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Valorizing nickel slag waste for sustainable mine land rehabilitation strategies: A circular economy approach to synergize green material engineering and ecosystem restoration

Retno Dewi Handayani S[1*], Suyud Warno Utomo[2], Irdika Mansur[3], Dwi Nowo Martono[4]

[1,2,4]*School of Environmental Science, Universitas Indonesia, Central Jakarta 10430, Indonesia.*
[3]*Faculty of Forestry and Environment, Institut Pertanian Bogor, Indonesia.*

Corresponding author: Retno Dewi Handayani S (*Email: retno.dewi01@ui.ac.id*)

Abstract

This study rehabilitates degraded post-nickel mining land using nickel slag waste within a circular economy framework, evaluating it as a sustainable planting media component to reduce topsoil reliance. A greenhouse experiment tested six media compositions combining nickel slag, overburden soil, manure, and topsoil (e.g., slag:manure at 40:10%, 80:20%). Growth of four tree species (Falcataria moluccana [Jeungjing], Myristica fragrans [Nutmeg], Anthocephalus macrophyllus [Red Jabon], Melaleuca leucadendron [Cajuput]) and three cover crops (Centrosema pubescens [Centro], Cymbopogon nardus [Citronella], Brachiaria decumbens [Bede Grass]) was assessed over 17–20 weeks. Media properties (texture, pH, CEC, nutrients) and plant parameters (root length, biomass, shoot-root ratio [SRR]) were analyzed using ANOVA. Findings showed species-media synergy: Red Jabon thrived best in 40% slag + 10% manure; Citronella excelled in 80% slag + 20% manure, yielding 3.7x and 6.6x higher biomass than Centro and Bede Grass respectively, with an ideal SRR (2.45) for stabilization. Jeungjing root length (4.93 cm) and dry weight (0.7 g) increased in overburden + 20% slag + 30% manure versus manure alone. Conversely, Cajuput root growth decreased (3.4 cm) in slag-topsoil-manure (20:15:15%) due to low P/K absorption. Nickel slag improved soil fertility: C-organic, CEC, total N, and P increased significantly after 20 weeks via litter decomposition, though plant uptake varied. Conclusion: Nickel slag (up to 80%) effectively substitutes topsoil, enhancing revegetation and waste repurposing. Species-specific formulations are critical, with Red Jabon and Citronella highly adaptable to slag media. Practical protocols: use 40% slag + 10% manure for Red Jabon; 80% slag + 20% manure for Citronella; avoid slag-topsoil-manure (20:15:15%) for Cajuput. Valorization replaces scarce topsoil, reducing costs. The framework integrates local resources (slag, manure) and native species, diverting slag from landfills, reducing fertilizer dependency, and enabling self-sustaining nutrient cycles.

Keywords: Circular economy, Industrial waste reuse, Mine soil reclamation, Nickel slag valorization, Soil remediation.

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Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
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1. Introduction

Nickel slag is a by-product and solid residue formed when nickel ore is smelted and discarded through cooling [1]. Nickel slag has physical characteristics in the form of solid granules with a grain size of 2 mm to 5 mm and a greyish-black color, as well as a chemical composition of SiO2, Fe2O3, Cr2O3, Al2O3, MgO, and several other oxides [2-6]. The content of nickel slag can be identified from the characterization results of nickel rock samples, which consist of SiO2, NiO2, and Liebenbergite (NiO2SiO4), characterizing the elements and compounds that make up the nickel rock material studied [7, 8]. Nickel slag can be utilized as a material for paving blocks and bricks. However, the absorption volume of nickel slag is still very low, at only 1% of the domestic nickel slag volume [9], causing nickel slag accumulation. Some mining companies use nickel slag as a surface material for mining road access and as an additive for abrasive materials for general industrial, ceramic, and cement purposes [10-12]. One potential use that can absorb more nickel slag is its application as a soil amendment to improve the condition of post-mining land.

Ground nickel slag contains three main elements, namely [13-16], which can be used as a nutrient source to increase plant productivity. Samnur, et al. [13] explained that nickel slag contains 32.86% Si, making it a potential source of Si. The addition of Si to plants affects cell density and increases cell resistance and strength [17-19] and helps leaves stand more erect when large amounts of nitrogen nutrients are added, thereby increasing photosynthesis rates and efficiency in capturing sunlight by up to 10% [20-22].

Soil in former mining locations has much lower nutrient content than the initial soil condition [23-25]. Open-pit mining activities cause changes in the landscape, steep slopes that result in waterlogging, changes in soil quality, and soil and plants that are easily eroded [26-29]. The topsoil is replaced by less fertile subsoil, while the fertile topsoil is buried underneath [30-32]. This results in plants not growing normally, becoming stunted, and eventually dying. The soil's ability to store and absorb water during the rainy season is also hindered due to the compact physical structure of the soil, affecting the porosity and permeability of the soil layers [33-36].

Reclamation is the process of restoring the condition of former mining land to its intended use [37]. Reclamation activities of former mining land need to be carried out to restore the lost land utility [38-40]. Soil condition improvement includes enhancing physical properties (texture, structure, and soil density), chemical properties (soil reaction, nutrient availability, and organic matter), and biological properties (presence of important macro- and microorganisms) [26]. One source for improving soil conditions that can be utilized is slag obtained from nickel ore processing activities and can be combined with the addition of organic materials [41-43].

The expected benefits of nickel slag as a soil amendment include increased absorption volume of nickel slag, increased nutrients (Si and Mg) in post-mining soil, recycling of nickel slag waste, reduced compost fertilizer costs, and increased plant growth. We hypothesize that the nutrient content of post-nickel mining soil can be increased by mixing or applying nickel slag together with nickel soil and organic materials (compost fertilizer). Niu, et al. [44] stated that the application of nickel slag significantly affects root growth, specifically the length of primary roots and increases the mass of secondary roots of Cajuput plants. Enhanced root growth and development will subsequently influence plant growth, particularly the diameter of Cajuput seedling stems [44-47]. Cajuput seedlings can grow in ultisol soil media containing nickel slag [48-51]. The concentration of nickel slag up to 30% of the weight of the ultisol soil media promotes the growth of Eucalyptus seedlings in nurseries [52, 53].

Overall, this study confirms that the composition of planting media with a mixture of nutrients containing nickel slag can improve post-mining soil conditions to increase plant growth. We conducted a laboratory-scale experiment to evaluate plant growth with a planting medium consisting of topsoil, a cover layer, and compost added with nickel slag as a planting medium. Nickel slag was chosen because of its high Si and Mg content and its abundant availability in nickel mining areas. Hypothesizing that the Si and Mg components of nickel slag increase nickel nutrient content, we aim to (i) evaluate plant growth by comparing the planting media used with and without the addition of nickel slag, and (ii) develop an innovative strategy for sustainable rehabilitation with the use of nickel slag composition formulations on planting media on former nickel mine soils.

2. Materials and Methods

This study aims to evaluate the growth of cover crops and trees in planting media that is specially formulated to support innovative strategies for revegetation activities in ex-mining areas. The methodological approach used includes two main stages: (1) comprehensive analysis of the physicochemical properties of the planting media and (2) laboratory-scale experiments under controlled conditions to test plant growth responses.

2.1. Rationale for Planting Media Analysis Methods

Planting media analysis was carried out to understand the characteristics of the planting substrate, especially in the context of nutrient content and its suitability to support plant growth. The methods chosen, such as the Pipette Method for soil texture and cation exchange capacity (CEC) analysis using NH_4OAc 1N pH 7, are standards in soil science to measure the distribution of soil particles (sand, silt, clay) and the availability of nutrients (Ca, Mg, K, Na). Analysis of organic carbon using the Walkley & Black method [54] and total nitrogen using the Kjeldahl method was chosen because of its relevance in assessing soil fertility, especially in degraded lands. Meanwhile, pH, phosphorus (Bray I), and heavy metal (Fe, Cu, Zn, Mn) analysis using DTPA extraction and Al with 1N KCl were conducted to identify potential limiting factors, such as metal toxicity or soil acidity.

2.2. Laboratory Scale Experiment Design

A laboratory-scale experiment was designed as an initial stage in the evaluation of revegetation before large-scale field trials. The selection of a greenhouse allows control of environmental factors (such as humidity, temperature, and light) and minimizes confounding variables. The planting medium consists of a mixture of topsoil, overburden, manure, and nickel slag originating from Obi Island. The use of nickel slag as a component of the planting medium is an innovative aspect, referring to its potential in ameliorating ex-mining soil. The composition of the media is regulated based on a certain percentage to assess the effect of the combination of materials on plant growth.

2.3. Media Preparation and Seed Selection

The planting medium was filtered and mixed homogeneously to ensure consistency, while 15x20 cm polybags were used as containers to facilitate observation of roots and early growth. Plant seedlings were selected based on uniformity of height and age, including cover species such as Centrocema pubescens and Brachiaria decumbens, and trees such as Melaleuca leucadendron and Myristica fragrans. These species were prioritized for their adaptability to marginal land and their ecological role in restoration.

2.4. Controlled Planting and Maintenance

The planting process involved transplanting seedlings into polybags with regular watering twice a day to prevent water stress. Maintenance included the installation of stakes on the Centro plants to support growth. This approach ensured that the results of observations reflected the plant's response to the planting medium, not external factors.

2.5. Significance of the Methodology

The integration of in-depth soil analysis and controlled experiments provides a scientific basis for designing effective revegetation strategies in post-mining areas. This stage also considers sustainability by utilizing local materials (nickel slag, manure) and native species, in line with the principles of ecosystem restoration based on local wisdom.

2.6. Planting Media Analysis

The planting media were analyzed in the laboratory to test their nutrient content. The nutrient content analysis of the planting media used samples of the media before planting cover crops or trees. The nutrient content analysis of the planting media included soil texture analysis of overburden soil (3 soil fractions) (Pipette Method), Ca-dd (NH4OAc 1 N pH 7), Mg-dd (NH4OAc 1 N pH 7), K-dd (NH4OAc 1 N pH 7), Na-dd (NH4OAc 1 N pH 7), Cation Exchange Capacity (CEC) (NH4OAc 1 N pH 7), organic carbon (Walkey & Black) [54], pH H2O (1:5), total N (Kjeldahl), total P (HCL 25%), and available P (Bray I). Analysis of Fe, Cu, Zn, and Mn (Available DTPA) ([55], as well as Al (KCl 1N method) [56].

2.7. Laboratory Scale Experiment

The laboratory-scale experiment for observing the growth of cover crops and trees was conducted in the greenhouse laboratory of the Department of Silviculture, Faculty of Forestry and Environment, Bogor Agricultural University. The laboratory scale is the initial step of evaluation before conducting larger-scale field trials. The tools and materials prepared include: 15 x 20 cm polybags, small shovels, digital scales, plastic tubs, plastic trays, mica boxes, plastic bags, sprayers, watering cans, topsoil, overburden, manure, nickel slag, and plant seedlings.

2.8. Preparation of Planting Media

The planting media, consisting of topsoil, overburden, manure, and nickel slag, were sourced from the mining area on Obi Island, South Halmahera, North Maluku. The compost fertilizer was sourced from East Halmahera Island. Topsoil is the uppermost soil layer, with an average thickness of 20-30 cm, considered to still contain nutrients useful for revegetation (planting) activities. Overburden is the soil layer beneath the topsoil, with a thickness of about 3-4 meters, used to backfill the former ore excavation area that is not mined again during reclamation activities. Compost fertilizer is made from cow manure mixed with black soil from the surrounding forest.

The overburden soil, topsoil, and compost fertilizer used as planting media were sieved and screened, except for the nickel slag, and then mixed to prepare the media. A plastic tub was placed on a scale and tared. The weight of the media materials was measured based on the percentage composition. The measured materials were then evenly mixed using a shovel. The media materials were placed into polybags until full, and the media in the polybags were watered.

2.9. Seedling Preparation

The cover crop seedlings, including Centro (Centrocema pubescens), Citronella (Cymbopogon nardus (L.)), and Bede Grass (Brachiaria decumbens), and tree seedlings, including Cajuput (Melaleuca leucadendron), Red Jabon (Anthocephalus macrophyllus), Jeungjing (Falcataria moluccana), and Nutmeg (Myristica fragrans), were sourced from ready-to-plant seedlings with the same average height and age group.

2.10. Planting and Maintenance

The seedlings ready for transplanting are watered to prevent wilting. A planting hole is made in the center of the polybag containing the media using a stick. The seedling roots are gently lifted, removing any media still attached to the roots. The seedlings are placed into the hole in the polybag, and the hole is closed again. The transplanted seedlings are watered twice a day, in the morning and evening. Plant maintenance includes staking for Centro seedlings and watering. Plant growth in a greenhouse laboratory (Figure 1).

Figure 1.
Plants in a greenhouse laboratory.

3. Data and Methodology

3.1. Plant Observation

Data collection was based on observations over 20 weeks (for tree plants) and 17 weeks (for cover crops) as follows:

3.1.1. Fresh Weight of Roots and Shoots, Root Length, And Number of Secondary Roots

Measurements of the fresh weight of roots and shoots (stems and leaves), root length, and number of secondary roots were conducted at harvest time for tree plants (week 20) and cover crops (week 17) [57]. The fresh weight of roots and shoots was measured by weighing each cleaned part of the shoots and roots using an analytical balance. Root length was measured on the primary roots of tree plants, while for cover crops, it was measured on the longest fibrous root (Figure 2). The number of secondary roots was based on the number of secondary roots attached to the primary root [58, 59].

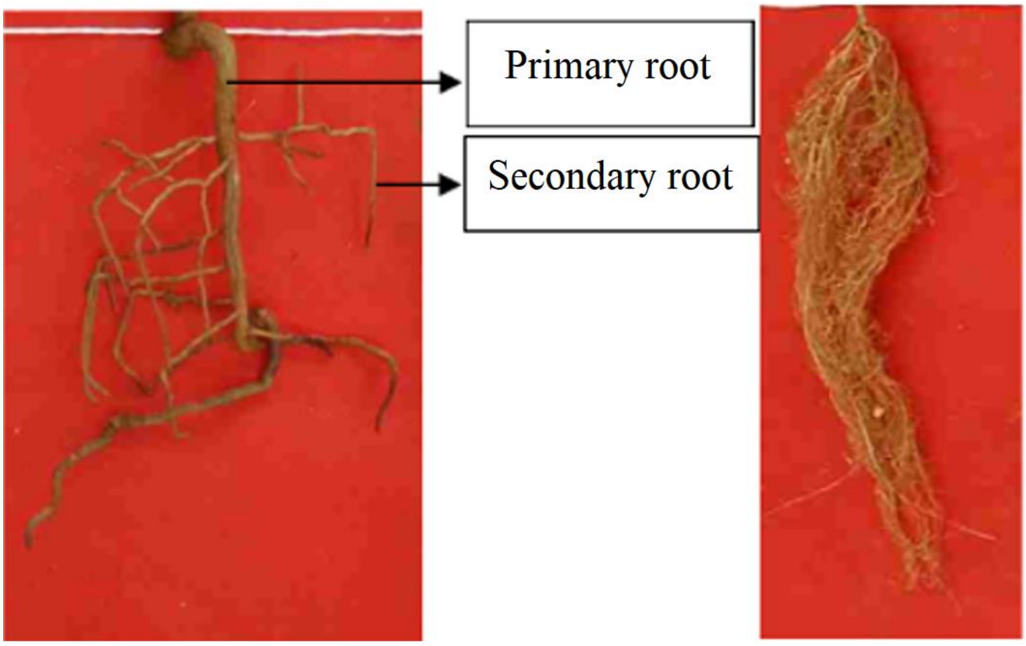

Figure 2.
Root morphology: (a) Tree plant roots; (b) Cover crop roots.

3.1.2. Plant Biomass and Shoot-to-Root Ratio (SRR)

Plant biomass is measured after harvest. Plant biomass includes the dry weight of roots, the dry weight of shoots, and total biomass. All plant samples are dried at a temperature of 70ºC for 2×24 hours in an oven [60, 61]. Afterward, the samples are stored in a desiccator before weighing the dry weight to ensure the moisture from the shoot (stems and leaves) and root samples is reduced until dry. Then, the dry weight of each root and shoot is weighed using an analytical balance. The shoot-to-root ratio (SRR) is the ratio of the dry weight of the shoot (stems and leaves) to the dry weight of the roots [62]. A good SRR value ranges between 1 and 3.

3.1.3. Experimental Design

This study observes the growth of plants treated with different types of planting media. The study uses a split-plot design. This design divides factors into two different groups: the main plot and the sub-plot. In this study, the split-plot design will be combined with a Completely Randomized Design (CRD).

The study uses two types of factors: the composition of the planting media, consisting of overburden soil, topsoil, manure, and nickel slag, with six treatment levels, and the type of plants (trees and cover crops) as the second factor. The type of plant is determined as the main plot factor because this factor already has sufficient information or has been repeatedly tested. Meanwhile, the composition of the planting media is determined as the sub-plot factor because the researcher expects the treatment effect of the planting media composition to be greater than the type of plant used [63]. The composition of the planting media for trees and cover crops is explained as follows:
Planting Media Composition Factors for Tree Plants:

M 0 = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil (w/w)
M 1 = 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil (w/w)
M 2 = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil (w/w)
M 3 = 50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil (w/w)
M 4 = 50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil (w/w)
M 5 = 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil (w/w)

These six treatments were tested on three plant species, namely Cajuput (M. leucadendron) (P1), Red Jabon (A. macrophyllus) (P2), Jeungjing (F. moluccana) (P3), and Nutmeg (M. fragrans) (P4). Each treatment was repeated 10 times, resulting in 6 treatments multiplied by 4 plant types multiplied by 10 repetitions = 240 polybags, with a requirement of 60 seedlings for each plant type used. The composition of the planting media treatments for tree plants in the combined design can be seen in Figure 3 and Figure 4 for randomization.

	Units	U1					U2				
	Repetitions	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
Plants	Media										
P1	M0	P1 M0 T1 U1	P1 M0 T2 U1	P1 M0 T3 U1	P1 M0 T4 U1	P1 M0 T5 U1	P1 M0 T1 U2	P1 M0 T2 U2	P1 M0 T3 U2	P1 M0 T4 U2	P1 M0 T5 U2
	M1	P1 M1 T1 U1	P1 M1 T2 U1	P1 M1 T3 U1	P1 M1 T4 U1	P1 M1 T5 U1	P1 M1 T1 U2	P1 M1 T2 U2	P1 M1 T3 U2	P1 M1 T4 U2	P1 M1 T5 U2
	M2	P1 M2 T1 U1	P1 M2 T2 U1	P1 M2 T3 U1	P1 M2 T4 U1	P1 M2 T5 U1	P1 M2 T1 U2	P1 M2 T2 U2	P1 M2 T3 U2	P1 M2 T4 U2	P1 M2 T5 U2
	M3	P1 M3 T1 U1	P1 M3 T2 U1	P1 M3 T3 U1	P1 M3 T4 U1	P1 M3 T5 U1	P1 M3 T1 U2	P1 M3 T2 U2	P1 M3 T3 U2	P1 M3 T4 U2	P1 M3 T5 U2
	M4	P1 M4 T1 U1	P1 M4 T2 U1	P1 M4 T3 U1	P1 M4 T4 U1	P1 M4 T5 U1	P1 M4 T1 U2	P1 M4 T2 U2	P1 M4 T3 U2	P1 M4 T4 U2	P1 M4 T5 U2
	M5	P1 M5 T1 U1	P1 M5 T2 U1	P1 M5 T3 U1	P1 M5 T4 U1	P1 M5 T5 U1	P1 M5 T1 U2	P1 M5 T2 U2	P1 M5 T3 U2	P1 M5 T4 U2	P1 M5 T5 U2
P2	M0	P2 M0 T1 U1	P2 M0 T2 U1	P2 M0 T3 U1	P2 M0 T4 U1	P2 M0 T5 U1	P2 M0 T1 U2	P2 M0 T2 U2	P2 M0 T3 U2	P2 M0 T4 U2	P2 M0 T5 U2
	M1	P2 M1 T1 U1	P2 M1 T2 U1	P2 M1 T3 U1	P2 M1 T4 U1	P2 M1 T5 U1	P2 M1 T1 U2	P2 M1 T2 U2	P2 M1 T3 U2	P2 M1 T4 U2	P2 M1 T5 U2
	M2	P2 M2 T1 U1	P2 M2 T2 U1	P2 M2 T3 U1	P2 M2 T4 U1	P2 M2 T5 U1	P2 M2 T1 U2	P2 M2 T2 U2	P2 M2 T3 U2	P2 M2 T4 U2	P2 M2 T5 U2
	M3	P2 M3 T1 U1	P2 M3 T2 U1	P2 M3 T3 U1	P2 M3 T4 U1	P2 M3 T5 U1	P2 M3 T1 U2	P2 M3 T2 U2	P2 M3 T3 U2	P2 M3 T4 U2	P2 M3 T5 U2
	M4	P2 M4 T1 U1	P2 M4 T2 U1	P2 M4 T3 U1	P2 M4 T4 U1	P2 M4 T5 U1	P2 M4 T1 U2	P2 M4 T2 U2	P2 M4 T3 U2	P2 M4 T4 U2	P2 M4 T5 U2
	M5	P2 M5 T1 U1	P2 M5 T2 U1	P2 M5 T3 U1	P2 M5 T4 U1	P2 M5 T5 U1	P2 M5 T1 U2	P2 M5 T2 U2	P2 M5 T3 U2	P2 M5 T4 U2	P2 M5 T5 U2
P3	M0	P3 M0 T1 U1	P3 M0 T2 U1	P3 M0 T3 U1	P3 M0 T4 U1	P3 M0 T5 U1	P3 M0 T1 U2	P3 M0 T2 U2	P3 M0 T3 U2	P3 M0 T4 U2	P3 M0 T5 U2
	M1	P3 M1 T1 U1	P3 M1 T2 U1	P3 M1 T3 U1	P3 M1 T4 U1	P3 M1 T5 U1	P3 M1 T1 U2	P3 M1 T2 U2	P3 M1 T3 U2	P3 M1 T4 U2	P3 M1 T5 U2
	M2	P3 M2 T1 U1	P3 M2 T2 U1	P3 M2 T3 U1	P3 M2 T4 U1	P3 M2 T5 U1	P3 M2 T1 U2	P3 M2 T2 U2	P3 M2 T3 U2	P3 M2 T4 U2	P3 M2 T5 U2
	M3	P3 M3 T1 U1	P3 M3 T2 U1	P3 M3 T3 U1	P3 M3 T4 U1	P3 M3 T5 U1	P3 M3 T1 U2	P3 M3 T2 U2	P3 M3 T3 U2	P3 M3 T4 U2	P3 M3 T5 U2
	M4	P3 M4 T1 U1	P3 M4 T2 U1	P3 M4 T3 U1	P3 M4 T4 U1	P3 M4 T5 U1	P3 M4 T1 U2	P3 M4 T2 U2	P3 M4 T3 U2	P3 M4 T4 U2	P3 M4 T5 U2
	M5	P3 M5 T1 U1	P3 M5 T2 U1	P3 M5 T3 U1	P3 M5 T4 U1	P3 M5 T5 U1	P3 M5 T1 U2	P3 M5 T2 U2	P3 M5 T3 U2	P3 M5 T4 U2	P3 M5 T5 U2
P4	M0	P4 M0 T1 U1	P4 M0 T2 U1	P4 M0 T3 U1	P4 M0 T4 U1	P4 M0 T5 U1	P4 M0 T1 U2	P4 M0 T2 U2	P4 M0 T3 U2	P4 M0 T4 U2	P4 M0 T5 U2
	M1	P4 M1 T1 U1	P4 M1 T2 U1	P4 M1 T3 U1	P4 M1 T4 U1	P4 M1 T5 U1	P4 M1 T1 U2	P4 M1 T2 U2	P4 M1 T3 U2	P4 M1 T4 U2	P4 M1 T5 U2
	M2	P4 M2 T1 U1	P4 M2 T2 U1	P4 M2 T3 U1	P4 M2 T4 U1	P4 M2 T5 U1	P4 M2 T1 U2	P4 M2 T2 U2	P4 M2 T3 U2	P4 M2 T4 U2	P4 M2 T5 U2
	M3	P4 M3 T1 U1	P4 M3 T2 U1	P4 M3 T3 U1	P4 M3 T4 U1	P4 M3 T5 U1	P4 M3 T1 U2	P4 M3 T2 U2	P4 M3 T3 U2	P4 M3 T4 U2	P4 M3 T5 U2
	M4	P4 M4 T1 U1	P4 M4 T2 U1	P4 M4 T3 U1	P4 M4 T4 U1	P4 M4 T5 U1	P4 M4 T1 U2	P4 M4 T2 U2	P4 M4 T3 U2	P4 M4 T4 U2	P4 M4 T5 U2
	M5	P4 M5 T1 U1	P4 M5 T2 U1	P4 M5 T3 U1	P4 M5 T4 U1	P4 M5 T5 U1	P4 M5 T1 U2	P4 M5 T2 U2	P4 M5 T3 U2	P4 M5 T4 U2	P4 M5 T5 U2

Figure 3.
Combination design of treatments in the mixed planting media composition experiment with tree plants.

RANDOMIZATION																			
U1																			
P2M5T3U1	P4M4T1U1	P1M5T3U1	P1M0T4U1	P3M5T5U1	P3M5T4U1	P4M3T4U1	P3M3T3U1	P2M0T1U1	P2M1T4U1	P2M2T2U1	P3M4T2U1	P4M4T3U1	P1M2T2U1	P1M1T5U1	P2M1T5U1	P4M1T2U1	P4M5T5U1	P1M4T1U1	P3M2T1U1
P2M3T3U1	P4M1T1U1	P1M2T3U1	P1M4T4U1	P3M1T5U1	P3M3T4U1	P4M1T4U1	P3M5T3U1	P2M4T1U1	P2M5T4U1	P2M4T2U1	P3M1T2U1	P4M3T3U1	P1M4T2U1	P1M3T5U1	P2M4T5U1	P4M3T2U1	P4M3T5U1	P1M5T1U1	P3M5T1U1
P2M1T3U1	P4M0T1U1	P1M0T3U1	P1M1T4U1	P3M3T5U1	P3M4T4U1	P4M4T4U1	P3M0T3U1	P2M3T1U1	P2M2T4U1	P2M5T2U1	P3M5T2U1	P4M1T3U1	P1M0T2U1	P1M4T5U1	P2M5T5U1	P4M5T2U1	P4M2T5U1	P1M1T1U1	P3M1T1U1
P2M2T3U1	P4M5T1U1	P1M1T3U1	P1M2T4U1	P3M4T5U1	P3M0T4U1	P4M0T4U1	P3M4T3U1	P2M2T1U1	P2M0T4U1	P2M3T2U1	P3M2T2U1	P4M0T3U1	P1M5T2U1	P1M5T5U1	P2M2T5U1	P4M0T2U1	P4M4T5U1	P1M3T1U1	P3M3T1U1
P2M4T3U1	P4M2T1U1	P1M3T3U1	P1M5T4U1	P3M2T5U1	P3M1T4U1	P4M5T4U1	P3M1T3U1	P2M5T1U1	P2M4T4U1	P2M1T2U1	P3M0T2U1	P4M2T3U1	P1M3T2U1	P1M0T5U1	P2M0T5U1	P4M2T2U1	P4M1T5U1	P1M2T1U1	P3M4T1U1
P2M0T3U1	P4M3T1U1	P1M4T3U1	P1M3T4U1	P3M0T5U1	P3M2T4U1	P4M2T4U1	P3M2T3U1	P2M1T1U1	P2M3T4U1	P2M0T2U1	P3M3T2U1	P4M5T3U1	P1M1T2U1	P1M2T5U1	P2M3T5U1	P4M4T2U1	P4M0T5U1	P1M0T1U1	P3M0T1U1
U2																			
P2M5T3U2	P4M4T1U2	P1M5T3U2	P1M0T4U2	P3M5T5U2	P3M5T4U2	P4M3T4U2	P3M3T3U2	P2M0T1U2	P2M1T4U2	P2M2T2U2	P3M4T2U2	P4M4T3U2	P1M2T2U2	P1M1T5U2	P2M1T5U2	P4M1T2U2	P4M5T5U2	P1M4T1U2	P3M2T1U2
P2M3T3U2	P4M1T1U2	P1M2T3U2	P1M4T4U2	P3M1T5U2	P3M3T4U2	P4M1T4U2	P3M5T3U2	P2M4T1U2	P2M5T4U2	P2M4T2U2	P3M1T2U2	P4M3T3U2	P1M4T2U2	P1M3T5U2	P2M4T5U2	P4M3T2U2	P4M3T5U2	P1M5T1U2	P3M5T1U2
P2M1T3U2	P4M0T1U2	P1M0T3U2	P1M1T4U2	P3M3T5U2	P3M4T4U2	P4M4T4U2	P3M0T3U2	P2M3T1U2	P2M2T4U2	P2M5T2U2	P3M5T2U2	P4M1T3U2	P1M0T2U2	P1M4T5U2	P2M5T5U2	P4M5T2U2	P4M2T5U2	P1M1T1U2	P3M1T1U2
P2M2T3U2	P4M5T1U2	P1M1T3U2	P1M2T4U2	P3M4T5U2	P3M0T4U2	P4M0T4U2	P3M4T3U2	P2M2T1U2	P2M0T4U2	P2M3T2U2	P3M2T2U2	P4M0T3U2	P1M5T2U2	P1M5T5U2	P2M2T5U2	P4M0T2U2	P4M4T5U2	P1M3T1U2	P3M3T1U2
P2M4T3U2	P4M2T1U2	P1M3T3U2	P1M5T4U2	P3M2T5U2	P3M1T4U2	P4M5T4U2	P3M1T3U2	P2M5T1U2	P2M4T4U2	P2M1T2U2	P3M0T2U2	P4M2T3U2	P1M3T2U2	P1M0T5U2	P2M0T5U2	P4M2T2U2	P4M1T5U2	P1M2T1U2	P3M4T1U2
P2M0T3U2	P4M3T1U2	P1M4T3U2	P1M3T4U2	P3M0T5U2	P3M2T4U2	P4M2T4U2	P3M2T3U2	P2M1T1U2	P2M3T4U2	P2M0T2U2	P3M3T2U2	P4M5T3U2	P1M1T2U2	P1M2T5U2	P2M3T5U2	P4M4T2U2	P4M0T5U2	P1M0T1U2	P3M0T1U2

Figure 4.
Randomization of experimental design for tree planting media composition.

Planting Media Composition Factors for Cover Crops:
M 0 = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil (w/w)
M 1 = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil (w/w)
M 2 = 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil (w/w)
M 3 = 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil (w/w)
M 4 = 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil (w/w)
M 5 = 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil (w/w)

These six treatments were tested on cover crops, namely Centro (C. pubescens) (P1), Citronella (C. nardus) (P2), and Bede Grass (B. decumbens) (P3). Each treatment was repeated 10 times, resulting in 6 treatments multiplied by 3 plant types multiplied by 10 repetitions = 180 polybags, with a requirement of 60 seedlings for each plant type used. The composition of the planting media treatments for cover crops in the experimental design can be seen in Figure 5 and Figure 6 for randomization.

	Units	U1					U2				
	Repetitions	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
Plants	Media										
P1	M0	P1 M0 T1 U1	P1 M0 T2 U1	P1 M0 T3 U1	P1 M0 T4 U1	P1 M0 T5 U1	P1 M0 T1 U2	P1 M0 T2 U2	P1 M0 T3 U2	P1 M0 T4 U2	P1 M0 T5 U2
	M1	P1 M1 T1 U1	P1 M1 T2 U1	P1 M1 T3 U1	P1 M1 T4 U1	P1 M1 T5 U1	P1 M1 T1 U2	P1 M1 T2 U2	P1 M1 T3 U2	P1 M1 T4 U2	P1 M1 T5 U2
	M2	P1 M2 T1 U1	P1 M2 T2 U1	P1 M2 T3 U1	P1 M2 T4 U1	P1 M2 T5 U1	P1 M2 T1 U2	P1 M2 T2 U2	P1 M2 T3 U2	P1 M2 T4 U2	P1 M2 T5 U2
	M3	P1 M3 T1 U1	P1 M3 T2 U1	P1 M3 T3 U1	P1 M3 T4 U1	P1 M3 T5 U1	P1 M3 T1 U2	P1 M3 T2 U2	P1 M3 T3 U2	P1 M3 T4 U2	P1 M3 T5 U2
	M4	P1 M4 T1 U1	P1 M4 T2 U1	P1 M4 T3 U1	P1 M4 T4 U1	P1 M4 T5 U1	P1 M4 T1 U2	P1 M4 T2 U2	P1 M4 T3 U2	P1 M4 T4 U2	P1 M4 T5 U2
	M5	P1 M5 T1 U1	P1 M5 T2 U1	P1 M5 T3 U1	P1 M5 T4 U1	P1 M5 T5 U1	P1 M5 T1 U2	P1 M5 T2 U2	P1 M5 T3 U2	P1 M5 T4 U2	P1 M5 T5 U2
P2	M0	P2 M0 T1 U1	P2 M0 T2 U1	P2 M0 T3 U1	P2 M0 T4 U1	P2 M0 T5 U1	P2 M0 T1 U2	P2 M0 T2 U2	P2 M0 T3 U2	P2 M0 T4 U2	P2 M0 T5 U2
	M1	P2 M1 T1 U1	P2 M1 T2 U1	P2 M1 T3 U1	P2 M1 T4 U1	P2 M1 T5 U1	P2 M1 T1 U2	P2 M1 T2 U2	P2 M1 T3 U2	P2 M1 T4 U2	P2 M1 T5 U2
	M2	P2 M2 T1 U1	P2 M2 T2 U1	P2 M2 T3 U1	P2 M2 T4 U1	P2 M2 T5 U1	P2 M2 T1 U2	P2 M2 T2 U2	P2 M2 T3 U2	P2 M2 T4 U2	P2 M2 T5 U2
	M3	P2 M3 T1 U1	P2 M3 T2 U1	P2 M3 T3 U1	P2 M3 T4 U1	P2 M3 T5 U1	P2 M3 T1 U2	P2 M3 T2 U2	P2 M3 T3 U2	P2 M3 T4 U2	P2 M3 T5 U2
	M4	P2 M4 T1 U1	P2 M4 T2 U1	P2 M4 T3 U1	P2 M4 T4 U1	P2 M4 T5 U1	P2 M4 T1 U2	P2 M4 T2 U2	P2 M4 T3 U2	P2 M4 T4 U2	P2 M4 T5 U2
	M5	P2 M5 T1 U1	P2 M5 T2 U1	P2 M5 T3 U1	P2 M5 T4 U1	P2 M5 T5 U1	P2 M5 T1 U2	P2 M5 T2 U2	P2 M5 T3 U2	P2 M5 T4 U2	P2 M5 T5 U2
P3	M0	P3 M0 T1 U1	P3 M0 T2 U1	P3 M0 T3 U1	P3 M0 T4 U1	P3 M0 T5 U1	P3 M0 T1 U2	P3 M0 T2 U2	P3 M0 T3 U2	P3 M0 T4 U2	P3 M0 T5 U2
	M1	P3 M1 T1 U1	P3 M1 T2 U1	P3 M1 T3 U1	P3 M1 T4 U1	P3 M1 T5 U1	P3 M1 T1 U2	P3 M1 T2 U2	P3 M1 T3 U2	P3 M1 T4 U2	P3 M1 T5 U2
	M2	P3 M2 T1 U1	P3 M2 T2 U1	P3 M2 T3 U1	P3 M2 T4 U1	P3 M2 T5 U1	P3 M2 T1 U2	P3 M2 T2 U2	P3 M2 T3 U2	P3 M2 T4 U2	P3 M2 T5 U2
	M3	P3 M3 T1 U1	P3 M3 T2 U1	P3 M3 T3 U1	P3 M3 T4 U1	P3 M3 T5 U1	P3 M3 T1 U2	P3 M3 T2 U2	P3 M3 T3 U2	P3 M3 T4 U2	P3 M3 T5 U2
	M4	P3 M4 T1 U1	P3 M4 T2 U1	P3 M4 T3 U1	P3 M4 T4 U1	P3 M4 T5 U1	P3 M4 T1 U2	P3 M4 T2 U2	P3 M4 T3 U2	P3 M4 T4 U2	P3 M4 T5 U2
	M5	P3 M5 T1 U1	P3 M5 T2 U1	P3 M5 T3 U1	P3 M5 T4 U1	P3 M5 T5 U1	P3 M5 T1 U2	P3 M5 T2 U2	P3 M5 T3 U2	P3 M5 T4 U2	P3 M5 T5 U2

Figure 5.
Combination design of treatments in the mixed planting media composition experiment with cover crops.

RANDOMIZATION														
U1														
P2M0T1U1	P3M4T2U1	P2M1T3U1	P2M5T2U1	P1M5T4U1	P2M3T4U1	P1M4T5U1	P3M1T4U1	P2M3T5U1	P3M4T3U1	P1M0T3U1	P3M2T5U1	P1M4T2U1	P3M4T1U1	P1M5T1U1
P2M1T1U1	P3M2T2U1	P2M3T3U1	P2M3T2U1	P1M4T4U1	P2M0T4U1	P1M0T5U1	P3M5T4U1	P2M5T5U1	P3M3T3U1	P1M4T3U1	P3M3T5U1	P1M0T2U1	P3M5T1U1	P1M4T1U1
P2M3T1U1	P3M1T2U1	P2M0T3U1	P2M1T2U1	P1M3T4U1	P2M4T4U1	P1M1T5U1	P3M2T4U1	P2M0T5U1	P3M5T3U1	P1M3T3U1	P3M1T5U1	P1M1T2U1	P3M1T1U1	P1M2T1U1
P2M4T1U1	P3M5T2U1	P2M5T3U1	P2M0T2U1	P1M0T4U1	P2M5T4U1	P1M3T5U1	P3M3T4U1	P2M4T5U1	P3M2T3U1	P1M1T3U1	P3M4T5U1	P1M3T2U1	P3M3T1U1	P1M1T1U1
P2M5T1U1	P3M0T2U1	P2M4T3U1	P2M2T2U1	P1M1T4U1	P2M1T4U1	P1M5T5U1	P3M4T4U1	P2M1T5U1	P3M0T3U1	P1M5T3U1	P3M5T5U1	P1M5T2U1	P3M0T1U1	P1M0T1U1
P2M2T1U1	P3M3T2U1	P2M2T3U1	P2M4T2U1	P1M2T4U1	P2M2T4U1	P1M2T5U1	P3M0T4U1	P2M2T5U1	P3M1T3U1	P1M2T3U1	P3M0T5U1	P1M2T2U1	P3M2T1U1	P1M3T1U1
U2														
P2M0T1U2	P3M4T2U2	P2M1T3U2	P2M5T2U2	P1M5T4U2	P2M3T4U2	P1M4T5U2	P3M1T4U2	P2M3T5U2	P3M4T3U2	P1M0T3U2	P3M2T5U2	P1M4T2U2	P3M4T1U2	P1M5T1U2
P2M1T1U2	P3M2T2U2	P2M3T3U2	P2M3T2U2	P1M4T4U2	P2M0T4U2	P1M0T5U2	P3M5T4U2	P2M5T5U2	P3M3T3U2	P1M4T3U2	P3M3T5U2	P1M0T2U2	P3M5T1U2	P1M4T1U2
P2M3T1U2	P3M1T2U2	P2M0T3U2	P2M1T2U2	P1M3T4U2	P2M4T4U2	P1M1T5U2	P3M2T4U2	P2M0T5U2	P3M5T3U2	P1M3T3U2	P3M1T5U2	P1M1T2U2	P3M1T1U2	P1M2T1U2
P2M4T1U2	P3M5T2U2	P2M5T3U2	P2M0T2U2	P1M0T4U2	P2M5T4U2	P1M3T5U2	P3M3T4U2	P2M4T5U2	P3M2T3U2	P1M1T3U2	P3M4T5U2	P1M3T2U2	P3M3T1U2	P1M1T1U2
P2M5T1U2	P3M0T2U2	P2M4T3U2	P2M2T2U2	P1M1T4U2	P2M1T4U2	P1M5T5U2	P3M4T4U2	P2M1T5U2	P3M0T3U2	P1M5T3U2	P3M5T5U2	P1M5T2U2	P3M0T1U2	P1M0T1U2
P2M2T1U2	P3M3T2U2	P2M2T3U2	P2M4T2U2	P1M2T4U2	P2M2T4U2	P1M2T5U2	P3M0T4U2	P2M2T5U2	P3M1T3U2	P1M2T3U2	P3M0T5U2	P1M2T2U2	P3M2T1U2	P1M3T1U2

Figure 6.
Randomization of Experimental Design for Cover Crop Planting Media Composition

The growth response of tree and cover crop species to different planting media treatments was analyzed. The growth parameter data obtained during the study were analyzed using analysis of variance (ANOVA) with SAS software version 9.4. Further mean comparison tests were conducted using Duncan's Multiple Range Test (DMRT) at α = 5% and 1% to determine the significance of treatment effects and the interaction between the two factors [64].

4. Result

4.1. Nutrient Content in Planting Media

Nutrient content in planting media is a crucial factor that significantly influences plant growth and productivity. The presence of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S), along with micronutrients like iron (Fe), zinc (Zn), and copper (Cu), determines the fertility of the soil or growing medium. These nutrients play vital roles in various plant physiological processes, including photosynthesis, root development, flowering, and fruit production. The availability of nutrients in the planting media depends on factors such as soil composition, organic matter content, pH level, and microbial activity. Proper nutrient management, through the application of fertilizers or organic amendments, is essential to maintain optimal nutrient levels and ensure healthy plant growth. Additionally, imbalances or deficiencies in nutrient content can lead to stunted growth, poor yields, and increased susceptibility to diseases, highlighting the importance of regular soil testing and tailored nutrient supplementation.

4.2. Nutrient Content in Planting Media for Cajuput

Table 1 shows that there is no decrease in pH for M0, M1, or M5 planting media, and it remains within neutral criteria. There was an increase in KTK, with M1 increasing 59% higher than M0, which was 30.47%, and M5, which was 40.6%. The content of total N, total P, Na, Fe, Cu, Zn, and Mn in all growing media increased at 20 weeks after planting, but P available and K available decreased. This indicates an increase in nutrients derived from the decomposition of organic litter, but elements P and K are still bound to organic matter, making nutrients P and K unavailable and undetectable when using the available nutrient content analysis method. Increased levels of C-organic in M0, M1, and M5 planting media also indicate the accumulation of organic nutrients into the planting media. The C-organic element in M0 increased by 47.28%, in M1 by 59.15%, and in M5 by 62.35%.

Table 1.
Changes in Nutrient Content Concentration in Cajuput Planting Media.

Parameters	Unit	0 Weeks After Planting			20 Weeks After Planting		
		M 0	**M 1**	**M 5**	**M 0**	**M 1**	**M 5**
Macro sins:							
pH		7.11	7.14	7.09	6.85	7.04	6.91
CEC	cmol (+)/kg	13.21	4.92	7.22	19.00	12.00	12.16
Sand	%	27.45	43.47	28.02	29.10	39.85	35.49
Dust	%	51.15	40.97	48.01	41.13	35.73	38.80
Clay	%	21.40	15.56	23.97	29.77	24.42	25.71
C-organic	%	1.55	0.96	1.02	2.94	2.35	2.71
N-total	%	0.16	0.12	0.14	0.25	0.2	0.22
Total P	Ppm	106.1	72.7	52.9	350.97	272.56	293.68
P available	Ppm	26.4	24.2	14.6	17.26	11.04	14.89
K	cmol (+)/kg	0.54	0.20	0.22	0.2	0.14	0.17
Micro harm:							
Ca	cmol (+)/kg	11.98	3.25	3.49	7.87	4.27	4.52
Mg	cmol (+)/kg	5.80	3.00	3.39	4.87	4.12	4.13
Na	cmol (+)/kg	0.21	0.12	0.12	0.32	0.22	0.23
Fe	Ppm	17.3	19.5	26.3	45.27	40.98	33.22
Cu	Ppm	1.27	0.96	0.94	3.82	2.64	2.89
Zn	Ppm	0.60	0.68	0.65	3.66	2.82	2.77
Mn	Ppm	12.92	10.06	10.35	24.86	19.08	12.63

Note: M0: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil; M1: 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil; M5: 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil; MST: week after planting.
Source: Laboratory Analysis Results, Department of Soil Science and Land Resources, Faculty of Agriculture, Bogor Agricultural University, 2022.

The total N nutrient content in M1 planting medium increased to 40% higher than M0 and M5, which reached 36% at 20 weeks after planting (Table 1). The addition of *nickel* slag and manure (40%:10%) to the overburden soil increased the total N nutrients for 20 weeks. The largest total P content in M5 planting medium was 81.99%, and the lowest in M0 was 69.77%, while in M1 it was 73.29%. The addition of nickel slag and manure, with or without *topsoil*, to the overburden soil can increase total nutrient accumulation of P over 20 weeks. A decrease in available P levels occurred in M0 and M1, but the highest decrease in available P was 54.38% in M1 and 34.62% in M0 at 20 weeks after planting. These results indicate that P-available is absorbed more with a *mixture of 40% nickel* slag into *the overburden* soil without *topsoil*. The increase in P-availability in M5 planting medium by 1.95% at 20 weeks after planting is suspected to be due to the accumulation of organic nutrients from fallen eucalyptus leaves. K levels decreased by 62.96% in M0 planting media, 30% in M1, and 22.73% in M5 at week 20. A decrease in K levels indicates that K is absorbed by plants in all growing media (M0, M1, and M5). With a mixture of nickel slag in overburden soil, the absorption of K is lower, but the absorption of K in the addition of 20% *nickel* slag with *top soil* is higher than 40% *nickel* slag without *top soil*.

Ca and Mg nutrient levels decreased by 34.3% and 16.03% in M0 planting medium at 20 weeks post-planting (Table 1). In M1 and M5 growing media, the levels of Ca and Mg increased. The increase in Ca levels in M1 planting medium was 23.89%, and 22.79% in M5 planting medium. The increase in Mg levels in M1 planting media was 52.51%, and 20.95% in M5 planting media. The nutrient levels of Na, Fe, Cu, Zn, and Mn increased in week 20 for all Eucalyptus planting media (M0, M1, and M5). The increase in Na in M0, M1, and M5 was 34.38%, 45.45%, and 47.83%. The increase in Cu in M0, M1, and M5 was 66.75%, 63.64%, and 67.47%. M0 planting medium resulted in the highest increase in Fe, Zn, and Mn content by 61.85%, 83.61%, and 48.03%. The lowest increase in Fe and Mn in M5 reached 20%. M1 and M5 planting media experienced an increase in the lowest Zn levels by 75.89% and 76.53%. The increase in micronutrients (Ca, Mg, Na, Fe, Cu, Zn, and Mn) is suspected to be due to the accumulation of organic nutrients from eucalyptus plants that have fallen off. Decrease in micronutrients due to absorption by Eucalyptus plants during 20 weeks of growth.

4.3. Nutrient Content in Planting Media for Centro Beans

Table 2 shows the pH value of the M0 planting medium at 7.04 and M1 at 7.16, which is neutral at 0 weeks after planting, and M3 of 7.79 (somewhat alkaline) at 0 weeks after planting. At 17 weeks after planting, the pH value remained neutral in the M0 planting medium at 7.34 and M1 at 7.45, and the M3 planting medium at 8.32, which remained somewhat alkaline. The increase in C-organic occurred by 2.36% in the M0 planting medium and 15.69% in the M1 planting medium, while there was a decrease in C-organic by 25.24% in the M3 planting medium. The increase in C-organic is thought to be due to the accumulation of organic matter from the Centro Nut section, while the decrease is associated with the reduction in C-organic. The increase in KTK occurred at 17 weeks after planting for M0, M1, and M3 planting media. The highest increase in KTK was 51.26% in M3, while M0 reached 15.28% and M1 reached 17.11%.

Table 2.
Changes in Nutrient Content Concentration in Centro Bean Planting Media.

Parameters	Unit	0 Weeks After Planting			17 Weeks After Planting		
		M 0	M 1	M 3	M 0	M 1	M 3
Macro sins:							
pH		7.04	7.16	7.79	7.34	7.48	8.32
CEC	cmol $^{(+)}$/kg	8.98	6.83	3.66	10.6	8.24	7.51
Sand	%	24.93	34.45	86.86	24.29	34.94	85.63
Dust	%	51.45	47.77	8.18	45.31	39.17	4.08
Clay	%	23.63	17.78	4.96	30.39	25.89	10.29
C-organic	%	1.24	0.86	1.03	1.27	1.03	0.77
N-total	%	0.12	0.11	0.13	0.11	0.08	0.06
Total P	Ppm	76	80.7	289.2	348.14	252.89	244.25
P available	Ppm	38.2	38.1	44	9.2	4.79	8.3
K	cmol $^{(+)}$/kg	0.29	0.3	0.17	0.12	0.13	0.08
Micro harm:							
Ca	cmol $^{(+)}$/kg	4.73	4.53	2.13	7.86	6.15	12.94
Mg	cmol $^{(+)}$/kg	3	4.19	0.9	4.26	4.39	3.63
Na	cmol $^{(+)}$/kg	0.22	0.15	0.17	0.22	0.16	0.18
Fe	Ppm	23.8	24.1	18.5	24.8	20.54	29.99
Cu	Ppm	1.27	0.93	1.9	1.28	1.21	1.66
Zn	Ppm	0.78	0.55	0.72	1.13	1.06	1.44
Mn	Ppm	14.59	9.7	13.44	12.48	12.09	10.41

Note: M0: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil; M1: 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil; M3: 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil; MST: weeks after planting.
Source: Laboratory Analysis Results, Department of Soil Science and Land Resources, Faculty of Agriculture, Bogor Agricultural University, 2022

N-total levels decreased at 17 weeks after planting for all types of planting media, with the highest decrease in M3 planting media by 53.85%, and the decrease in N-total levels in M0 planting media by 8.44% and M1 by 27.27% (Table 2). The increase in P-total levels occurred in M0 and M1, where the highest increase in M0 planting medium was 78.16%, while the decrease in P-total occurred in M3 by 68.10%. Thus, the increase in P-total levels is suspected to be due to the large number of root fibers involved, because there was no addition of fertilizer for 17 weeks. This is also supported by the large decrease in P-available, reaching 75.9% and 87.43%, as well as a decrease in N-total in the planting medium at 17 weeks after planting. On the other hand, there was a decrease in the total P-level in the M3 planting medium by 15.63%, which is suspected to be due to fewer root fibers mixed in the planting medium during harvest activities at 17 weeks after planting. Decreased concentrations of P-available and K were observed in all planting media at 17 weeks post-planting. The level of P-available in M1 and M3 planting media decreased by more than 80%, while in M0 planting media it reached 75.92%. These results may indicate a higher absorption of P-available by Centro Beans when grown in a planting medium with a mixture of up to 80% nickel slag. The K level in all growing media decreased by more than 50%.

Increased levels of Ca, Mg, and Zn were observed in all Centro Bean planting media (M0, M1, and M3) at 17 weeks post-planting (Table 2). The increase in Ca, Mg, and Zn indicates the accumulation of these elements in organic matter from the Centro Nut tissue. The highest increase in Ca, Mg, and Zn levels in M3 planting media was 83.54%, 75.21%, and 50%, respectively, which suggests that the accumulation of Ca, Mg, and Zn in organic matter increased when Centro Beans were grown on nickel slag + manure planting medium (80%:20%). Conversely, M1 planting medium produced an increase in Ca and Mg levels by 26.34% and 4.56%, lower than M0 planting medium, which was 39.82% and 29.58%. This indicates that the accumulation of Ca and Mg in organic matter decreases when Centro Beans are grown on overburden + nickel slag + manure (50%:30%:20%). The increase in Zn levels was higher in M1 planting medium by 48.11% than in M0 planting medium by 30.97%. This demonstrates that the accumulation of Zn in organic matter increases when Centro Beans are grown on overburden + nickel slag + manure planting medium (50%:30%:20%). The increase in Na levels was observed only in M1 planting medium by 6.25% and in M3 by 5.56%. The Na increase indicates that the accumulation of Na in organic matter from the Centro Nut tissue grown on overburden + nickel slag + manure mixed planting medium (50%:30%+20%) is not significantly different from that grown in nickel slag + manure planting medium (80%:20%). The increase in Fe levels was 4.19% in M0 planting media and 38.18% in M3 planting media, while a decrease of 14.70% was observed in M1. These results suggest that the accumulation of Fe in organic matter in nickel slag planting media + manure (80%:20%) is higher than in overburden planting media + manure + topsoil (50%:30%+20%). The increase in Cu levels occurred in M0 planting media by 0.78% and in M1 by 23.14%, whereas M3 showed a decrease of 12.63%. Cu accumulation in organic nutrients is higher when there is a mixture of nickel slag without topsoil into the overburden soil. The increase in Mn levels was observed only in M1 planting media by 19.77%, while decreases of 14.46% and 22.54% were noted in M0 and M3, respectively. These results indicate that Mn absorption by Centro Nuts increases when grown on nickel slag + manure planting media (80%:20%).

4.4. Summary of Tree Growth Analysis Results

The analysis of variance results from the effects of tree species (Cajuput, Red Jabon, Jeungjing, and Nutmeg), types of growing media, and their interactions on growth observation parameters, namely: root length, number of secondary roots, fresh weight of shoots and roots, dry weight of shoots and roots, biomass, and NPA are presented in Table 3.

Table 3.
Summary of tree growth analysis results.

No.	Parameter	Tree Species	Growing Media Type	Interaction
1	Root length	*	ns	*
2	Number of secondary roots	*	ns	ns
3	Fresh weight of shoots (g)	*	ns	ns
4	Fresh weight of roots (g)	*	ns	ns
5	Dry weight of shoots (g)	*	ns	ns
6	Dry weight of roots (g)	*	ns	*
7	Total biomass (g)	*	ns	ns
8	Shoot-to-root ratio (NPA)	*	ns	*

Note: **) significant at 1% level; *) significant at 5% level; ^{ns}) not significant/no effect.

Table 3 shows that tree species significantly affect the parameters of root length, secondary root number, fresh weight of shoots and roots, dry weight of shoots and roots, total biomass, and shoot-to-root ratio (NPA). The type of growing media treatment given to the trees does not significantly affect tree growth. The interaction between tree species and growing media type significantly affects the parameters of root length, root dry weight, and NPA.

- Analysis of the effect of tree species on growth: The tree species factor results in significantly different growth. The effect of the tree species factor indicates that each tree species (Cajuput, Red Jabon, Jeungjing, and Nutmeg) has different growth rates. Therefore, a further DMRT test was conducted to see which tree species resulted in better growth. The results of the further DMRT test on the effect of tree species on the parameters of root length, secondary root number, fresh weight of shoots and roots, dry weight of shoots and roots, total biomass, and NPA are presented in Tables 4 and 5.

4.4.1. Number of Secondary Roots, Fresh Weight of Shoots, Fresh Weight of Roots, and Root Length

Table 4 shows that the Cajuput species produced the highest number of secondary roots, averaging 25 secondary roots, while Jeungjing and Nutmeg produced the lowest number of secondary roots, with 14 and 12 secondary roots, respectively.

The Red Jabon species produced the highest fresh weight of shoots and roots, while the Jeungjing species produced the lowest fresh weight of shoots and roots. The average fresh weight of shoots and roots of Red Jabon was 35.58 g and 19.77 g, respectively. These results indicate that, although the number of secondary roots of the Red Jabon species was lower than that of Cajuput, averaging 16 secondary roots up to 20 weeks, Red Jabon had a higher growth ability compared to Cajuput. The Red Jabon species has a higher capacity to develop shoot and root cells, whereas the Jeungjing species exhibits a lower growth ability compared to other species used in this study. However, the root growth rate of nutmeg plants is higher than that of the other three types of tree plants.

Table 4.
Results of DMRT test on the effect of tree species on the number of secondary roots, fresh weight of shoots, roots, and root length.

Tree Species	Parameter			
	Number of Secondary Roots	Fresh Weight of Shoots (g)	Fresh Weight of Roots (g)	Root length (cm)
Cajuput	25.58 ± 7.96 ^{a}	18.18 ± 6.04 ^{b}	8.21 ± 3.30 ^{b}	16.63 ± 6.57 ^{b}
Red Jabon	16.45 ± 4.92 ^{b}	35.58 ± 9.34 ^{a}	19.77 ± 9.23 ^{a}	4.66 ± 2.50 ^{p}
Jeungjing	13.85 ± 5.52 ^{c}	8.05 ± 6.51 ^{d}	2.27 ± 1.70 ^{c}	7.68 ± 5.49 ^{c}
Nutmeg	12.47 ± 3.68 ^{c}	10.50 ± 2.88 ^{c}	7.78 ± 2.26 ^{b}	19.70 ± 6.59 ^{A}

Note: FW: Fresh Weight; DW: Dry Weight; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

The root morphology of Cajuput, Red Jabon, Jeungjing, and Nutmeg is shown in Figure 3. It can be seen that the various growing media treatments (M0—5) in this study did not result in different numbers of secondary roots for each tree species. On the other hand, the four tree species produced different root appearances. The Cajuput species produced the highest number of secondary roots, while the Jeungjing and Nutmeg species produced the lowest number of secondary roots.

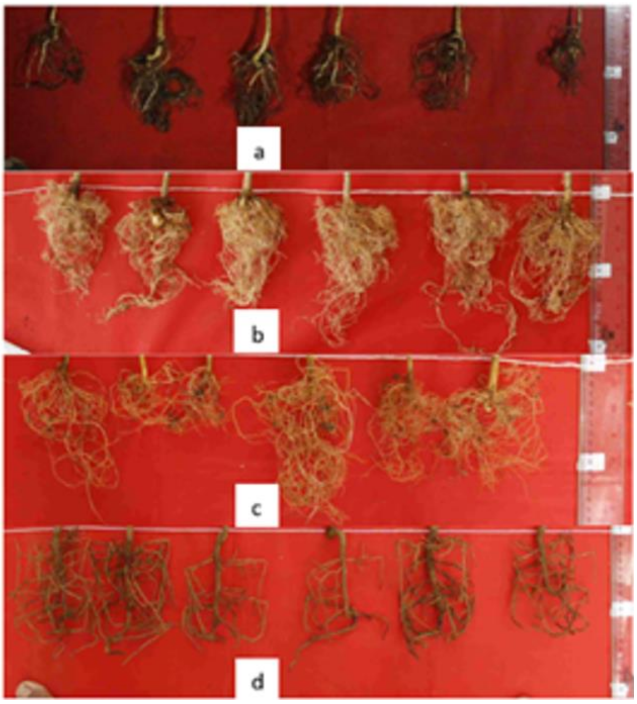

Figure 7.
Root morphology of tree species at 20 weeks.
Note: After planting from left to right M0, M1, M2, M3, M4, M5:
(a) Cajuput; (b) Red Jabon; (c) Jeungjing ; (d) Nutmeg.

4.4.2. Dry Weight of Shoots and Roots, Total Biomass, and NPA

Based on Table 5, the Red Jabon species produced the highest dry weight of shoots, roots, and total biomass, reaching 9.36 g, 4.24 g, and 13.60 g, respectively. This indicates the ability of Red Jabon to grow higher compared to other species. Meanwhile, the Jeungjing species produced the lowest dry weight of shoots, roots, and total biomass, reaching 3.46 g, 0.93 g, and 4.40 g, respectively. This shows that the Jeungjing species has a lower growth ability compared to the Cajuput, Red Jabon, and Nutmeg species.

Table 5.
Results of DMRT test on the effect of tree species on dry weight of roots, total biomass, and NPA.

Tree Species	Parameter			
	Dry Weight Tuna (g)	Dry Weight of Roots (g)	Total Biomass (g)	NPA
Cajuput	5.95 ± 1.79 b	2.84 ± 1.24 b	8.78 ± 2.85 b	2.33 ± 0.74 b
Red Jabon	9.36 ± 2.68 a	4.24 ± 1.31 a	13.60 ± 3.27 a	2.35 ± 0.79 b
Jeungjing	3.46 ± 2.72 d	0.93 ± 0.76 d	4.40 ± 3.45 d	4.07 ± 1.93 a
Nutmeg	4.02 ± 1.11 c	2.16 ± 0.69 c	6.18 ± 1.68 c	1.94 ± 0.45 c

Note: DW: Dry Weight; NPA: Shoot-to-Root Ratio; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

The Nutmeg, Cajuput, and Red Jabon tree species produced lower NPA values than sAlbizia (Table 5). The average NPA value for Nutmeg was 1.9, while Cajuput and Red Jabon produced NPA values of 2, which meet the NPA range criteria of 1,3. Meanwhile, Jeungjing, which did not meet the NPA range criteria, produced a value of 4. These results indicate that each tree species used in this study has different abilities in the growth of above-ground parts (stems, branches, leaves) and below-ground parts (roots).

4.5. Analysis of the Interaction Effect of Tree Species and Growing Media Type on Plant Growth

The DMRT test results in Table 6 show that root length, dry weight of roots, and NPA of the tree species used in this study are not only influenced by the tree species factor but also by the interaction with the growing media factor applied to the plants. The interaction of Cajuput species with growing media M2 and M4 resulted in an average root length that was not significantly different from the interaction of Cajuput species with growing media M0, reaching 19.30 cm. The interaction of Cajuput species with growing media M1 resulted in an average dry weight of roots and NPA that were not significantly different from the interaction of Cajuput species with growing media M0, reaching 3.33 g and 2.01, respectively. Meanwhile, the interaction of Cajuput species with growing media M5 resulted in the lowest root length, dry weight of roots, and NPA, which were significantly different from the interaction of Cajuput species with growing media M0. These results indicate that only the growing media of 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil reduced the root growth ability of Cajuput.

Table 6.
Results of DMRT test on the interaction effect of tree species and growing media on root length, dry weight of roots, and NPA.

Tree Species	Growing Media	Parameter		
		Root Length (cm)	Dry Weight of Roots (g)	NPA
Cajuput	M0	18.10 ± 4.86 ab	3.26 ± 1.09 bcd	2.34 ± 0.70 efg
Cajuput	M1	16.50 ± 6.10 bc	2.78 ± 1.36 def	2.24 ± 0.62 efg
Cajuput	M2	18.10 ± 6.87 abc	3.33 ± 1.45 cde	2.09 ± 0.70 efg
Cajuput	M3	13.10 ± 6.45 cd	2.30 ± 1.04 ef	2.54 ± 0.93 efg
Cajuput	M4	19.30 ± 8.73 ab	3.20 ± 1.26 cde	2.01 ± 0.36 efg
Cajuput	M5	14.70 ± 5.14 bc	2.15 ± 0.93 f	2.78 ± 0.88 cdef
Red Jabon	M0	4.86 ± 1.52 fgh	5.38 ± 2.01 a	2.20 ± 1.14 efg
Red Jabon	M1	6.40 ± 4.81 fg	4.53 ± 1.07 ab	1.88 ± 0.46 fg
Red Jabon	M2	4.85 ± 1.53 fgh	4.26 ± 1.13 abc	2.46 ± 0.72 efg
Red Jabon	M3	4.55 ± 2.29 gh	3.94 ± 0.77 abc	2.43 ± 0.62 efg
Red Jabon	M4	4.20 ± 0.59 gh	3.48 ± 1.11 bcd	2.60 ± 0.87 defg
Red Jabon	M5	3.10 ± 1.02 h	3.83 ± 0.71 abc	2.51 ± 0.72 efg
Jeungjing	M0	5.67 ± 2.35 fgh	0.71 ± 0.81 i	4.64 ± 1.60 ab
Jeungjing	M1	6.70 ± 3.33 efg	0.69 ± 0.36 i	3.81 ± 1.59 bc
Jeungjing	M2	6.06 ± 2.40 fg	0.80 ± 0.80 i	5.04 ± 1.92 a
Jeungjing	M3	10.60 ± 5.93 de	1.41 ± 0.93 gh	3.00 ± 1.14 cde
Jeungjing	M4	6.31 ± 2.37 efg	1.06 ± 0.94 hi	4.75 ± 3.33 ab
Jeungjing	M5	9.95 ± 9.82 ef	0.90 ± 0.50 hi	3.58 ± 1.26 bcd
Nutmeg	M0	19.20 ± 5.25 ab	1.85 ± 0.46 fg	1.82 ± 0.19 fg
Nutmeg	M1	23.80 ± 6.48 a	1.88 ± 0.75 fg	2.18 ± 0.47 efg
Nutmeg	M2	19.00 ± 5.42 ab	2.15 ± 0.55 ef	1.66 ± 0.25 g
Nutmeg	M3	21.40 ± 8.02 ab	1.94 ± 0.55 f	2.33 ± 0.54 efg
Nutmeg	M4	20.60 ± 6.77 ab	2.53 ± 0.80 def	1.82 ± 0.26 fg
Nutmeg	M5	14.20 ± 4.34 bc	2.58 ± 0.73 def	1.85 ± 0.53 fg

Note: M0: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil; M1: 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil; M2: 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil; M3: 50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil; M4: 50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil; M5: 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil; NPA: Shoot-to-Root Ratio; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

The interaction of Red Jabon species with growing media M1, 5 resulted in average root length and NPA that were not significantly different from the interaction of Red Jabon species with growing media M0, reaching 6.4 cm and 1.88 (Table 6). The interaction of Red Jabon species with growing media M1, M3, and M5 resulted in an average dry weight of roots that was not significantly different from the interaction of Red Jabon species with growing media M0, reaching 5.38 g. Meanwhile, the interaction of Red Jabon species with growing media M4 resulted in the lowest dry weight of roots, which was significantly different from the interaction of Red Jabon species with growing media M0. The low dry weight of Red Jabon roots indicates that only the growing media of50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil reduced the root growth ability of Red Jabon.

Only the interaction of Jeungjing species with growing media M3 resulted in average root length, dry weight of roots, and NPA that were significantly different from the interaction of Jeungjing species with growing media M0, reaching 10.60 cm, 1.41 g, and 3.00 (Table 6). These results indicate that the growing media consisting of 50% overburden soil, 20% nickel slag, 30% manure, and 0% topsoil can enhance the root growth of Jeungjing plants. The interaction of Nutmeg species with growing media M1 5 resulted in average root length, dry weight of roots, and NPA that were not significantly different from the interaction of Nutmeg species with growing media M0, reaching 23.80 cm, 2.58 g, and 1.66, respectively. These results suggest that the growth of Nutmeg plants is not affected by overburden growing media with or without the addition of nickel slag or topsoil.

4.6. Summary of Cover Crop Growth Analysis Results

The analysis of variance results from the growth of cover crops shown in Table 7 indicate that the cover crop species factor affects root length, fresh weight of roots, fresh weight of shoots, dry weight of roots, dry weight of shoots, total biomass, and NPA. The growing media type factor only affects the parameters of fresh weight of shoots, dry weight of shoots, total biomass, and NPA. The interaction of cover crop species and growing media affects the parameters of fresh weight of roots, fresh weight of shoots, dry weight of roots, dry weight of shoots, and total biomass. These results show that the growth ability of the cover crop species used in this study varies. The characteristics of each growing media type also have an impact on the growth of the cover crop species.

Table 7.
Summary of cover crop growth analysis results.

No.	Parameter	Cover Crop Species	Growing Media Type	Interaction
1	Root Length (cm)	*	ns	ns
2	Fresh Weight of Shoots	*	*	*
3	Fresh Weight of Roots (g)	*	ns	*
4	Dry Weight of Shoots (g)	*	*	*
5	Dry Weight of Roots (g)	*	ns	*
6	Total Biomass (g)	*	*	*
7	Shoot-to-Root Ratio (NPA)	*	*	ns

4.7. Analysis of the Effect of Cover Crop Species on Growth

The cover crop species factor results in significantly different growth. The effect of the cover crop species factor indicates that each cover crop species (Centro Bean, Citronella, and Bede Grass) has different growth performance. Therefore, a further DMRT test was conducted to see which cover crop species resulted in better growth. The results of the further DMRT test on the effect of cover crop species on the parameters of root length, fresh weight of shoots and roots, dry weight of shoots and roots, total biomass, and NPA are presented in Tables 8, 9.

4.7.1. Root Length, Fresh Weight of Shoots, Fresh Weight of Roots, and Dry Weight of Shoots

Table 8 shows that the Centro Bean and Bede Grass species produced the highest root lengths, averaging >21 cm, while Citronella produced the highest fresh weight of shoots, fresh weight of roots, and dry weight of shoots. For the Citronella species, the average fresh weight of shoots reached 50.89 g, the fresh weight of roots reached 19.51 g, and the dry weight of roots reached 18.31 g. These results indicate that the root growth ability of the Citronella species is higher compared to the Centro Bean or Bede Grass.

Table 8. Results of DMRT test on the effect of cover crop species on root length, fresh weight of shoots, and dry weight of shoots.

Cover Crop Species	Parameter			
	Root Length (cm)	Fresh Weight of Shoots (g)	Fresh Weight of Roots (g)	Dry Weight of Shoots (g)
Centro Bean	23.27 ± 6.45 [a]	12.70 ± 9.40 [b]	1.87 ± 1.19 [b]	6.14 ± 3.85 [b]
Citronella	6.53 ± 2.66 [b]	50.89 ± 16.26 [a]	19.51 ± 8.37 [a]	18.31 ± 6.51 [a]
Bede Grass	21.22 ± 5.56 [a]	7.84 ± 4.21 [c]	1.54 ± 1.15 [b]	3.33 ± 1.48 [c]

Note: FW: Fresh Weight; DW: Dry Weight; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

4.7.2. Dry Weight of Roots, Total Biomass, and NPA

Table 9 shows that Citronella obtained the highest dry weight of roots and total biomass, as well as an NPA value that meets the standard for good growth (NPA range of 1-3). The average dry weight of roots for the Citronella species reached 8.31 g, total biomass reached 26.62 g, and NPA reached 2.45 at week 17 (Table 9). In line with the results for fresh weight of shoots, fresh weight of roots, and dry weight of shoots for the Citronella species, these results indicate that the root growth ability of the Citronella species is higher compared to Centro Bean or Bede Grass. The NPA values for the Centro Bean and Bede Grass species exceed the standard value for good growth, which is 1–3, indicating that the growth of the shoot parts is higher than the root parts.

Table 9.
Results of DMRT test on the effect of cover crop species on dry weight of roots, total biomass, and NPA.

Cover Crop Species	Parameter		
	Dry Weight of Roots (g)	Total Biomass (g)	NPA
Centro Bean	1.04 ± 0.61 [b]	7.18 ± 4.34 [b]	6,06 ± 2.93 [a]
Citronella	8.31 ± 3.89 [a]	26.62 ± 9.51 [a]	2,45 ± 0.91 [b]
Bede Grass	0.69 ± 0.44 [b]	4.02 ± 1.75 [c]	5,71 ± 2.88 [a]

Note: DW: Dry Weight; NPA: Shoot-to-Root Ratio; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

4.8. Analysis of the Effect of Growing Media Type on Cover Crop Growth

The growing media type factor results in significantly different cover crop growth parameters. The effect of the growing media factor indicates that the physical and chemical properties of each growing media type (M0, 5) influence the growth performance of the cover crops used. Therefore, a further DMRT test was conducted to see which growing media type resulted in better cover crop growth. The results of the further DMRT test on the effect of growing media type on the parameters of fresh weight of shoots, dry weight of shoots, total biomass, and NPA are presented in Table 10.

Fresh weight of shoots, dry weight of shoots, total biomass, and NPA of cover crops after treatment with different growing media types.

Based on the results of the further DMRT test on the effect of growing media type on growth parameters in Table 10, the growing media type affects the parameters of fresh weight of shoots, dry weight of shoots, total biomass, and NPA of cover crops. The growing media types M2, M3, M4, and M5 produced the highest fresh weight of shoots, dry weight of shoots, and total biomass. The growing media type M2, 5 is a growing media with a mixture of nickel slag up to 80% without a mixture of overburden soil or topsoil.

Table 10.
Results of DMRT test on the effect of growing media type on, fresh weight of shoots, dry weight of shoots, total biomass, and NPA.

Growing Media	Parameter			
	Fresh Weight of Shoots (g)	**Dry Weight of Shoots (g)**	**Total Biomass (g)**	**NPA**
M 0	19.82 ± 20.07 ^{b}	7.43 ± 6.25 ^{b}	10.64 ± 10.19 ^{c}	4.36 ± 2.08 ^{b}
M 1	23.48 ± 26.01 ^{ab}	8.91 ± 9.21 ^{b}	13.36 ± 14.71 ^{bc}	3.32 ± 1.57 ^{c}
M 2	26.68 ± 21.10 ^{ab}	10.20 ± 7.58 ^{a}	13.58 ± 11.49 ^{a}	6.18 ± 4.88 ^{a}
M 3	25.61 ± 20.69 ^{ab}	10.08 ± 7.69 ^{a}	13.21 ± 10.82 ^{ab}	4.61 ± 2.18 ^{ab}
M 4	26.53 ± 22.53 ^{a}	10.49 ± 8.39 ^{a}	14.05 ± 12.22 ^{a}	4.70 ± 2.52 ^{ab}
M 5	26.79 ± 25.27 ^{a}	10.71 ± 8.61 ^{a}	14.02 ± 12.03 ^{a}	4.99 ± 2.61 ^{ab}

Note: M0: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil; M1: 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil; M2: 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil; M3: 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil; M4: 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil; M5: 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil; NPA: Shoot-to-Root Ratio; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

The growing media types M2, 5 produced fresh weight of shoots up to 26.79 g, dry weight of shoots up to 10.71 g, and total biomass up to 14.05 g (Table 10). On the other hand, the growing media types M2–5 did not produce the best NPA values, which reached values >4, indicating that the shoot growth of the plants was higher than the root growth. These results show that growing media mixtures with nickel slag up to 80% without overburden soil or topsoil can enhance shoot growth but do not improve root growth.

The growing media types M0, 1, which are growing media with 50% overburden soil, produced the lowest dry weight of shoots, total biomass, and NPA compared to the growing media types M2, 5 (Table 10). The growing media type M1 (with 50% overburden soil mixed with nickel slag without topsoil) improved the root growth of cover crops more than M0 (50% overburden soil mixed with topsoil without nickel slag). This is indicated by NPA values of M1 being lower than M0, but with total biomass results not differing between M1 and M0. Thus, the presence of nickel slag in the growing media can provide better nutrition for cover crops compared to media without nickel slag.

4.9. Analysis of the Interaction Effect of Cover Crop Species and Growing Media Type on Plant Growth

The results of the DMRT test on the interaction effect of cover crop species and growing media type are presented in Tables 11 and 12. The interaction of cover crop species and growing media type affects the fresh weight of shoots, fresh weight of roots, dry weight of shoots, dry weight of roots, and total biomass. The interaction of cover crop species and growing media type in this study affects the growth of both the shoot and root parts of cover crops.

Table 11.
Results of DMRT test on the interaction effect of cover crop species and growing media type on fresh weight of shoots and roots.

Cover Crop Species	Growing Media	Parameter					
		Fresh Weight of Shoots (g)				**Fresh Weight of Roots (g)**	
Centro Bean	M0	5.97	±	2.41 ^{ef}	0.95	±	0.37 ^{c}
Centro Bean	M1	4.31	±	6.19 ^{f}	0.85	±	0.74 ^{c}
Centro Bean	M2	16.60	±	10.05 ^{bc}	2.19	±	0.96 ^{c}
Centro Bean	M3	18.97	±	12.00 ^{b}	2.68	±	1.61 ^{c}
Centro Bean	M4	14.63	±	6.95 ^{bcd}	2.23	±	1.06 ^{c}
Centro Bean	M5	16.07	±	5.51 ^{b}	2.38	±	0.76 ^{c}
Citronella	M0	44.74	±	13.59 ^{a}	16.71	±	7.26 ^{b}
Citronella	M1	56.75	±	8.24 ^{a}	25.17	±	7.63 ^{a}
Citronella	M2	48.76	±	16.85 ^{a}	16.42	±	10.00 ^{b}
Citronella	M3	50.21	±	14.04 ^{a}	19.16	±	6.96 ^{ab}
Citronella	M4	51.04	±	18.02 ^{a}	19.66	±	8.51 ^{ab}
Citronella	M5	53.78	±	23.90 ^{a}	19.89	±	8.38 ^{ab}
Bede Grass	M0	7.51	±	2.88 ^{ef}	1.08	±	0.75 ^{c}
Bede Grass	M1	5.84	±	3.41 ^{ef}	1.09	±	0.53 ^{c}
Bede Grass	M2	9.54	±	5.13 ^{cde}	1.94	±	1.46 ^{c}
Bede Grass	M3	8.40	±	4.11 ^{de}	1.94	±	1.82 ^{c}
Bede Grass	M4	8.50	±	4.87 ^{de}	1.50	±	0.67 ^{c}
Bede Grass	M5	7.53	±	5.08 ^{ef}	1.70	±	1.05 ^{c}

Note: M0: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil; M1: 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil; M2: 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil; M3: 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil; M4: 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil; M5: 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil; numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

4.9.1. Fresh Weight of Shoots, And Fresh Weight of Roots

The interaction of Citronella species with growing media types produced the highest fresh weight of shoots and roots, reaching 56.75 g and 25.17 g at week 17. The fresh weight of Citronella shoots was not affected by the growing media type, as indicated by the same letter notation results. The highest fresh weight of Citronella roots was obtained from the interaction with growing media types M1 and M3, 5. These results show that the root growth of Citronella plants is better in growing media mixtures with nickel slag, with or without 50% overburden soil or topsoil.

The interaction of Bede Grass species with growing media resulted in the lowest fresh weight of shoots and roots (Table 12). The interaction of Bede Grass species with growing media produced letter notations that were not different, indicating that the growing media type did not affect the fresh weight of shoots and roots of Bede Grass plants. Bede Grass plants produced a fresh weight of shoots reaching 9.54 g and a fresh weight of roots reaching 1.94 g at week 17. Bede Grass plants can grow in mixed soil media with or without 50% overburden, as well as in nickel slag mixtures with or without topsoil.

The root morphology of Centro Bean, Citronella, and Bede Grass is shown in Figure 8. The cover crop species treated with growing media M1, 5 exhibited different growth abilities. The growing media types M1 and 5 influenced the growth of Lemongrass but did not affect the growth of Centro Bean and Bede Grass.

Figure 8.
Root morphology of cover Crop plants at 17 weeks after planting from left to right: M0, M1, M2, M3, M4, M5: (a) Centro bean; (b) Citronella; (c) Bede grass.

4.9.2. Dry Weight of Shoots, Dry Weight of Roots, and Total Biomass

The results of the DMRT test on the interaction effect of species and growing media in Table 12 show that the interaction of Citronella species with growing media produced the highest average dry weight of shoots, dry weight of roots, and total biomass. The average dry weight of Citronella shoots was not affected by the growing media type, as indicated by the same letter notation, reaching 20 g at week 17. The interaction of Citronella species with growing media M1 produced the highest average dry weight of roots and total biomass, reaching 11.42 g and 31.8 g. These results indicate that the growing media type does not affect the shoot growth of Citronella plants but does affect root growth. The growing media type of overburden + nickel slag + manure (50:30:20%) is the best growing media type for the root growth of Citronella plants.

Table 12.
Results of DMRT test on the interaction effect of cover crop species and growing media on shoot and root dry weight, as well as total biomass.

Cover Crop Species	Growing Media	Parameter								
		Shoot Dry Weight (g)			Root Dry Weight (g)			Total Biomass (g)		
Centro Bean	M0	3.57	±	0.98 c	0.68	±	0.18 c	4.25	±	1.11 d
Centro Bean	M1	2.55	±	2.59 c	0.53	±	0.33 c	3.08	±	2.91 d
Centro Bean	M2	7.25	±	4.30 b	1.09	±	0.53 c	8.34	±	4.32 c
Centro Bean	M3	8.44	±	4.64 b	1.52	±	0.92 c	9.96	±	5.54 c
Centro Bean	M4	7.09	±	2.81 b	1.18	±	0.46 c	8.27	±	3.18 c
Centro Bean	M5	8.13	±	2.62 b	1.29	±	0.37 c	9.42	±	2.94 c
Citronella	M0	14.93	±	4.93 a	8.06	±	3.78 b	22.99	±	7.85 b
Citronella	M1	20.56	±	3.44 a	11.42	±	3.33 a	31.98	±	6.36 a
Citronella	M2	17.41	±	6.96 a	7.61	±	5.43 b	25.02	±	11.05 ab
Citronella	M3	18.66	±	5.92 a	7.24	±	2.55 b	25.90	±	8.28 ab
Citronella	M4	19.20	±	7.24 a	8.02	±	3.56 b	27.22	±	10.18 ab
Citronella	M5	19.13	±	9.18 a	7.40	±	3.30 b	26.53	±	11.98 ab
Bede Grass	M0	3.38	±	1.04 c	0.66	±	0.29 c	4.03	±	1.28 d
Bede Grass	M1	2.29	±	1.16 c	0.65	±	0.31 c	2.94	±	1.30 d
Bede Grass	M2	4.11	±	2.07 c	0.60	±	0.34 c	4.71	±	2.38 d
Bede Grass	M3	3.33	±	1.75 c	0.81	±	0.72 c	4.14	±	2.28 d
Bede Grass	M4	2.89	±	1.34 c	0.61	±	0.30 c	3.50	±	1.54 d
Bede Grass	M5	3.93	±	1.06 c	0.79	±	0.52 c	4.72	±	1.30 d

Note: • M0: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil
• M1: 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil
• M2: 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil
• M3: 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil
• M4: 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil
• M5: 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil
Numbers in the same column followed by the same letter are not significantly different at the 5% DMRT test.

The type of growing media with a mixture of nickel slag without overburden soil resulted in the growth of the shoot part of Centrocema plants, as indicated by the interaction results of Centrocema plant species with growing media types M2—5, which produced higher shoot dry weight and total biomass than the interaction with growing media types M0—1 (Table 12). The average shoot dry weight of Centrocema plants was 7–8 g, and the total biomass was 8.34–9.96 g at week 17. The growth of the shoot and root parts of Bede grass species was not affected by the type of growing media, as indicated by the same letter notation results.

5. Discussion

The interaction factor between Jeungjing plants and the type of growing medium affects the root growth of Jeungjing seedlings. The interaction of Jeungjing plants with overburden soil medium combined with nickel slag and manure (20:30%) produced the highest root length, root dry weight, and NPA (Shoot-Root Ratio). This growing medium of overburden with nickel slag and manure (20:30%) can enhance root growth compared to overburden medium with manure and topsoil (30:20%). The overburden medium with nickel slag and manure (20:30%) can be used as an alternative growing medium to replace overburden combined with manure and topsoil (30:20%) for Jeungjing seedlings. The root growth of nutmeg seedlings was not affected by overburden growing medium treatments combined with nickel slag and manure, with or without topsoil. However, the addition of nickel slag did not decrease the root growth of nutmeg seedlings. This result aligns with Neswati, et al. [54] research on land suitability for nutmeg in former nickel mining areas of PT Vale Indonesia Tbk in South Sulawesi indicates that the primary growth-limiting factor is not soil nutrient content but nutrient retention, which relates to the soil's capacity to bind nutrients and the average rainfall (precipitation). The study found that the shoot and root growth of nutmeg seedlings, unaffected by different growing medium treatments, suggests that overburden combined with nickel slag and manure (40:10%) is suitable as a growing medium for nutmeg seedlings. Various combinations of overburden soil with nickel slag and manure, with or without topsoil, significantly decrease root length growth and NPA of Cajuput and Jeungjing seedlings, as well as root dry weight of Cajuput, Red Jabon, and Jeungjing seedlings. Conversely, overburden growing medium with nickel slag addition produced root growth of Cajuput, Red Jabon, and Jeungjing seedlings that did not differ from overburden medium combined with manure and topsoil (30:20%). Additionally, overburden growing medium combined with nickel slag and manure in ratios of (40:10%), (30:20%), (20:30%), or with nickel slag, manure, and topsoil (20:15:15%) produced root growth of Red Jabon seedlings comparable to overburden medium combined with manure and topsoil (30:20%). However, overburden growing medium combined with nickel slag, manure, and topsoil (20:20:10%) is not recommended as an alternative to the overburden medium with manure and topsoil (30:20%) for Red Jabon seedling root growth, as it results in decreased root growth, evidenced by lower root dry weight parameters.

Among the four tree species used in this study, Red Jabon demonstrated the best root and shoot growth potential when grown in media supplemented with nickel slag. The growth of roots and shoots, as measured by fresh and dry weights of shoots and roots, total biomass, and Shoot-Root Ratio (SRR), was higher in Red Jabon seedlings compared to Cajuput, Jeungjing, and Nutmeg.

When comparing the root growth of Cajuput seedlings in various growing media combinations, no significant differences were observed. These combinations included overburden with manure and topsoil (30:20%), overburden with nickel slag and manure (40:10%, 30:20%, 20:30%), and overburden with nickel slag, manure, and topsoil (20:20:10%). This result aligns with Sadono [65] who found no significant differences in the diameter growth of Cajuput stands planted in three different locations within the Cajuput plantation area in RPH Gubugrubuh, where total nitrogen content was similar (0.18%, 0.17%, and 0.14%). However, the growing medium of overburden combined with nickel slag, manure, and topsoil (20:15:15%) is not recommended as an alternative growing medium to replace overburden with manure and topsoil (30:20%) for Cajuput seedling root growth, as it reduces root growth as evidenced by decreased root length, root dry weight, and SRR.

The reduced root growth of Cajuput seedlings in the overburden medium with nickel slag, manure, and topsoil (20:15:15%) corresponds with lower P and K nutrient uptake, as well as a higher decrease in Ni and ash content in the growing medium at week 20 compared to the combination of nickel slag and manure (40:10%). The improved root growth of Cajuput in the nickel slag and manure (40:10%) combination aligns with findings from Saeid [48], Guerra Sierra, et al. [49], Dhaliwal, et al. [50] and Abbas, et al. [51] showing that Cajuput seedlings can grow in ultisol growing media containing nickel slag [51]. This is further supported by Jala and Goyal [52] and Haynes [53] who found that nickel slag concentrations up to 30% of ultisol soil weight enhance Cajuput seedling growth in nurseries. Increasing nickel slag content from 20% to 40% in the growing medium can improve Cajuput seedling growth.

This is consistent with Barrow and Hartemink [66] research, which found that a plant's ability to absorb nutrients has a stronger influence on P uptake compared to soil effects, and that P uptake decreases with increasing pH Barrow and Hartemink [66] supports these findings, showing that nickel slag application significantly affects root growth, specifically primary root length and secondary root mass in Cajuput plants. This is further corroborated by Niu, et al. [44] who indicate that increased root growth and development subsequently influence plant growth, particularly the stem diameter of Cajuput seedlings [47].

The overburden soil media with combinations of manure and topsoil (30:20%), nickel slag and manure (40:10%), and nickel slag, manure, and topsoil (20:15:15%) in this study produced stable soil reactions at neutral conditions up to week 20, despite indications of organic litter decomposition from Cajuput, Jones and Nachtsheim [63] plants. The indication of organic litter decomposition was evidenced by increased CEC and contents of organic C, total N, total P, Na, Fe, Cu, Zn, and Mn at week 20. This aligns with Liu, et al. [67] study showing that litter decomposition of Betula luminifera and Cinnamomum glanduliferum increased soil organic C, total N, and total P contents [67]. By week 20, the growth of Cajuput, Red Jabon, Jeungjing, and Nutmeg plants was able to produce decomposable litter, thus improving the physical and chemical properties of the overburden soil. The single factor of cover crop species significantly influenced root and shoot growth. Growth differences among the three cover crop species in this study corresponded with the observed variations in biomass production and soil nutrient enhancement Faria, et al. [68] findings, where biomass differed between Bede Grass and Brachiaria ruziziensis grown in mixed media of soil (Red-Yellow Latosol) and sand (4:1) [68]. Similarly, it was found that Centro Bean, Pueraria phaseoloides, Pannicum maximum, and Setaria splendida produced different growth rates when grown in former gold mine soil media. The effect of cover crop species as a single factor showed varying growth rates for each species when treated with different growing media in this study. Lemongrass produced the highest fresh and dry weights of roots and shoots, as well as total biomass, and a Shoot-Root Ratio (SRR) within the good growth standard (1-3). Although Citronella root length was lower compared to Centro Bean and Bede Grass, its root and shoot dry weights were higher. This indicates that Citronella has a higher growth capacity in both roots and shoots compared to Centro Bean or Bede Grass. The Citronella SRR at week 17 was 2.45, showing that shoot and root growth rates were equal. The good root and shoot growth capacity of Citronella aligns with the Environmental and Forestry Instrumentation Standardization Agency criteria for selecting cover crops for coal mine land revegetation: fast-growing, easily decomposable, good root system, and easy and inexpensive propagation. This is supported by Vogel, et al. [69], Pelicice, et al. [70], Fitri, et al. [71] and Nadirah, et al. [72] who noted that Citronella has strong fibrous roots consisting of fine threads that can bind soil particles into stable aggregates, thus preventing soil erosion in critical areas like former mining lands. Although Centro Bean growth and root length, as well as Bede Grass root length, were higher than Citronella, their fresh and dry weights of roots and shoots, and total biomass were lower than Citronella. The SRR values of Centro Bean and Bede Grass exceeded the good growth standard of 1-3, indicating that their shoot growth was higher than root growth. These findings align with Abbas, et al. [51] showing that Centro Bean could grow in former coal mine soil media, reaching 182.83 cm in height, 48.0 cm in root length, 50.3 leaves, and 21.0 root nodules. The cover crop growing media factor significantly influenced shoot growth. Nickel slag media up to 60%, 70%, and 80% with manure addition, as well as nickel slag + manure + topsoil (30:20:50%) media, significantly increased fresh and dry shoot weights, total biomass, and plant SRR compared to when nickel slag was combined with overburden soil or overburden + manure + topsoil (50:30:20%) media. These media produced higher P and N levels than when nickel slag was combined with overburden soil or overburden + manure + topsoil (50:30:20%) media. This aligns with Yang, et al. [73] findings that optimal P nutrition benefits stem growth, while optimal N content benefits root and leaf growth for Phoebe bournei seedlings. However, the increase in N and P nutrients with nickel slag addition differs from Rosalina, et al. [1] results, which reported that nickel slag increased total N in red-yellow podzolic soil only at 8 tons/ha addition, while it increased available P at 8, 12, and 16 tons/ha additions. The increase in N and P nutrients in growing media with nickel slag addition varies depending on the soil combined with nickel slag. The interaction factor between Bede Grass and growing media types did not affect shoot or root growth. This aligns with Silva, et al. [74] study, where Bede Grass fresh and dry weights of shoots and roots continued to increase with plant age when grown in Latosol soil contaminated with 0-80 mg Co up to 60 DAPS. These results indicate that Bede Grass growth is only influenced by its adaptation ability to overburden or nickel slag growing media. The interaction factor between Centro Bean and Citronella species and growing media types significantly influenced root and shoot growth. Nickel slag media up to 80% with manure addition significantly increased Lemongrass root growth, specifically fresh root weight, while overburden + nickel slag + manure (50:30:20%) media increased dry root weight and total biomass.

Regarding the interaction factor between Centro Bean plant species and growing media, the results show that overburden growing media supplemented with up to 30% manure, with or without nickel slag or topsoil, increased the shoot dry weight and total biomass of Centro Bean plants. Meanwhile, growing media with 80% nickel slag and 20% manure addition was able to increase the shoot fresh weight of Centro Bean plants. The increase in biomass with the addition of manure aligns with the results of Mekapogu et al. [2], which showed that Centro Bean biomass could increase up to 1.18 kg/plot with the addition of 10 tons/ha of compost to former mining land. This differs from the results of Audet, et al. [27] which showed that root length and the number of root nodules were influenced by manure addition, which could increase root length and the number of root nodules. This difference is due to the fact that plant growth in media with manure addition will vary for each former mining site. The use of 80% nickel slag + 20% manure can replace the use of up to 30% manure in overburden and can result in an increase in shoot fresh weight of Centro Bean plants.

Table 13.
Comparison table of the effect of planting media combinations on plant root and crown growth.

Plant	Combination Planting Media	Root Growth	Canopy Growth	Recommendations	Supporting Studies
Jeungjing	Overburden + nickel slag + manure (20:30%)	Highest: Root length, root dry weight, NPA (SRR).	Not specifically explained.	Recommended as an alternative to overburden + fertilizer + topsoil (30:20%).	Neswati, et al. [54]
	Overburden + fertilizer + topsoil (30:20%)	Lower than the combination with nickel slag.	-	Not recommended.	-
Nutmeg	Overburden + nickel slag + fertilizer (40:10%)	Unaffected; steady growth.	Not affected.	Suitable for planting media.	Neswati, et al. [54]
	Other combinations (with/without topsoil)	There was no significant decrease.	-	-	-
Cajuput	Overburden + nickel slag + fertilizer (40:10%)	Increased due to better P and K absorption.	-	Recommended (40% slag is optimal).	Saeid [48]
	Overburden + nickel slag + fertilizer + topsoil (20:15:15%)	Decreased root length, root dry weight, and SRR.	-	Not recommended.	Niu, et al. [44]
Red Jabon	Overburden + nickel slag + fertilizer (40:10%, 30:20%, 20:30%)	Root growth was no different from the control medium (30:20%).	Highest crown growth among all species.	Recommended	-
	Overburden + nickel slag + fertilizer + topsoil (20:20:10%)	Decrease in root dry weight.	-	Not recommended.	-
Citronella	Media with 80% slag + 20% fertilizer	Highest dry weight of roots and shoots. SRR = 2.45 (ideal).	Highest total biomass.	Recommended for revegetation of critical land.	Vogel, et al. [69]
Centro	Overburden + fertilizer (up to 30%)	High root length, but SRR >3 (dominant shoot).	Low biomass compared to Citronella.	Recommended with SRR monitoring notes.	Abbas, et al. [51]

	Slag 80% + fertilizer 20%	The length of the roots increases.	Fresh weight of the crown increases.	Can replace fertilizer use up to 30%.	-
Bede Grass	All media combinations	Root and crown growth are stable, not affected by the media.	-	Adaptive for overburden/slag media.	Silva, et al. [74]

Additional Information:

1. Growth Limiting Factors:
   a. Nutmeg: The main factors are nutrient retention and rainfall, not soil nutrient content.
   b. Cajuput: P absorption is influenced by plant ability, not soil effects.
   c. Red Jabon: Positive response to the addition of nickel slag due to increased availability of N and P.
2. Changes in Soil Properties:
   a. The combination of media with slag + fertilizer maintains neutral pH until the 20th week.
   b. Litter decomposition increases C-organic, CEC, and nutrients (N, P, Fe, Cu, Zn, Mn) [67].
3. Optimal Media Criteria:
   a. Citronella: Strong root fibers for soil stabilization.
   b. Nickel Slag: Concentration ≤40% increases plant growth (especially Cajuput and Red Jabon).

Based on the discussion above, this study has several novelties that distinguish it from previous studies, especially in the context of utilizing nickel slag-based planting media for post-mining land revegetation. Here are the points of novelty:

1. Innovation in the Combination of Planting Media with Nickel Slag
   a. Novelty: This study tests the combination of nickel slag (mining industry waste) with overburden, manure, and topsoil in different proportions (e.g., 20:30%, 40:10%, 20:15:15%) as planting media.
   b. Differences with Previous Research:
      i. Previous studies, such as Neswati, et al. [54] focused on land suitability for nutmeg plants in ex-mining areas without testing nickel slag as a media component.
      ii. Research by Saeid [48] only evaluated nickel slag on ultisol media without combining it with overburden and manure.
      iii. New Contribution: The combination of nickel slag with manure has been shown to increase root and shoot growth of certain plants (e.g., Red Jabon, Cajuput) and can replace topsoil use by up to 30-40%, which was previously considered crucial in revegetation.
2. Identification of the Most Responsive Species to Nickel Slag
   a. Novelty: This study found that Red Jabon showed the best growth response (roots and shoots) on media with nickel slag, while Nutmeg was not affected.
   b. Differences with Previous Studies:
      i. Previous studies, Niu et al. [44], focused on plants such as Cajuput or cover grass, without comparing responses between tree species.
      ii. New Contribution: Red Jabon was identified as the most adaptive species to nickel slag, opening up the opportunity for its use as a pioneer plant in ex-nickel mining areas.
3. Optimization of Nickel Slag Concentration for Plant Growth
   a. Novelty: This study found that nickel slag concentrations of up to 40% (in combination with manure) increased Cajuput growth, in contrast to previous recommendations (maximum 30%) Jala and Goyal [52]).
   b. Differences with Previous Studies:
      i. Previous studies (e.g., Jala and Goyal [52]) only tested nickel slag on ultisol media for seedlings, without exploring combinations with overburden and fertilizers.
      ii. New Contribution: Increasing nickel slag concentrations of up to 40% proved safe and effective for Cajuput, indicating the potential for large-scale slag waste utilization.
4. Mechanism of Soil Properties Improvement Through Litter Decomposition
   a. Novelty: This study reveals that the decomposition of plant litter (Cajuput, Red Jabon, etc.) in overburden + nickel slag media increases C-organic, CEC, and nutrient availability (N, P, Fe, Cu, Zn, Mn) until the 20th week.
   b. Differences with Previous Research:
      i. Liu et al. [66] study focused on litter decomposition in natural forests, not in post-mining media enriched with nickel slag.
      ii. New contribution: The combination of nickel slag with revegetation plants creates an independent nutrient cycle, reducing dependence on external fertilizer inputs.
5. Specific Planting Media Recommendations for Each Species
   a. Novelty: This study provides guidelines for different planting media proportions for each species, such as:
      i. Red Jabon: Overburden + nickel slag + fertilizer (40:10%).
      ii. Cajuput: Nickel slag + fertilizer (40:10%), avoid additional topsoil (20:15:15%).
      iii. Citronella: Nickel slag 80% + fertilizer 20% for soil stabilization.
   b. Differences with Previous Research:

i. Previous research (e.g., Fitri, et al. [71]) only evaluated standard media (soil + fertilizer) without varying nickel slag or overburden.
ii. New Contribution: Evidence-based recommendations for the selective use of nickel slag, according to species characteristics.

6. Use of SRR (Shoot-Root Ratio) as an Indicator of Media Suitability
   a. Novelty: This study uses SRR to assess the balance of root-shoot growth, where SRR 1-3 is considered ideal. Citronella (SRR 2.45) met this criterion, while Centro and Bede Grass had SRR >3 (dominant canopy).
   b. Differences with Previous Studies:
      i. Previous studies (e.g., Vogel, et al. [69]) only measured total biomass without analyzing the root-shoot ratio.
      ii. New Contribution: SRR becomes a quantitative indicator to assess the efficiency of plant adaptation in marginal media.
7. Integration of Mining Waste with Local Wisdom
   a. Novelty: This study combines nickel slag (industrial waste) with local manure (cow dung) and native species (e.g., Nutmeg, Red Jabon) as a sustainable restoration solution.
   b. Differences with Previous Research:
      i. Research in Obi Island generally focuses on chemical remediation without combining slag waste with local organic fertilizers.
      ii. New Contribution: A circular economy-based restoration model that utilizes mining waste and local resources.

This study not only tests nickel slag as a planting medium, but also designs an integrated revegetation system that considers:

1. Optimal combination of nickel slag with local materials (overburden, manure).
2. Specific response of each plant to the medium.
3. Mechanism of increasing soil fertility through litter decomposition.
4. Success criteria based on SRR and measurable growth parameters.

This novelty makes this research relevant for practical applications of post-nickel mining land revegetation, while reducing the dependence on topsoil and hill.

6. Conclusion

The interaction between Jeungjing plants and planting media was shown to significantly affect root growth, with the combination of overburden + nickel slag + manure (20:30%) producing the best root growth (length, dry weight, and SRR). This finding confirms the innovation of using nickel slag as a partial substitute for topsoil, which has not been explored in previous studies Neswati, et al. [54]. On the other hand, nutmeg root growth was not affected by the addition of nickel slag, indicating its high adaptability to marginal media, a new finding that is in line with the mechanism of nutrient retention and resistance to rainfall variations.

Red Jabon stands out as the tree species with the best growth potential (roots and crowns) in media containing nickel slag, outperforming Cajuput, Jeungjing, and nutmeg. This positive response confirms the novelty of the study in identifying the most adaptive species to slag waste, while recommending the combination of 40% slag + manure (40:10%) as the optimal formula for Red Jabon. Meanwhile, Cajuput root growth was stable in almost all media combinations except slag + fertilizer + topsoil (20:15:15%), which actually reduced P and K absorption. This finding strengthens the study of Saeid [48] but with the innovation of increasing slag levels to 40%, exceeding the previously recommended limit of 30%.

In cover crops, Citronella showed superior growth performance (biomass, SRR 2.45) compared to Centro and Bede Grass, thanks to its fibrous root system that stabilizes the soil. This superiority is supported by Citronella's ability to grow optimally in media with 80% slag + 20% fertilizer, a breakthrough in the use of large-scale slag for revegetation. Meanwhile, Bede Grass growth was more influenced by natural adaptation capabilities than media composition, confirming the findings of Silva, et al. [74].

The addition of nickel slag to the planting medium increased the availability of N and P nutrients, although plant responses varied depending on species and soil type. The combination of slag and manure not only reduced dependence on fertilizer and topsoil but also created a sustainable nutrient cycle through the decomposition of plant litter, as seen in the increase in C-organic and CEC in the 20th week. These findings highlight the potential of a circular economy in mine rehabilitation: utilizing slag waste and local fertilizers to build long-term soil fertility. Thus, this study not only proves nickel slag as an effective planting medium component for revegetation but also designs a species-specific formula, optimizes waste utilization, and integrates sustainable restoration ecology principles.

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