

## Soil types influence early shoot and root growth of *Neolamarckia macrophylla* (Roxb.) Bosser (Red laran) seedlings

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### Abstract

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*Neolamarckia macrophylla*, commonly referred to as red laran, has not been extensively studied in Sabah, Malaysia. This species is known for its rapid maturation and pest resistance, making it a viable option for plantations because of its adaptability and profitability. This study examined the growth of *N. macrophylla* in cocopeat, poor soil, topsoil, and organic amendments under rhizotron conditions. The application of cocopeat enhanced the root size and morphology through soil moisture retention and facilitating adequate aeration. Notably, nutrient-deficient soils caused the seedlings to develop thicker stems and larger leaves, indicating the plant’s resilience in nutrient-poor environments. Optimal root development was observed when the topsoil was combined with rice husk. These findings suggest that *N. macrophylla* is well-suited for reforestation and land rehabilitation, particularly when appropriate soil amendments are utilised.

### Keywords

belowground, exotic species, fast growing, forest plantation, forest restoration, root growth

### Introduction

A significant issue concerning the threat to tropical forests is the extensive degradation occurring over large areas, which is accompanied by the loss of ecological function (PHILLIPS, 1997). While some of these areas have the potential to recover naturally, human intervention is often necessary for restoration enabling these areas to become a new generation of forest plantations in the future (SILVA et al., 2019). This can be achieved by establishing large-scale forest plantations on degraded areas to facilitate reforestation (LAMB, 1998). This is supported by DAVIS et al., (2012), where due to the unprecedented levels of deforestation, particularly

in tropical regions, the establishment of forest plantations serves as a measure to restore ecological stability to the land. Consequently, as the availability of natural forests diminishes, the activity of forest plantation establishment has concurrently increased (LINTANGAH et al., 2010). Global demands for wood timber supply have led to the planting of selected species depending on their capability to adapt to local conditions and their unique fast-growing characteristics (DODET and COLLET, 2012). Agroforestry and plantation systems are part of the overall ecosystem mechanisms in the way that trees interact with other organisms in the managed landscapes (GRANDEZ-RIOS et al., 2025). This is to meet the industrial demand for raw materials derived from commer-

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cial forest products (HANDAYANI et al., 2019).

In 1985, in order to fulfil demand from many parts of the world, the Malaysian government initiated the establishment of large-scale Compensatory Forest Plantation activities by adapting various fast-growing exotic species (HAMID and ABIRI, 2022). Due to this, Malaysia managed to establish nearly one million hectares of forest plantations in 2019 (RATNASING et al., 2020). In October 2013, *Neolamarckia macrophylla* (red laran) species, which is not well-known in Sabah, was utilised in two forest management units (FMU), which are the Usahawan Borneo Group and Sapulut Forest Developments involving 200 ha (CHUNG et al., 2016) et al., 2016). Exotic species which are introduced in such efforts through commercial plantations are usually equipped with important features such as high capability of adaptation, fast-growing, succession of invasion and only need slight or intermediate shade tolerance (DODET and COLLET, 2012).

*N. macrophylla* (Rubiaceae) known as red jabor (IRAWAN and PURWANTO, 2014) or semama are endemic in Celebes and Moluccas. *N. macrophylla* can grow up to 40–45 m straight and tall with columnar bole that is up to 80% free from branches. The reason it is called “red laran” is due to the crimson colour of its juvenile stem and leaf midrib (CHUNG et al., 2016). It is also classified a light-demanding tree (EFENDI et al., 2019). Further, its self-pruning characteristics give benefits in nourishing the soil (HALAWANE et

al., 2015). This species is given preference because it grows within a short period of time, is known to be pest-resistant with strong adaptability which makes it economically profitable (IRAWAN and PURWANTO, 2014). The choice of fast-growing exotic tree species is usually guided by the factors of productivity, in addition to their ability to improve the soil in the eroded areas (MOSLEHI et al., 2025).

Soil and roots play important roles for plants in the uptake of water and nutrients directly from soil and this makes it important to understand how soil influences the roots effect (LOGSDON, 2015). Soil amendments and planting media influence shoot and root growth of seedlings (AWANG et al., 2009). The soil characteristics have a very strong impact on the establishment of tree seedlings as it determine the amount of nutrients available, the growth of roots, and the interactions between the plant and the soil microorganisms (SÁNCHEZ-LEDESMA et al., 2025). Thus, the aim of this study was to evaluate the effects of various soil amendments or planting media on early shoot and root growth of *N. macrophylla* seedlings.

## Materials and methods

### Study site

The four-months study (August 2021–November 2021)

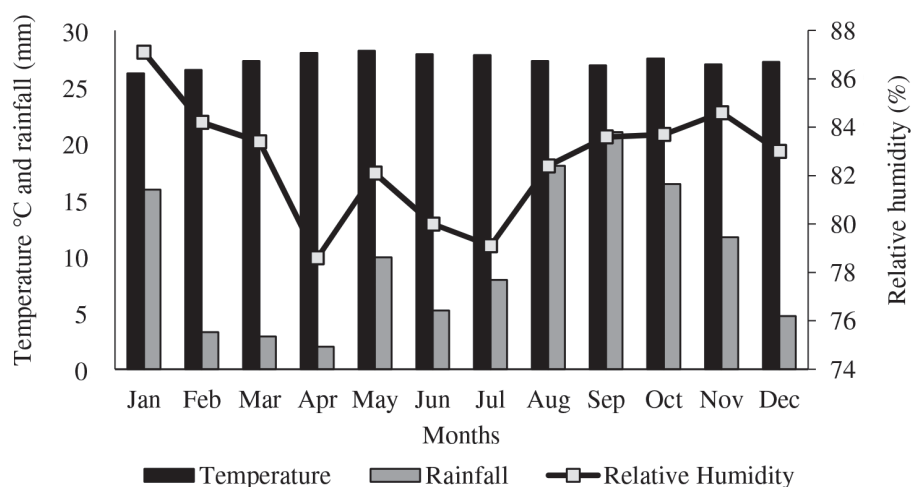


Fig. 1. Monthly temperature, rainfall, and relative humidity data from a weather station at Kota Kinabalu for the year 2021.

Table 1. Physical and chemical characteristics of the substrates (nutrients in meq 100 g<sup>-1</sup>)

Treatments	pH	Organic matter (%)	N (in meq 100 g <sup>-1</sup> )	P (in meq 100 g <sup>-1</sup> )	K(in meq 100 g <sup>-1</sup> )	Texture (sand%-Silt%-Clay%)
Cocopeat (T1)	5.7	85.0	0.06	0.003	0.04	Fibrous (>95% organic fibres)
Poor soil (T2)	4.7	2.0	0.16	0.005	0.10	72-18-10 (sandy loam)
Topsoil as control (T3)	5.5	3.8	0.31	0.015	0.22	56-27-17 (loam)
Mixture of topsoil and rice husk (T4)	6.3	14.5	0.54	0.030	0.41	41-34-25 (clay loam)
Mixture of topsoil and sand (T5)	6.8	0.9	0.11	0.004	0.07	86-9-5 (sandy)

was conducted at the Faculty of Tropical Forestry, Universiti Malaysia Sabah (UMS), Kota Kinabalu, Sabah, Malaysia (6°02'10.7" N and 116°07'34.9" E). In 2021, the weather conditions for the experimental site ranged between 26.2–28.2 °C for temperature, 78.6–87.1% for relative humidity, and 2.0 mm to 21.0 mm for rainfall (JABATAN METEOROLOGI MALAYSIA, 2021) (Fig. 1).

### Plant preparation and research design

Rhizotrons were used in this study, made from transparent polycarbonate material (HASSAN et al., 2020) measuring 15 cm × 15 cm × 100 cm. A total of 30 rhizotrons were used during the study. There were five (5) treatments which are cocopeat (T1), poor soil (T2), topsoil as control (T3), mixture of topsoil and rice husk (T4) and mixture of topsoil and sand (T5) with six replications for each treatment. For T1 the soil media was according to ratio 1:1 (VILLANUEVA et al., 2010). The quantity of growing media topsoil 80% and rice husk was 20% (T4) (MARJENAH et al., 2016) while topsoil and sand (T5) used the mixture of 2:1 ratio (KHATTA et al., 2023). The poor soil used in this experiment was sourced from desolate areas near the study site, while the topsoil was from the Tamparuli Forest Reserve located approximately 30 km from UMS. The topsoil was dried for seven days inside the greenhouse.

Nets were installed at the openings in each rhizotron to prevent the soil from coming out. Each of the soil – filled rhizotrons was subjected to a compaction process using a hand compactor (hand tamper) to mimic natural conditions in the field (AMBAS et al., 2024). The physical and chemical characteristic of the treatments before the nutrient washing and fertilization are presented in Table 1. After the compaction process, five litres of water were poured through each rhizotron to remove water-soluble plant nutrients to achieve soil homogeneity. Fertilization was applied once during the early of the experiment after the nutrient washing process, seedlings was grown solely on the inherent nutrient content of the respective substrates until the week of harvesting. A compound NPK fertilizer (15:15:15) was incorporated into the experiment, where each seedling was supplied with 0.120 g per rhizotron on a biweekly basis. This dosage corresponds to an estimated field application rate of 50 kg ha<sup>-1</sup>. Each rhizotron was then marked to indicate four depths which are 0–25 cm, 25–50 cm, 50–75 cm and 75–100 cm (HASSAN et al., 2020).

All the treatments were arranged using a Completely Randomized Design (CRD). A month-old seedling of *N. macrophylla* was supplied by Forest Research Centre (FRC), Sandakan. The origin of the seedlings was from shoot cutting and none were from seed germination. The age of the seedlings upon transplanting into the rhizotrons was 3 months. Then seedlings were planted in the rhizotrons available for the different soil treatments. The seedlings transplanted into the rhizotrons were allowed to go through the hardening process for a week to adapt to their new environment before data collection commenced. Harvesting throughout this study was divided into two stages.

### Data collection

For the aboveground or shoot parameters, vernier calipers were used to measure the root collar diameter of the seedlings (TAKOUTSING et al., 2013) and height of the seedlings was measured using measuring tape. Leaf area index (LAI) is the total leaf area (m<sup>2</sup>) per ground area (m<sup>2</sup>) (TSIALTAS and MASLARIS, 2008). Total leaf area (m<sup>2</sup>) was measured using a leaf area meter (Li-3000) (TEWOLDE et al., 2005). Shoot biomass was measured by harvesting and drying the shoot in an oven for 48 hours at 70 °C (AMBAS et al., 2024). The shoot biomass of 30 plants was analysed (each rhizotron only had one plant). Parameters measured for roots for each of the four soil depths included root intensity (RI) (intersection m<sup>-1</sup> gridline), root length density (RLD), root biomass (RB) (HASSAN et al., 2020) and specific root length (SRL) (HASSAN et al., 2021b). In order to count the roots, the grid lines in the images were intercepted, and the values for the number of roots were converted to RI (intersections m<sup>-1</sup> grid line) (HASSAN et al., 2021b). The root images were taken by using a digital camera with a 16-megapixel resolution (Nikon Coolpix S6800) as a non-destructive method (HASSAN et al., 2021a). Harvesting was performed twice. Once it reaches 8 weeks after transplant (WAT) and 16 WAT for the final harvest. For each harvesting it involves three replicates for each treatment with a total of 15 plants.

### Statistical analysis

Statistical Package for Social Sciences software was used for statistical analysis (IBM SPSS Statistics 28.0). One-way ANOVA and post hoc pairwise comparisons using Tukey's HSD were used to test whether there were any significant differences ( $p < 0.05$ ) in shoot and root parameters between the soil treatments.

## Results

### Aboveground components

#### Height and root collar diameter increments

Both root collar diameter increment (RCDI) and height increment (HI) showed non-significant differences between the soil treatments ( $p > 0.05$ ) as shown in Table 2. The RCDI values however were similar ( $0.44 \pm 0.09$  mm (topsoil) to  $0.78 \pm 0.62$  mm (cocopeat)) across treatments which show similarity in the thickness of the stem. On the same note, HI was  $2.13 \pm 0.44$  cm (topsoil and ricehusk) to  $2.88 \pm 0.49$  cm (poor soil). Although there were no notable differences, a clear pattern was followed in the growth of height as the seedlings planted in the poor soils revealed the highest increment, whereas the ones in the topsoil + rice husk treatment had the lowest HI.

#### Leaf area index (LAI)

Table 3 shows that the mean leaf area index did not differ significantly among the soil treatments ( $p > 0.05$ ). How-

Table 2. Root collar diameter increment (RCDI) and height increment (HI) of *N. macrophylla* seedlings under five soil treatments (16 WAT). There was no significant difference between treatments in the light of one-way ANOVA with Tukey HSD post hoc ( $p > 0.05$ ,  $n = 3$ ).

Aboveground parameters	Treatments (Mean $\pm$ standard deviation)					<i>p</i> -value
	Cocopeat	Poor soil	Topsoil	Topsoil + Rice husk	Topsoil + Sand	
RCDI (mm)	0.78 $\pm$ 0.62	0.78 $\pm$ 0.07	0.44 $\pm$ 0.09	0.45 $\pm$ 0.03	0.49 $\pm$ 0.11	$p > 0.391$
	2.31 $\pm$ 1.83	2.88 $\pm$ 0.49	2.51 $\pm$ 0.56	2.13 $\pm$ 0.44	2.50 $\pm$ 0.86	$p > 0.909$

Table 3. The leaf area index (LAI) of seedlings of *N. macrophylla* under five soil treatments with 16 WAT. There were no significant differences between treatments according to one-way ANOVA and Tukey HSD post hoc test ( $p > 0.05$ ,  $n = 3$ ).

Treatment	Leaf area index ( $m^2 m^{-2}$ )	
	Mean $\pm$ standard deviation	<i>p</i> -value
Cocopeat	2.51 $\pm$ 1.93	$p > 0.341$
Poor soil	3.95 $\pm$ 0.86	
Topsoil	2.68 $\pm$ 1.13	
Topsoil + Rice Husk	1.96 $\pm$ 0.60	
Topsoil + Sand	2.87 $\pm$ 0.33	

Table 4. Dry shoot biomass of seedlings of *N. macrophylla* placed under 16 WAT under various soil treatments less than five. The difference between treatments was insignificant according to one-way ANOVA with Tukey-HSD post hoc test ( $p > 0.05$ ,  $n = 3$ ).

Treatment	Dried shoot biomass (g)	
	Mean $\pm$ standard deviation	<i>p</i> -value
Cocopeat	155.18 $\pm$ 146.89	$p > 0.76607$
Poor soil	200.19 $\pm$ 68.95	
Topsoil	200.19 $\pm$ 68.95	
Topsoil + Rice Husk	114.00 $\pm$ 16.64	
Topsoil + Sand	154.33 $\pm$ 34.15	

ever, the poor soil treatment resulted in the highest leaf area index ( $1.96 \pm 0.60 m^2 m^{-2}$ ) compared to other treatments while the lowest mean LAI was for the topsoil and rice husk treatment ( $3.95 \pm 0.86 m^2 m^{-2}$ ).

### Dried shoot biomass (DSB)

The results from one-way ANOVA indicated that there are no significant differences between treatments ( $p > 0.05$ ) for dried shoot biomass of *N. macrophylla* as shown in Table 4. The DSB showed a range of values of 114.00 g to 200.19 g across treatments. The maximum mean of DSB was found in poor soil treatment ( $200.19 \pm 68.95$  g) and the minimum mean in the topsoil and rice husk treatment ( $114.00 \pm 16.64$  g). At the same time, cocopeat ( $155.18 \pm 146.89$  g), topsoil ( $152.83 \pm 53.38$  g), and topsoil and sand ( $154.33 \pm 34.15$  g) treatments had rather similar shoot biomass performance.

### Root parameters

#### Root intensity (RI)

As shown in Fig. 2, at 8 WAT a significant difference ( $p < 0.05$ ) was observed in Fig. 2, at 8 WAT a significant difference ( $p < 0.05$ ) was observed at all depths for all treatments. The highest RI was found in the cocopeat treatment ( $126.45 \pm 20.00$  at 8 WAT) and ( $86.94 \pm 5.20$  at 16 WAT) which showed a positive effect on early root growth. By 16 WAT, it was demonstrated that roots continued to develop. Cocopeat continued to give the highest RI of treatments at depths between 50–100 cm and this would indicate further penetration of roots being supported. It is also worth noting that the topsoil + rice husk treatment experienced higher root establishment at depths of 25–5 cm at 16 WAT than at 8 WAT, which depicts the gradual root adjustment to the amended media over time. Topsoil and ricehusk and topsoil and sand treatments, on the other hand, had only minor improvements on RI yet were found to be weaker

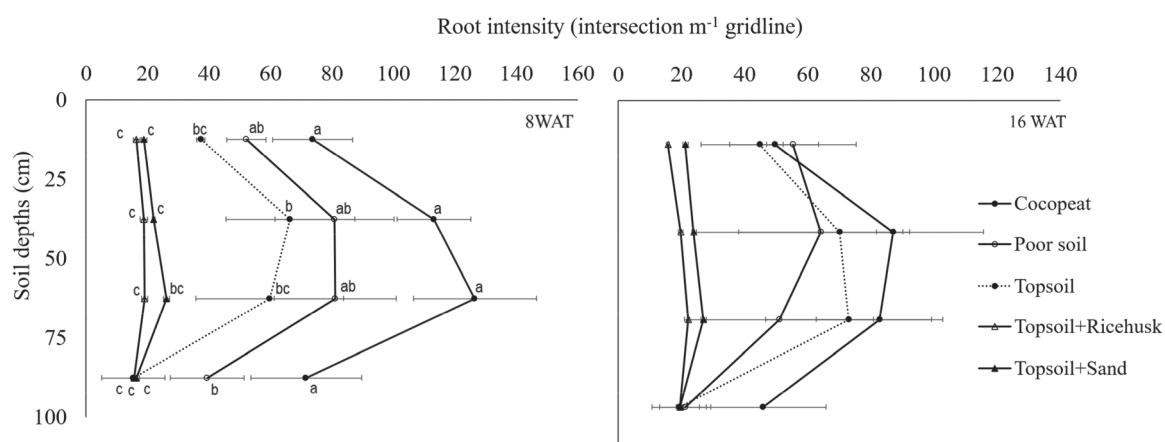


Fig. 2. Root intensity (intersections  $m^{-1}$  gridline) of *N. macrophylla* at four soil depths under five soil treatments at 8 and 16 WAT. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test (8 WAT:  $p < 0.05$ ,  $n = 3$ ; 16 WAT:  $p > 0.05$ ,  $n = 3$ ).

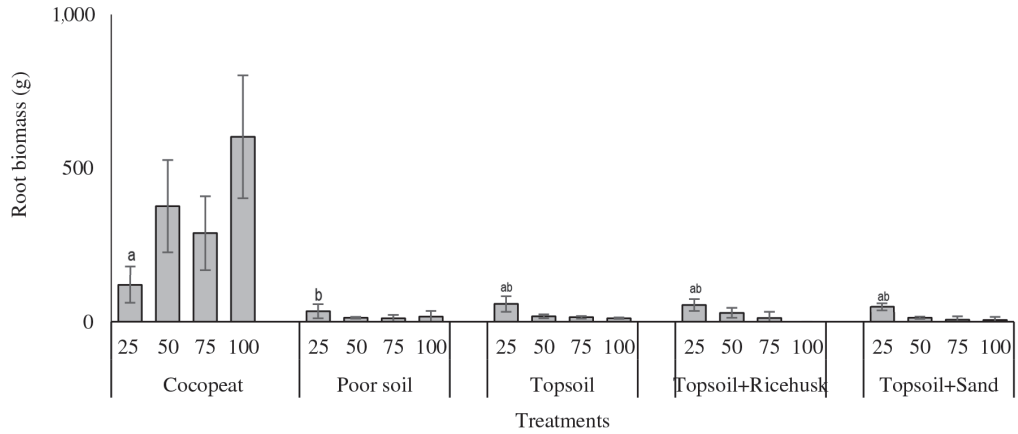


Fig. 3. Root biomass (g) of *N. macrophylla* at four soil depths under five soil treatments. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test ( $p < 0.05$ ,  $n = 3$ ). Error bars indicate standard deviation.

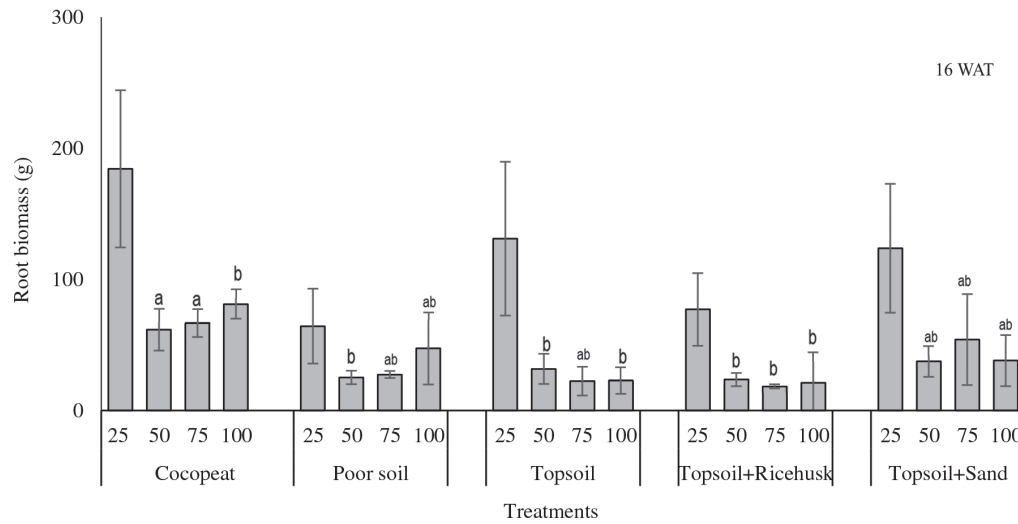


Fig. 4. Root biomass (g) of *N. macrophylla* at four soil depths under five soil treatments. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test ( $p < 0.05$ ,  $n = 3$ ). Error bars indicate standard deviation.

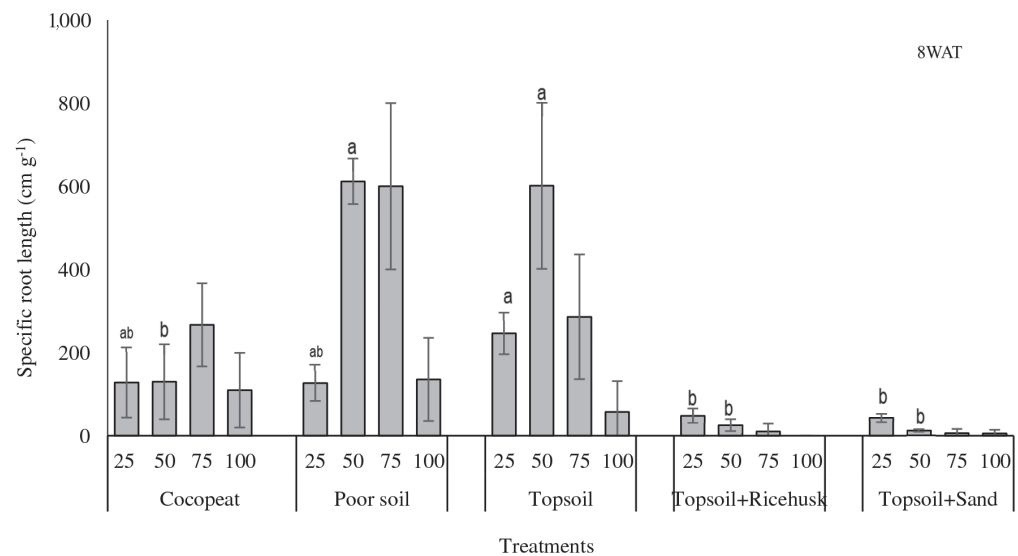


Fig. 5. Specific root length ( $\text{cm g}^{-1}$ ) of *N. macrophylla* at four soil depths under five soil treatments. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test ( $p < 0.05$ ,  $n = 3$ ). Error bars indicate standard deviation.

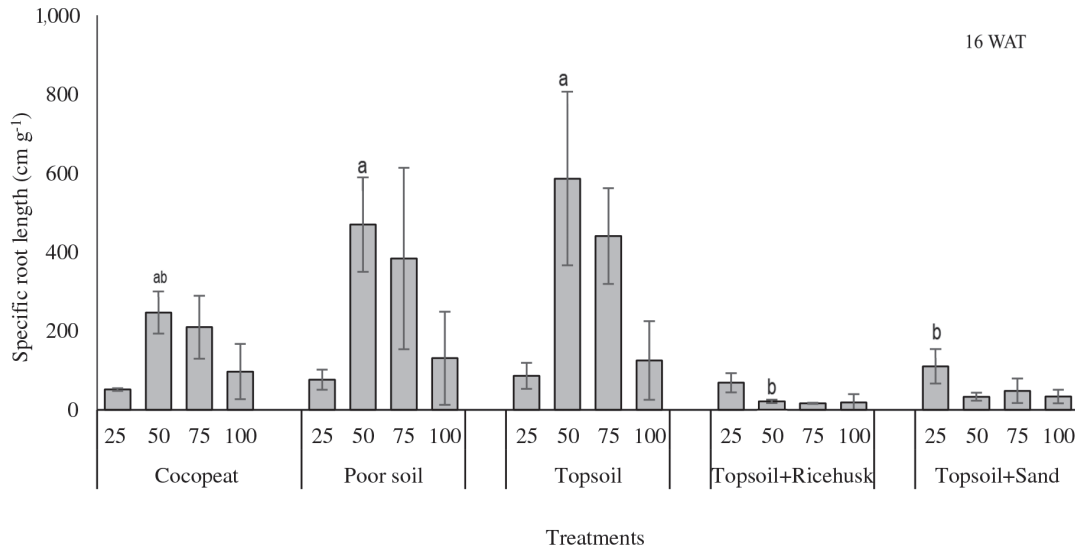


Fig. 6. Specific root length ( $\text{cm g}^{-1}$ ) of *N. macrophylla* at four soil depths under five soil treatments. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test ( $p > 0.05$ ,  $n = 3$ ). Error bars indicate standard deviation.

as compared to cocopeat and other amended media, particularly in deep layers. But at 16 WAT, the differences were not significant anymore ( $p > 0.05$ ).

#### Root biomass (RB)

The results of ANOVA showed significant differences ( $p < 0.05$ ) in RB between treatments at 8 WAT and 16 WAT at each soil depth. As shown in Fig. 3, for root biomass at 8 WAT ( $602.00 \pm 200.00$ ) the cocopeat treatment markedly outperformed all other treatments at the deepest soil layer, reaching more than 600 g compared to all other treatments. In contrast, the lowest RB was shown by the poor soil treatment while topsoil, topsoil and rice husk, topsoil and sand demonstrated intermediate performance. By 16 WAT, as shown in Fig. 4, the pattern of root

biomass at different depths was more similar for most treatments and the total biomass values increased, indicating that roots were still developing. Cocopeat was still the top producer of biomass in total. The poor soil treatment, however, remained the least productive, although some biomass increase was observed in the upper layer at 8 WAT ( $33.73 \pm 22.47$ ) and 16 WAT ( $64.23 \pm 28.59$ ).

#### Specific root length (SRL)

The results of ANOVA showed significant differences ( $p < 0.05$ ) in SRL between treatments at 8 WAT and 16 WAT at each soil depth. As shown in Fig. 5, at 8 WAT the poor soil ( $611.97 \pm 54.61$ ) and topsoil ( $601.32 \pm 200.00$ ) treatment had significantly higher SRL values than the other treatments, especially at 25–50 cm depth. It showed that plants

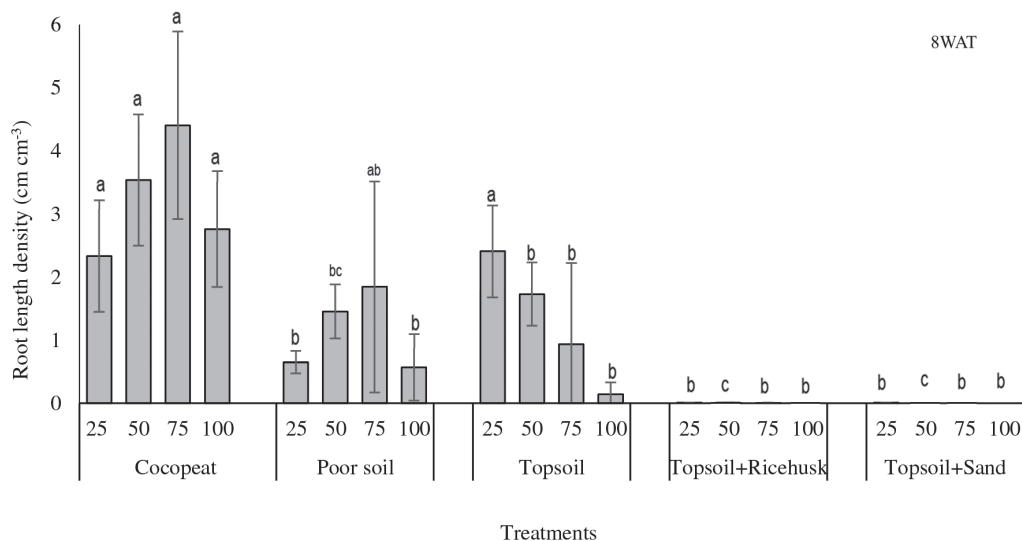


Fig. 7. Root length density ( $\text{cm cm}^{-3}$ ) of *N. macrophylla* at four soil depths under five soil treatments. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test ( $p < 0.05$ ,  $n = 3$ ). Error bars indicate standard deviation.

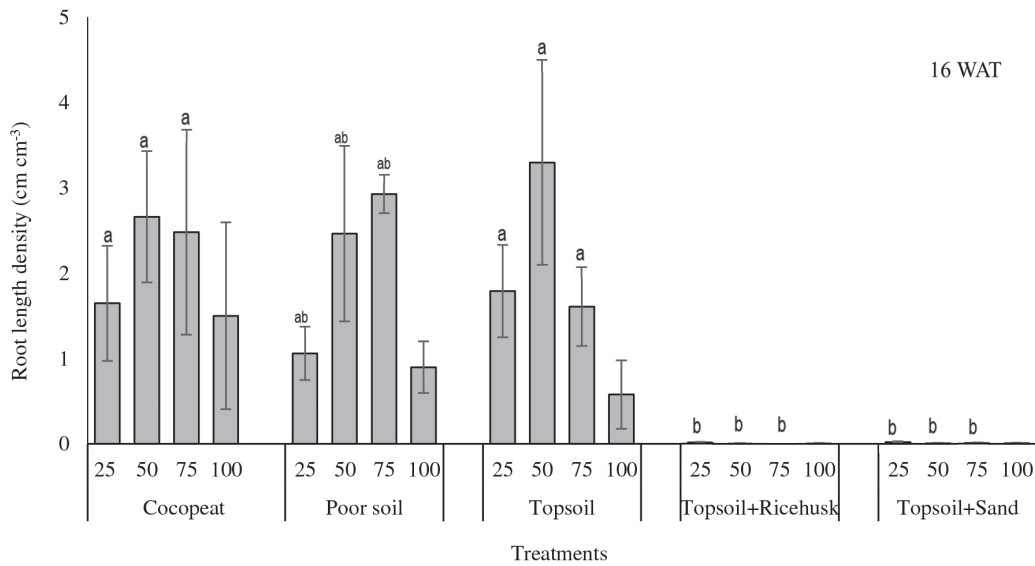


Fig. 8. Root length density ( $\text{cm cm}^{-3}$ ) of *N. macrophylla* at four soil depths under five soil treatments. Means with the same letter for each soil depth do not differ significantly between treatments based on one-way ANOVA followed by Tukey's HSD test ( $p < 0.05$ ,  $n = 3$ ). Error bars indicate standard deviation.

that grow in poor soil and topsoil treatments had roots that were finer and longer. The opposite observation was found for the topsoil, topsoil and rice husk, topsoil and sand treatments, where the SRL was lowest, suggesting roots were shorter and thicker. At 16 WAT (Fig. 6), SRL slightly decreased in the poor soil and topsoil treatment, but increased in the topsoil and rice husk and topsoil and sand treatments at the same depths. There is a significant difference ( $p < 0.05$ ) using one-way ANOVA followed by Tukey's HSD.

#### Root length density (RLD)

As shown in Fig. 7 at 8 WAT *N. macrophylla* showed significant differences ( $p < 0.05$ ) at all levels of soil depths. Cocopeat always recorded the greatest values of RLD of 2.33 to 4.40  $\text{cm cm}^{-3}$  which indicated that it supported the initial proliferation of the root better. It was then followed by the topsoil treatment which also had an intermediate value between 0.14 to 2.40  $\text{cm cm}^{-3}$  according to depth. Conversely, topsoil and ricehusk, topsoil and sand treatment recorded low values of RLD, had low values of root development with the values being near zero at all depths. The 16 WAT (Fig. 8) shows that the patterns of RLD remained slightly different due to the further growth and redistribution of roots in the soil profile. Although the overall RLD of cocopeat remained the highest, it remained a slight decrease between 1.50 and 2.66  $\text{cm cm}^{-3}$  but the values of poor soil and topsoil treatments were slightly higher than 8 WAT, especially at 50–75 cm soil depth (2.46 to 3.30  $\text{cm cm}^{-3}$ ).

#### Discussion

For RCDI in Table 2, cocopeat is known to have acceptable pH, electrical conductivity, and other chemical properties. It also holds a lot of water which means there is not a lot of space for air. This reduces the air-water bal-

ance in the medium which can make it harder for oxygen to get to the roots (AWANG et al., 2009). Even so, the poor soil treatment matched the cocopeat treatment in RCDI performance, which may be due to more roots growing when the plant is stressed, which increased the stem and the thickness of the root collar in places where nutrients are low (RAHMANI et al., 2021). Similar reasons might be applicable to the HI, where poor soil treatment outperformed all other treatments despite its low nutrient status. The abiotic stress caused by the poor soil may have led to the plant's elongated growth, possibly a stress response mechanism to maximise light capture under suboptimal conditions (OLDROYD and LEYSER, 2020). According to JULIANDARI (2025), this type of species is frequently selected because it establishes rapidly, thereby supporting faster reforestation and the restoration of degraded land. Table 3 shows the LAI results, which is a crucial indicator of productivity and reflect leaf surface availability for photosynthetic activity (HINOJO-HINOJO and GOULDEN, 2020). Plants growing in poor soils tended to increase their leaf area, likely to enhance carbon assimilation and light capture, which is consistent with stress-adaptive strategies that allow adjustment to low soil fertility (LAMBERS et al., 2008).

Cocopeat has a lightweight, highly fibrous structure, which makes uniform compaction difficult. Variation in bulk density among rhizotrons (not measured in the present study) may have produced differential water and air distribution, contributing to the high inter-replicate variability. Future work should measure and standardise substrate bulk density prior to planting. Moreover, the inherently low nutrient levels of cocopeat imply that small variations in the retention or leaching of fertilizer may cause variations in the performance of the seedlings among the replicates. The elevated water retention of cocopeat can also form local areas of excess moisture un-

der variable compaction again increasing the anomalies in root and shoot development. A combination of these physical and chemical factors could have been the reason why the cocopeat treatment was more varied.

Based on Table 4, poor soil treatment despite its reduced nutrient content and reduced water-holding capacity had the highest dried shoot biomass. This reaction can be explained with respect to the improved root allocation plans within nutrient-restricted situations in which plants generally allocate more energy to root development to boost nutrient foraging effectiveness, which in turn can be converted to shoot development (HODGE, 2004). Moreover, the abundance of positive soil microorganisms, which is a significant part of soil organic matter, might have led to the enhancement of nutrient cycling and plant uptake and partially offset the drawbacks of the poor soil (BRENNAN and ACOSTA-MARTINEZ, 2017). In general, the observations reveal that *N. macrophylla* can have some adaptive mechanisms allowing it to stay productive in its shoots even in non-optimal soil conditions.

As shown in Fig. 2, cocopeat, which showed better results has high porosity and holds water well, helping to ensure good aeration and has access to moisture by the plants (ILAHY and AHMAD, 2017). A study by SHINTIAVIRA et al., 2023 reported that cocopeat has a lower pH, electrical conductivity, and more moisture than other media, and that it performs better than rice husk in all kinds of media, increasing the number and length of roots. In comparison, poor soil and topsoil treatments had fewer roots, especially at deeper soil layers, because of their lower fertility and compaction (SHELEME et al., 2023). This is because the reduced pore space in compacted soils also raises the soil's strength, making it difficult for roots to penetrate the soil (LYNCH et al., 2022). According to DARLIS et al. (2024), *N. macrophylla* is one of the species chosen to be planted in ex-gold mining areas with poor soil conditions. On the other hand, the better performance of topsoil and rice husk treatments at 16 WAT suggests that using organic amendments with local soils is a cheap way to maintain good root development (RAVIV et al., 2002). According to BAIYERI and NWAJUANI (2024), better soil structure, sufficient water supply, nutrient retention and gaseous exchanges are all made possible by topsoil.

Based on Figs 3 and 4, the cocopeat treatment was better at 8 WAT and 16 WAT for root biomass. The favourable physical characteristics of cocopeat treatment, which is made from coconut husk fibres, provide ideal conditions for root growth by guaranteeing steady moisture availability (ATZORI et al., 2021) and enough oxygen for root respiration (NOMOTO et al., 2024). Furthermore, the high cation exchange capacity of cocopeat promotes nutritional availability and retention (ASWATH and PILLAI, 2004). This is supported by ARISTA (2023), as cocopeat had a good influence on the growth performance of *N. macrophylla* in contrast with the poor soil treatment. Plants often grow more fine roots in order to penetrate huge amounts of soil when the soil is nutrient-poor (ŚWIĄTEK AND PIETRZYKOWSKI, 2021). Low nutrient

levels in poor soil always prevent *N. macrophylla* from growing properly, which hinders plant growth during revegetation operations (ASMARAHMAN et al., 2023).

The findings for SRL highlight how growth media affects root morphology over time. A high SRL denotes a resource-acquisitive strategy, whereby plants grow longer, thinner roots to increase their surface area and absorb nutrients while using less biomass (KRAMER-WALTER et al., 2016). This highlights why poor soil resulted in less root biomass compared to the other treatments. The type of treatment influenced how far the roots can forage deep into the soil. Plants need to have an extensive root system to absorb water and nutrients well, rather than just being heavy or thick. A plant with limited roots can get more nutrients from the soil if those roots cover a wider space. That is because longer roots have access to more water and nutrients deeper in the soil (EISSENSTAT, 1992). The SRL and RLD were always positively related to RLD (BAKKER et al., 2019). Based on what is illustrated in Figs 7 and 8, the cocopeat treatment provided excellent support for root development as it provided the right amount of moisture and oxygen for roots to thrive. Cocopeat acts as a rooting media, has the ability to balance air-water ratios and directly provides a stable structure for root expansion (KUMAR et al., 2019). Poor aeration can cause the roots to grow more slowly and often grow shorter as the roots keep exploring downwards, resulting in shorter and deformed roots (ASADY and SMUCKER, 1989), 1989). Furthermore, combining topsoil and sand may produce a substrate that is less able to store water and nutrients, which may further restrict root growth (SCANLAN et al., 2022). Plants frequently display stunted root systems in nutrient-deficient or degraded soils as a result of the combined stressors of limited resources and poor physical properties, which is part of plant survival strategies under a degraded ecosystem (Kumari et al., 2022).

In general, the observed difference between the five treatments can be partially attributed to natural differences in the water-retention capacities, aeration, nutrient concentration, especially the low nutrient level of cocopeat, and micro-structural dissimilarity that affect root accessibility to water and nutrients.

## Conclusions

This study revealed that soil treatments exert a significant influence on the growth of *N. macrophylla*, affecting both above-ground and below-ground development. Cocopeat offers optimal physical support for roots, characterised by its high porosity, moisture retention, and aeration. Conversely, suboptimal soil conditions induced stress in the plants, as evidenced by increased stem width, high leaf area index, and elongated roots, even in nutrient-deficient environments. These findings suggest that *N. macrophylla* can adapt its growth of both shoots and roots under suboptimal conditions, rendering it a viable candidate for reforestation and soil rehabilitation. Additionally, the improved outcomes observed with the topsoil and

rice husk mixtures indicate that organic soil amendments can be used to enhance sustainable plantation strategies. Overall, understanding the impact of soil treatments on plant growth can provide more effective practices for restoration ecology and forest management.

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