survive in 13 deciSiemens per meter (dS m^{-1}) conductance (Lawn & Cottrell, 2016). The plant was important in stabilizing coastal dunes in Australia to control sand erosion (Lawn & Cottrell, 2016). Any vegetation cover can minimize erosion by shielding the otherwise exposed soil surface from the impacts of raindrops. However, erosion-prone soils are depleted in nutrients to support any plant growth. *V. marina*, being a deep-rooted legume, has a unique ability to use water from deep sandy soil and fix atmospheric N. Fixed N supports plant growth, root proliferation, organic matter accumulation, and microbial activity, thus enhancing soil aggregation and formation of stable soil structure (Bronick & Lal, 2005; Six et al., 2002; Tisdall & Oades, 1982).

V. marina was introduced in Sri Lanka by a tsunami in 2004, and it can be a potential tool to address road cuts and landslide issues in Sri Lanka. However, it is yet to be assessed if *V. marina* will adapt and grow in severely degraded lands such as exposed subsoils (SSs) and decomposing parent material (DPM) generally found in road cuts. Soil amendments such as biochar can also enhance the restoration of degraded soil. Since biochar can be cost-prohibitive, locally available biomass to produce biochar must be explored to restore road-cut soils. The objectives of this study were to (i) assess the growth of *V. marina* in ideal soil conditions and degraded soil with or without biochar, (ii) evaluate its effect on soil nutrient contents, and (iii) its root nodulation and N fixation potential in severely degraded soils. The successful growth of *V. marina* on nutrient constraint eroded soils can signify its adaptability efficiency in degraded sloppy road cuts and landslide-susceptible areas. As a result, *V. marina* will be a potential tool in erosion prevention and sustainable landslide management.

Core Ideas

- *Vigna marina* can potentially grow under extremely degraded soil conditions.
- Poor soil fertility favors the root nodulation and biological nitrogen fixation of *V. marina*.
- Biochar enhances legume growth, root nodulation, and biological N fixation in degraded soils.

2 | METHODS

In this study, the growth of the *V. marina* was tested in soil amended with optimized nutrients and four other substrates or soil mediums ranging from degraded parent materials to subsoils. The physiological adaptability of the plant was recorded by measuring different morphological traits, including root and stem height, number of leaves, and number of nodules in individual treatment groups. In addition, the changes in soil nutrient status due to *V. marina* were measured as differences in soil nitrogen (N), phosphorus (P), and potassium (K) at the onset and the end of the experiment.

2.1 | Experimental design

A greenhouse pot experiment was conducted at the Faculty of Agricultural Sciences of the Sabaragamuwa University of Sri Lanka (FAS-SUSL) (6°42′19.7″N 80°47′17.1″E) for 2 months in 2019. Black-colored polyethylene pots (250 gauge and 36 × 25 cm) were used in the experiment. Each pot was filled with different substrate treatments. The treatments included (i) reference treatment or ideal soil medium (RT), (ii) SS, (iii) DPM, (iv) 20% (v/v) *Pinus* wood biochar (PWB) treated subsoil (SSb), and (v) 20% (v/v) PWB treated decomposing parent material (DPMb). Biochar treatments DPMb and SSb received only biochar, and no fertilizers were added to any treatments other than the RT. The Sri Lanka Department of Agriculture recommended RT (a mixture of substrates) for growing common beans (*Phaseolus vulgaris* L.). The recommended composition was a 1:1:1 ratio of topsoil, sand, and organic manure (cattle manure), urea at 190 kg ha^{-1}, triple super phosphate at 285 kg ha^{-1}, and muriate of potash at 150 kg ha^{-1} as the basal dressing and urea 190 kg ha^{-1} as the top dressing (4 weeks after planting) (Department of Agriculture Sri Lanka, 2023). The SS and DPM were collected from steep slope (80%–90%) surfaces of the demonstration farm at the FAS-SUSL. Biochar used in treatments SSb and DPMb was prepared from locally available *Pinus* wood using the cone pit method at a temperature of 400–450°C (Kwapinski, 2019; Lehmann & Joseph, 2015). *Pinus* wood was collected from a *Pinus* Forest in Belihuloya, Sri Lanka. A cone-shaped pit was prepared to limit oxygen and fire. Dried *Pinus* wood was cut into 25 cm pieces, filled into the pit, and burned. When the wood pieces turned black and developed a white ash coating, the fire was extinguished using water. Then the wood pieces were pounded and grounded using a hammer. All five treatments were replicated five times in a complete randomized design.

Germinated *V. marina* seeds were planted at 2 cm depth in all the treatment pots at one plant per pot. Manual scarification was done to stimulate the germination of seeds. Pots were kept in the polytunnel at 30°C for 2 months. Each pot was watered once a week with 3–4 liters of water. There were six holes (diameter 5 mm) at the bottom of each pot to allow excess moisture to drain. At the end of the growth period (after 2 months), the numbers of leaves, leaflets, and shoots were counted for each pot. The lengths of the most extended shoot and aboveground biomass (dry) were measured for each treatment. All the vegetation one cm above the soil surface was collected. The harvested biomass was wrapped using paper bags and kept in the oven for 24 h at 65°C before measuring dry aboveground biomass. The number and dry weight of root nodules per pot were also measured at the end of the experiment. Nitrogen content of the root nodules was measured using the Kjeldahl method (Bremner, 1960). Substrate N, P, K, pH, and electrical conductivity (EC) were measured at the beginning and the end of the experiment. The N, P, and K were analyzed using the Kjeldahl (Bremner, 1960), Olsen (Sims, 2000), and flame photometric methods (Mehlich, 1953), respectively. The pH and EC were measured using a tabletop pH/EC meter (Orion star a214 pH/EC benchtop meter, Thermo Fisher Scientific, MA, USA) with 1:2 dilution (soil:water) (Miller & Curtin, 2006).

2.2 | Data analysis

Statistical analysis was performed in the statistical software SAS 9.0. Analysis of variance (ANOVA) is a parametric test that compares the means of three or more groups. ANOVA is commonly used in experimental research to determine if there are significant differences in the means of treatment groups, which can help identify the effect of an independent variable on a dependent variable. Therefore, ANOVA test was used and performed in SAS using PROC ANOVA to evaluate the treatment effects on the dry weight of aboveground biomass, length of most extended shoot, the difference between initial and final soil NPK, and dry weight and N content of root nodules. The treatments were different substrates (RT, SS, DPM, SSb, and DPMb). The normal distribution of data was validated before statistical analysis. The code PROC CADMOD was used in SAS to determine the treatment effects on nonparametric data, such as the number of leaves, leaflets, shoots, and root nodules. When the main effect was significantly different, means were separated by the least significant difference test. A pair-wise comparison was made to test the difference between initial and final soil nutrient contents for each treatment. Statistical significance was evaluated at probability value or p-value <0.05.

3 | RESULTS AND DISCUSSION

3.1 | Initial substrate characteristics

At the onset of the experiment, the RT had the most excellent NP values since it was prepared following the recommended composition for optimal plant growth. The NPK values of the RT were 5.47, 3.50, and 0.45 mg g^{-1}, respectively. Nitrogen contents of the SS and SSb were 0.56 and 0.28 mg g^{-1}, respectively. In DPM and DPMb treatments, N content was below the detection level (<0.0001 mg N g^{-1}). SS and DPM generally make B and C horizons, respectively (Trumbore & Harden, 1997). The B horizon is an illuviated layer and a zone of accumulation, mainly accumulated by clay, soluble salts, gypsum, aluminum, and iron. Erosion and artificially modified landscapes can leave a B horizon on the surface. The C layer mostly consists of parent material, with minimal to no alterations due to the soil-forming processes. Horizons B and C contain few of the most crop essential nutrients and organic matter. Therefore, nutrient availability (N and P) in SS and DPM substrates used in the experiment is lower than in the RT (Table 1). Moreover, increasing soil depth typically diminishes the concentration of roots, active microbes, organic matter, and bioavailable nutrients. Less available nutrients lead to considerable growth reduction. Therefore, incorporating organic soil amendments, such as compost, manure, and biochar, is recommended to improve the properties of SS and DPM (Cooper et al., 2020).

Lower N observed in the SSb compared to SS could partly be due to the complexation of the biochar and N. The Kjeldahl method used in this study has a limitation in quantifying N from heterocyclic compounds (bound in carbon ring) and nitrate, nitrite groups (UC Davis, 2021). However, heterocyclic N-compounds like pyridinic-N, pyrrolic-N, and

TABLE 1 Initial characteristics of the different treatments used in this experiment.

Treatment[a]	N (mg g^{-1})	P (mg g^{-1})	K (mg g^{-1})	pH	EC (µS cm^{-1})
RT	5.47	3.50	0.45	6.82	320.8
SS	0.56	0.97	0.93	4.96	35.49
DPM	<0.0001	0.67	0.56	6.23	15.09
SSb	0.28	1.23	0.91	4.97	39.44
DPMb	<0.0001	0.51	0.68	6.23	17.88

[a] Treatments included (i) RT, (ii) SS, (iii) DPM, (iv) 20% (v/v) PWB SSb, and (v) 20% (v/v) DPMb.

Abbreviations: DPM, decomposing parent material; DPMb, PWB treated decomposing parent material; PWB, *Pinus* wood biochar; RT, reference treatment; SS, subsoil; SSb, treated subsoil.

quaternary-N dominate biochar as functional N-groups (Leng et al., 2020). The Kjeldahl method only measures N bound to organic compounds (protein, amino acids, and nucleic acids) and ammonium in the sample.

The soil pH values for RT and DPM with or without biochar were in the range of 6.0–7.0. The SS treatment with or without biochar had a pH < 5.0. In general, the soil's acidic condition may be attributed to the loss of cationic nutrients from the exposed SS via erosion and leaching, as oxidation generates a net increase in the H^+ ion. Soil organic matter is also known to deplete with the depth of soil. Generally, SS contains less amount of organic matter due to less root growth and erosion in hilly areas (Jobbagy & Jackson, 2000). In addition to the lack of organic matter, the lower buffering capacity of SS could also contribute to the acidic nature of the SS. The EC, which increases with ion concentration, was 320.8 µS cm^{-1} for RT since it was fertilized with the mineral fertilizer mixture of NPK, which contains ammonium (NH_4^+), phosphate (PO_4^{2-}), and potassium (K^+) ions. The SS, DPM, SSb, and DPMb had EC of 35.49, 15.09, 39.44, and 17.88 µS cm^{-1}, respectively. Lower EC compared to RT may be attributed to less NP concentration. Among unfertilized treatments, the SS with or without biochar had lower pH than DPM or DPMb and, therefore, slightly greater EC than DPM treatments.

3.2 | Growth parameters of *V. marina*

Following a 2-month growth, *V. marina* had the greatest aboveground biomass, number of shoots, length of the longest shoot, and number of leaves and leaflets in the RT (Figure 1, Table 2). Moreover, the leaves were darker green in the RT. An ample supply of plant nutrients via chemical fertilizers (Zaghloul et al., 2015) and optimal growing substrate played a vital role in plant growth and productivity in the RT, as evidenced by the best growth parameters under that treatment (Table 2).

Between SS and DPM, there were no differences in growth parameters ($p < 0.05$), and they had the least growth (Table 2). The SS and DPM treatments yielded 6% and 7% of the RT aboveground biomass, respectively. The number of leaves and leaflets in the SS and DPM treatments were 10% and 11% of those in RT, respectively. The SS and DPM had ≥35% and ≥40% of growth parameters in their corresponding treatments with biochar (SSb or DPMb). With poor growth in SS and DPM treatment, exposed SS and DPM in the landslide-prone area may be challenging for the proper development of *V. marina*. However, observable growth indicates their potential nature (Figure 1), which was enhanced using biochar.

Biochar treatments had greater growth parameters than the treatments without biochar (SSb > SS, DPMb > DPM) (Table 2, Figure 1). The growth parameters were similar between the SSb and DPMb. The biochar-added SS and DPM (SSb and DPMb) had growth parameters lower than the RT. The biochar-added treatments (SSb and DPMb) had 53%–65% less number of shoots than the RT but twice as much compared to no-biochar treatments (SS and DPM). The longest shoot and the number of leaves and leaflets were recorded in the order RT > SSb = DPMb > SS = DPM (Table 2). The longest shoot in the biochar-added treatments (SSb and DPMb) was shorter than in the RT by 40% but longer than in no-biochar treatments (SS and DPM) by 44%–61%. The SSb and DPMb had about 70% fewer numbers of leaves than the RT but 138%–188% more leaves than the SS and DPM. Similarly, the numbers of leaflets in the biochar-added treatments (SSb and DPMb) were lower than in the RT by about 70% and higher than in SS and DPM by 115%–167%. These results emphasize that biochar amendment significantly improved the growing conditions for *V. marina* in both SS and DPM. There were also reports of significant improvement following biochar application in the growth of other legumes, such as green bean (*Vigna radiata* L.) (Prapagdee & Tawinteung, 2017) and mung bean (*Vigna mungo* L.) (Kannan et al., 2021). Beneficial properties of biochar depend on the feedstock and pyrolysis process conditions (Weber & Quicker, 2018). Understanding and achieving the desired biochar properties that increase *V. marina* growth would enhance soil restoration efforts.

With the addition of biochar, the pH in the SS and DPM treatments increased from 4.96 to 5.02 and 6.23 to 6.30, respectively, indicating a shift toward a pH range

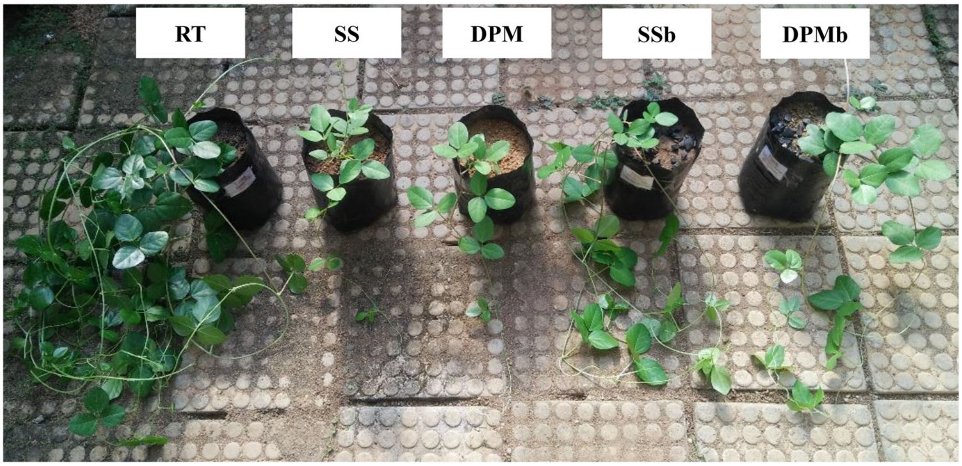

FIGURE 1 Aboveground biomass of *Vigna marina* plant under treatments, including (i) reference treatment (RT), (ii) subsoil (SS), (iii) decomposing parent material (DPM), (iv) 20% (v/v) *Pinus* wood biochar (PWB) treated subsoil (SSb), and (v) 20% (v/v) PWB treated decomposing parent material (DPMb).

TABLE 2 Summary of the growth parameters of *Vigna marina* in different substrates.

Treatment[a]	Aboveground biomass (g)	Number of shoots	Length of the longest shoot (cm)	Number of leaves	Number of leaflets
RT	22.82[b] a	17 a	172.22 a	82 a	249 a
SS	1.47 d	4 dc	63.62 c	8 c	27 c
DPM	1.70 cd	3 d	70.36 c	8 c	27 c
SSb	3.99 b	8 b	102.64 b	23 b	72 b
DPMb	3.13 bc	6 bc	100.56 b	19 b	58 b
***p* value**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**

[a] Treatments included (i) RT, (ii) SS, (iii) DPM, (iv) 20% (v/v) PWB SSb, and (v) 20% (v/v) DPMb.

[b] Different lowercase letters behind the mean values refer to a significant difference at a given *p*-value in the column.

Abbreviations: DPM, decomposing parent material; DPMb, PWB treated decomposing parent material; PWB, *Pinus* wood biochar; RT, reference treatment; SS, subsoil; SSb, treated subsoil.

(6.5–7.5) favorable to nutrient availability and microbial activity. Biochar application is known to improve soil functions in acidic soils as it raises soil pH variably depending on the quality of biochar. Chintala et al. (2014) reported that soil pH increased from 4.5 to >6.0 using corn stover biochar versus 4.5–5.6 using switchgrass biochar. Zhang et al. (2019) reported a rise in soil pH from 5.37 to 6.05 using peanut shell biochar. Biochar pH is important in this process, and values can range from 4.6 to 9.3 depending on the properties of the original feedstock and the production condition (Basiri et al., 2019). The pH of *Pinus* wood biochar used in this study was 6.2. Acidic soil restricts root access to water and nutrients. When soil pH drops below 5.0, aluminum (Al) becomes soluble. Aluminum retards root growth and restricts access to water and nutrients. Under acidic conditions, the major plant nutrients (N, P, K, Ca, sulfur [S], manganese [Mn]) and trace elements, may be minimally or not available. Acidic soil is a major factor restricting the survival and growth of *Rhizobium* spp. and disturbs nodule formation. Biochar application enhances the availability of plant nutrients, increases soil nutrient retention, and creates favorable conditions for the *Rhizobium* bacteria for N fixation and nodulation by providing accommodation and feed (soluble organic carbon) for microbiota (Beesley et al., 2011). Moreover, biochar increases the cation exchange capacity, moisture-holding capacity, and drainage by increasing the pore volume of the soil substrate (Schulz & Glaser, 2012). Biochar increases soil fertility and increases the biomass of the plant. The estimated residence time of biochar-carbon is in the range of hundreds to thousands of years in the soil (Blackwell et al., 2009). Therefore, a one-time application of biochar is enough for several decades, if not centuries. The adaptability of *V. marina* under nutrient-deficit substrates such as SS and DPM underscores its versatility, tolerability, and least demanding nature. Adding amendments such as biochar at optimal rates to landslide-susceptible areas is a potential tool in our

TABLE 3 Root nodules parameters as affected by different treatments.

Treatment[a]	Number of root nodules	Dry weight of root nodules (mg)	Nitrogen content of root nodules (mg g^{-1})
RT	19[b] d	9.2 d	26.7 e
SS	36 c	26.5 c	53.2 d
DPM	43 b	46.2 b	58.0 c
SSb	58 a	79.0 a	69.0 b
DPMb	56 a	71.1 a	83.9 a
***p* value**	**0.0001**	**0.0001**	**0.0001**

[a] Treatments included (i) RT, (ii) SS, (iii) DPM, (iv) 20% (v/v) PWB SSb, and (v) 20% (v/v) DPMb.

[b] Different lowercase letters behind the mean values refer to a significant difference at a given *p*-value in the column.

Abbreviations: DPM, decomposing parent material; DPMb, PWB treated decomposing parent material; PWB, *Pinus* wood biochar; RT, reference treatment; SS, subsoil; SSb, treated subsoil.

FIGURE 2 Root systems with nodules under treatments, including (i) reference treatment (RT), (ii) subsoil (SS), (iii) decomposing parent material (DPM), (iv) 20% (v/v) *Pinus* wood biochar (PWB) treated subsoil (SSb), and (v) 20% (v/v) PWB treated decomposing parent material (DPMb).

efforts to mitigate landslides through the natural plant–soil system.

3.3 | Root nodulation

There was a significant treatment effect on the dry weight, number, and N content of root nodules (Table 3). The number and dry weight of nodules were in the order SBb = DPMb > DPM > SS > RT (Table 3, Figure 2). The RT had the lowest number and dry weight of nodules (19 and 9.2 mg) (Table 3). Rapid nitrate (NO_3-) release by chemical N fertilizers harms soil microbial activities (Gunapala & Scow, 1998). Nodulation by an active, growing legume is suppressed by NO_3^- ions (Zahran, 1999). The pH of RT at the end was 5.12. Acidic pH also adversely influences on survival and growth of most active strains of *Rhizobium* spp. (Jo et al., 1980). Furthermore, increased H^+ concentration and increasing the solubility of the toxic metal ions, such as Al, Cu, and Mn retard N fixation (Fageria et al., 2002). The N-constrained environment and supplemental micro–macro nutrients from the biochar in SSb and DPMb might have provided stimulants for the nodule formation. The number of nodules was ~2× higher in the biochar-added treatments (SSb and DPMb) than in the RT. Similarly, the biochar-added treatments had 30% and 60% more nodules than their corresponding no-biochar treatments. The SSb and DPMb had around 7× the nodules dry weight of the RT and greater by 54% and 199% than their complementary no-biochar treatments (SS and DPM).

Crop biomass production is correlated to root architectural development, particularly in N-sufficient soils (Hammer et al., 2009). In the case of eroded soil, in addition to the root system, the nodulation by N fixing bacteria is critical to supply N needed for the plant to grow. Our results showed that *V. marina* benefitted from biological N fixation to establish itself in eroded nutrient-depleted soil. Biochar enhanced *V. marina* growth to achieve better canopy cover. Improved plant canopy reduces soil erosion by interception of raindrops, improving infiltration rate and soil water extraction via canopy transpiration (Ma et al., 2014). Further studies on *V. marina* root traits are warranted to understand its contribution to soil structure and aggregates beneficial to preventing erosion.

The nodules N contents were in the order DMPb > SSb > DPM > SS > RT. The DPMb and SSb had 215% and 159% more N in root nodules than the RT. They had 44% and 30% more root nodules N than their corresponding no-biochar treatments. The SS and DPM had 2× nodules N than the RT. Nitrogen fixation, as a result of nodulation, is promoted by relatively low levels of available nitrate or ammonium (Zahran, 1999). The initial N contents of the DPM and DPMb were <0.0001 mg N g^{-1} (undetectable), SS and SSb had 0.56 and 0.26 mg N g^{-1} (compared to 5.47 in the RT), which provided an optimal environment for nodulation, and subsequently, greater biological nitrogen fixation (BNF). The SSb and DPMb had higher nodulation and BNF with the added benefit of biochar. The SS substrate was acidic (pH 4.96), adversely affecting most of the bacteria. Furthermore, the initial pH of DPM was 6.23, closer to the optimal pH range (6.5–7.5). Therefore, the nodulation and the total N content were higher with the DPM than with SS. Increased formation of root nodules will result in greater BNF within the plants. The *V. marina* plants meet the N need from the BNF; hence, no additional fertilizer is needed, or only a minimal amount is needed. Additionally, the low C:N ratio of legumes increases microbial decomposition, increases mineralization, and releases nutrients to the soil by increasing the availability of soil N with the breakdown of *V. marina* residue (Jensen et al., 2012).

These findings underscore that the decomposed and exposed SS in the slope failure areas can be restored using biochar as a soil amendment for *V. marina*. In addition, biochar maintains optimal pH, adsorbs toxic materials from a substrate, and maintains balanced moisture content (Schulz & Glaser, 2012), providing a favorable environment, such as safe accommodation, nutrients, and energy for microbiota (Beesley et al., 2011).

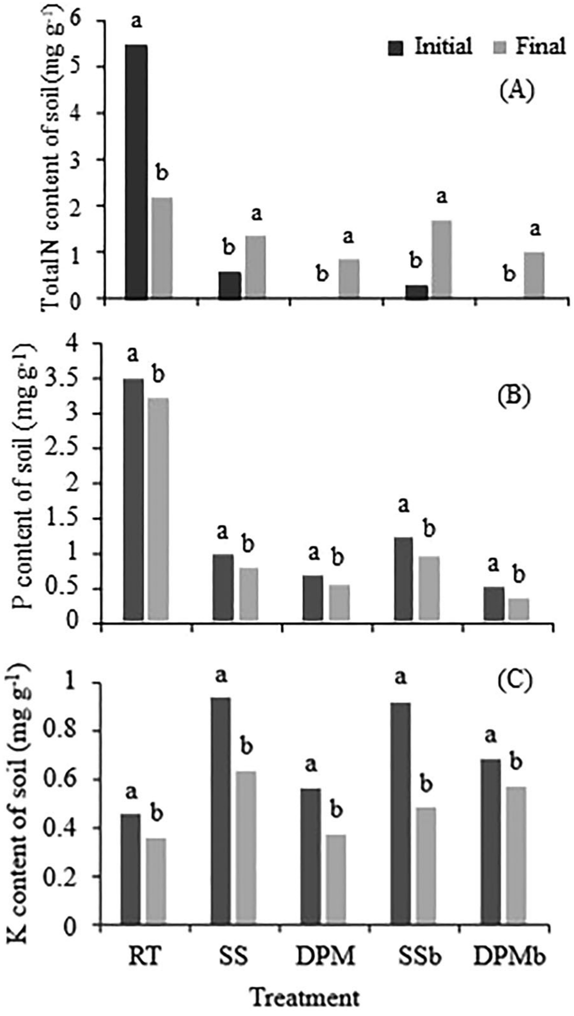

FIGURE 3 Initial and final soil nitrogen (A), phosphorus (B), and potassium (C) contents in the different substrates; (i) reference treatment (RT), (ii) subsoil (SS), (iii) decomposing parent material (DPM), (iv) 20% (v/v) *Pinus* wood biochar (PWB) treated subsoil (SSb), and (v) 20% (v/v) PWB treated decomposing parent material (DPMb). Pair-wise comparison between initial and final nutrient content for each treatment was conducted, and different lowercase letters above the mean values refer to a significant difference at $p < 0.05$.

3.4 | Post-harvest substrate characteristics

3.4.1 | Soil residual N and N-credits

Nitrogen is the most limiting crop nutrient; therefore, the RT with optimum initial N had higher plant N uptake and, subsequently, greater growth than other treatments. Due to the luxury effect of applied N, there was minimal nodulation and BNF in the RT treatments, which aligns with other studies that reported reduced BNF with fertilizer N application (Choudhury & Kennedy, 2004; Reinprecht et al., 2020; Tamagno et al., 2018). As a result, the majority of plant N uptake is supplied by mineral N in the substrate, not BNF, which led to soil N depletion by 60.5% in the RT treatment (Figure 3A). Additionally, applied N is highly water soluble and can easily be lost through leaching and denitrification.

Contrary to the RT, there were gains in soil N (N credit) for all other treatments. The gain in soil N was in the order SSb > DPMb > DPM > SS > RT. (Table 4). The gain in N is due to the enhanced BNF as a feedback mechanism of legume for the N-constrained environment. Amending exposed subsoil with biochar (SSb) showed a greater N gain (393%) than only SS treatment (138%) following the growth of *V. marina*. The same was true in the case of DPM. Biochar and *V. marina* synergistically enhanced soil N content. The added benefit of

TABLE 4 Summary of soil NPK differences between initial and final values in the experiment.

Treatment[a]	Soil N credit (mg g^{-1})	Soil P depletion (mg g^{-1})	Soil K depletion (mg g^{-1})
RT	−3.31[b] e	0.29 a	0.10 d
SS	0.77 d	0.18 bc	0.30 b
DPM	0.83 c	0.12 c	0.19 c
SSb	1.38 a	0.29 a	0.45 a
DPMb	0.99 b	0.17 bc	0.11 d
***p* value**	**0.0001**	**0.06**	**0.0001**

[a] Treatments included (i) RT, (ii) SS, (iii) DPM, (iv) 20% (v/v) PWB SSb, and (v) 20% (v/v) DPMb.

[b] Different lowercase letters behind the mean values refer to a significant difference at a given *p*-value in the column.

Abbreviations: DPM, decomposing parent material; DPMb, PWB treated decomposing parent material; PWB, *Pinus* wood biochar; RT, reference treatment; SS, subsoil; SSb, treated subsoil.

biochar includes nutrient availability like B, Mo, K, Ca, and P, which stimulate higher BNF (Rondon et al., 2007). Rao (2014) and Bellenger et al. (2020) suggested that greater availability of nutrients, especially Mo (molybdenum), improves the BNF in soybean significantly as Mo is the primary constituent of nitrogenase enzyme complex (molybdenum–iron/Mo–Fe). There are other studies that reported enhanced BNF and bean production following biochar application (Güereña et al., 2015; Rondon et al., 2007; Xiu et al., 2021).

3.5 | Soil residual phosphorus and potassium

There was a considerable depletion in soil P across the treatments (Figure 3B). Phosphorus is the second major nutrient for crop growth and development, especially at the plant's early growth stages (Hayat et al., 2010). Phosphorus plays a significant role in root development, nutrient uptake, and growth of legume crops (Kabir et al., 2013). Particularly, legumes need more P for energy transformation in root nodules. Therefore, there was a trend for greater soil P depletion in the RT and the biochar-added treatments with greater nodulation than their corresponding no-biochar treatments.

There was a significant depletion in soil K across the treatments (Figure 3C). Soil K depletion was in the order SSb > SS > DPM > DPMb > RT (Table 4). Potassium is the third major nutrient for crop growth and development, especially for the reproduction of plants. Moreover, K is required to maintain plant health, synthesize protein and starch, and enhance photosynthesis. In addition, potassium is one of the essential nutrients needed for biological N fixation and nodule formation (Abd-Alla & Wahab, 1995; Duke et al., 1980). Potassium is also vital in maintaining nitrogenase activity per unit root weight and per unit nodule weight of legumes (Høgh-Jensen, 2003).

4 | CONCLUSION

V. marina has the potential to establish well under degraded soil conditions (i.e., SS and DPM). The poor fertility status of the substrate favored the BNF by *V. marina*. Amending degraded soils with locally available biochar enhanced the growth of *V. marina*. In conjunction with biochar, *V. marina* synergistically improved soil N supply. Further in situ research is warranted to evaluate the potential use of *V. marina* in controlling soil erosion on road cuts and other exposed areas of land resources. A healthy legume canopy would help prevent soil erosion by shielding the soil from rain impacts. Exploring the root traits of *V. marina* that directly affect the mechanical reinforcement of soil through the restoration of soil structure and aggregates will provide a comprehensive understanding of *V. marina's* benefits in erosion prevention efforts.

AUTHOR CONTRIBUTIONS

Sujani De Silva: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Visualization; Writing – original draft; Writing – review & editing. **Priyantha Indralal Yapa**: Conceptualization; Investigation; Methodology; Project administration; Resources; Supervision; Writing – review & editing. **Kushani Mahatantila**: Conceptualization; Investigation; Methodology; Project administration; Supervision; Writing – review & editing. **Saurav Das**: Formal analysis; Supervision; Writing – review & editing. **Bijesh Maharjan**: Formal analysis; Supervision; Writing – review & editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interests.

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