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Nickel slag as a nursery medium for the genus *Rhizophora* to support environmental sustainability

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ABSTRACT

Rhizophora mangroves play an important role in maintaining shoreline stability and supporting the sustainability of coastal ecosystems. The success of mangrove rehabilitation is strongly influenced by the quality of nursery media; however, commonly used media are still dominated by muddy substrates with low porosity and aeration, which are less optimal for root development and seedling growth. Nickel slag, an industrial by-product, has a coarse and porous structure and contains inorganic minerals such as CaO, MgO, and SiO_2, making it potentially suitable as a soil ameliorant. This study aimed to analyze the effects of nickel slag size and concentration on nursery media conditions and the growth of *Rhizophora* mangrove seedlings. The study was conducted for three months in North Maluku using a factorial completely randomized design with three nickel slag size variations, namely coarse (SNK), fine (SNH), and mixed (SNC), and four concentration levels of 25%, 50%, 75%, and 100% of the planting media, with five replications for each treatment. The observed parameters included survival rate, seedling height, number of leaves, chlorophyll content, number of root fibers, media pH, and the contents of N, P, K, Ca, Mg, and SiO_2. Data were analyzed using ANOVA followed by Tukey's post hoc test at a 95% confidence level, while media chemical parameters were analyzed descriptively. The results showed that all treatments maintained a 100% seedling survival rate. The SNC 50 treatment produced the best response, with the highest seedling height (18.6 cm), number of leaves (3.2 leaves), chlorophyll content (64.36 SPAD units), and number of root fibers (19.8). The addition of nickel slag at moderate concentrations improved media conditions by enhancing porosity, aeration, and nutrient uptake, thereby better supporting the growth of *Rhizophora* mangrove seedlings.

Keywords: ameliorant, circular economy, concentration, substrate, rehabilitation.

INTRODUCTION

Mangrove ecosystems are among the most important coastal ecosystems, playing a crucial role in maintaining the ecological and socio-economic stability of coastal environments. Mangrove forests can protect coastal areas from erosion and attenuate wave energy, including that generated by tsunamis, thereby serving as natural barriers for coastal protection (Asari et al., 2021; Choundary et al., 2024). In addition, mangroves function as effective blue carbon sinks and contribute significantly to global climate change mitigation efforts (Haidir et al., 2023; Mugilan et al., 2024). These ecosystems also act as natural sediment traps, reservoirs of organic carbon, and sources of nutrients through the decomposition of organic matter, a process facilitated by the activities of bioturbating organisms such as crabs and shrimp (Hua et al., 2024; Sarker et al., 2021).

Mangroves play a vital ecological role in supporting biodiversity in coastal regions. These ecosystems provide habitat, spawning grounds, and nursery areas for a wide range of fish, crustaceans, birds, reptiles, and other benthic organisms (Yunus et al., 2020; Arceo-Carranza et al., 2021; Kathiresan, 2021; Sari et al., 2022). Among the various mangrove genera, *Rhizophora* is one of the most dominant and widely distributed genera across different types of coastal substrates (Arfan et al., 2023). The successful growth of *Rhizophora* is strongly influenced by the characteristics of the growing medium, particularly during the nursery stage. Suitable substrates play a critical role in supporting root development, microbial activity, and nutrient availability for plant growth (Balke et al., 2011). Under natural conditions, *Rhizophora* species generally grow optimally in muddy or fine clay substrates that can retain moisture and provide adequate support for the development of stilt roots (Dewianti and Agustina, 2019; Prihandana et al., 2021).

Mangrove substrates are generally rich in organic matter derived from litterfall and detritus, which support nutrient cycling and ecosystem productivity (Dewiyanti et al., 2021). However, high organic matter content can also contribute to increased substrate acidity as a result of microbial decomposition processes (Lang et al., 2024). In some cases, mangrove nursery media experience degradation of their physical and chemical properties, including low porosity, poor aeration, high salinity, and nutrient imbalances. Low porosity causes the growing medium to become compacted, thereby restricting oxygen diffusion and root system development. Excessive anaerobic conditions can inhibit mangrove seedling growth and reduce the success of rehabilitation efforts (Kim et al., 2020; Marchand et al., 2011). Therefore, improvements in growing media are required not only to enhance nutrient availability but also to improve the physical properties of the substrate, particularly soil porosity and aeration.

One material with considerable potential for use as a soil amendment (ameliorant) is nickel slag. As one of the world's largest nickel producers, Indonesia generates substantial quantities of nickel slag as a solid industrial by-product of nickel ore smelting through the Rotary Kiln Electric Furnace (RKEF) process. According to Appendix XIV of Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning the Implementation of Environmental Protection and Management, nickel slag generated from the nickel ore smelting process is classified as registered non-hazardous and non-toxic waste (non-B3 waste; code N102). Consequently, it has the potential to be reused in various sectors in accordance with applicable environmental management regulations. To date, the utilization of nickel slag remains relatively limited, with most of the material being stockpiled. Several studies have reported the use of nickel slag as a construction material, including as a component in concrete mixtures, paving blocks, and road base materials (Wu et al., 2018; Komba and Rachman, 2018). Furthermore, nickel slag has demonstrated considerable potential for application in land reclamation and the rehabilitation of degraded lands (Rembah et al., 2021; Gultom, 2024).

Nickel slag contains inorganic compounds such as CaO, MgO, and SiO_2, which are known to increase soil pH, reduce aluminum saturation, and enhance nutrient availability for plant growth (Rosalina et al., 2018). In addition to its chemical composition, nickel slag possesses physical characteristics, including a coarse and porous particle structure, which may improve the porosity and aeration of growing media (Ng et al., 2021; Prakash et al., 2021; Tian et al., 2021). Improved porosity can enhance air circulation, water movement, and root penetration within nursery substrates. Adequate aeration also promotes gas exchange in the soil and increases the medium's capacity to retain moisture, which is essential for mangrove seedlings during their early growth stages (Moretti et al., 2020). Furthermore, improved physical and chemical properties of the growing medium can create a more favorable environment for soil microorganisms involved in nitrogen fixation, phosphate solubilization, and organic matter decomposition (Asari et al., 2021; Yadafa et al., 2012).

The application of nickel slag as a soil amendment in mangrove nursery media has the potential to support sustainable coastal ecosystem rehabilitation while promoting circular economy principles through the beneficial utilization of industrial by-products. However, studies investigating the effects of nickel slag on mangrove nursery substrate conditions and the growth performance of *Rhizophora* seedlings remain limited. Therefore, this study aimed to analyze the effects of nickel slag application on nursery substrate conditions and to evaluate how changes in substrate characteristics influence the growth and survival of *Rhizophora* mangrove seedlings. The findings of this study are expected to provide scientific evidence regarding the potential of nickel slag as a soil amendment capable of improving nursery substrate characteristics and supporting optimal mangrove growth, thereby contributing to the sustainable rehabilitation of mangrove ecosystems.

MATERIALS AND METHODS

Study area and research period

The study was conducted over a three-month period, from September to December 2025, in the province of North Maluku (Figure 1). The study area was selected due to the high level of nickel mining and processing activities in the region, which generate substantial quantities of nickel slag as a by-product of the smelting process. In addition, North Maluku contains extensive mangrove ecosystems, making it a relevant location for investigating the potential use of nickel slag to support mangrove nursery development and rehabilitation efforts. These conditions make the region representative for evaluating the potential application of nickel slag as a soil amendment in nursery media for *Rhizophora* mangrove seedlings.

Materials and equipment

The equipment used in this study included buckets and small shovels for substrate mixing, a ruler for measuring seedling height, a digital camera for documentation, a digital balance, a soil pH meter, a soil nutrient checker, a SPAD meter, a 3-mm nickel slag sieve, plant labels and stationery, zip-lock plastic bags for substrate sample storage, and a laptop equipped with IBM SPSS Statistics version 25 for data analysis. Calcium (Ca) and magnesium (Mg) concentrations were analyzed using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP–OES), while SiO_2 content was determined using a spectrophotometric method. The materials used in this study consisted of *Rhizophora* propagules of relatively uniform size, nickel slag, natural mangrove substrate collected from the vicinity of the study area as the growing medium, and polybags used as nursery containers.

Methodology

Experimental design

The experiment employed a two-factor factorial completely randomized design (CRD). The

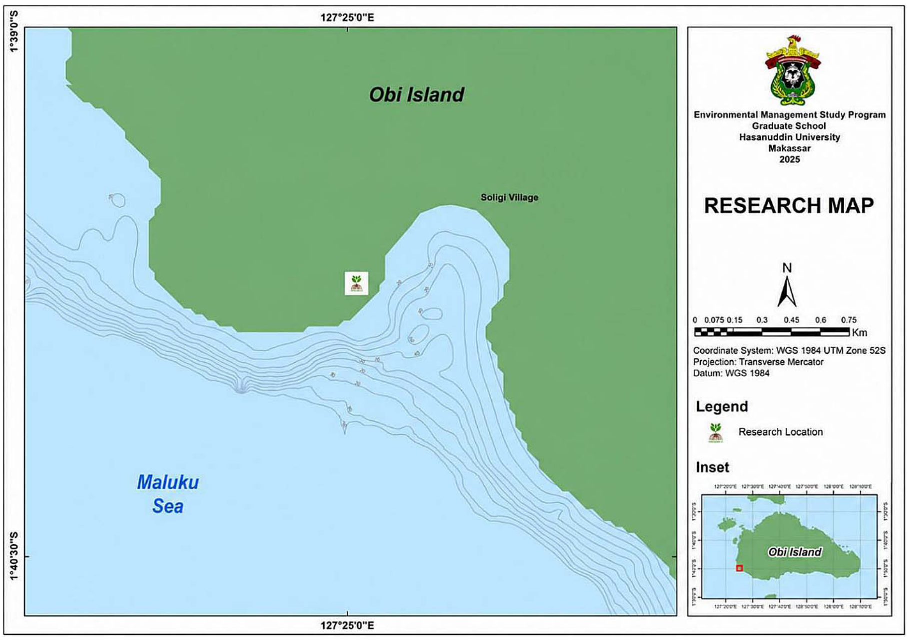

Figure 1. Location of the study area in North Maluku, Indonesia

two treatment factors were nickel slag particle size and nickel slag concentration in the nursery medium. The particle size treatments consisted of coarse slag, fine slag, and mixed slag, while slag concentration treatments consisted of 25%, 50%, 75%, and 100% of the total growing medium. Each treatment combination was replicated five times, with each replicate consisting of one *Rhizophora* propagule (Figure 2).

Preparation of growing media

Natural mangrove substrate was first cleaned to remove litter, roots, and other coarse materials before being used as nursery media. Nickel slag was separated according to particle size using a 3-mm sieve. Slag particles smaller than 3 mm were classified as fine slag, whereas particles larger than 3 mm were classified as coarse slag. Mixed slag was used without additional sieving to represent the original condition of the material. The nickel slag was then weighed according to the treatment concentrations of 25%, 50%, 75%, and 100% of the total growing medium and thoroughly mixed with the natural mangrove substrate. Following homogenization, the prepared media were placed into polybags according to their respective treatment combinations. A portion of the growing medium from each treatment was collected for initial laboratory analysis prior to seedling establishment.

Seedling establishment and maintenance

Rhizophora propagules were planted in the prepared growing media according to the designated treatment combinations. Each treatment consisted of five replicates. Seedlings were maintained for a period of three months, with observations conducted at two-week intervals. No additional fertilizers were applied throughout the experimental period in order to directly assess the effects of nickel slag on both growing medium characteristics and seedling growth. Irrigation was not provided, as the nursery media received a natural water supply through tidal inundation at the study site. Consequently, adequate moisture levels were maintained throughout the experiment, closely resembling the natural habitat conditions of mangrove ecosystems.

Growth parameter measurements

The growth parameters observed in this study included seedling survival rate, seedling

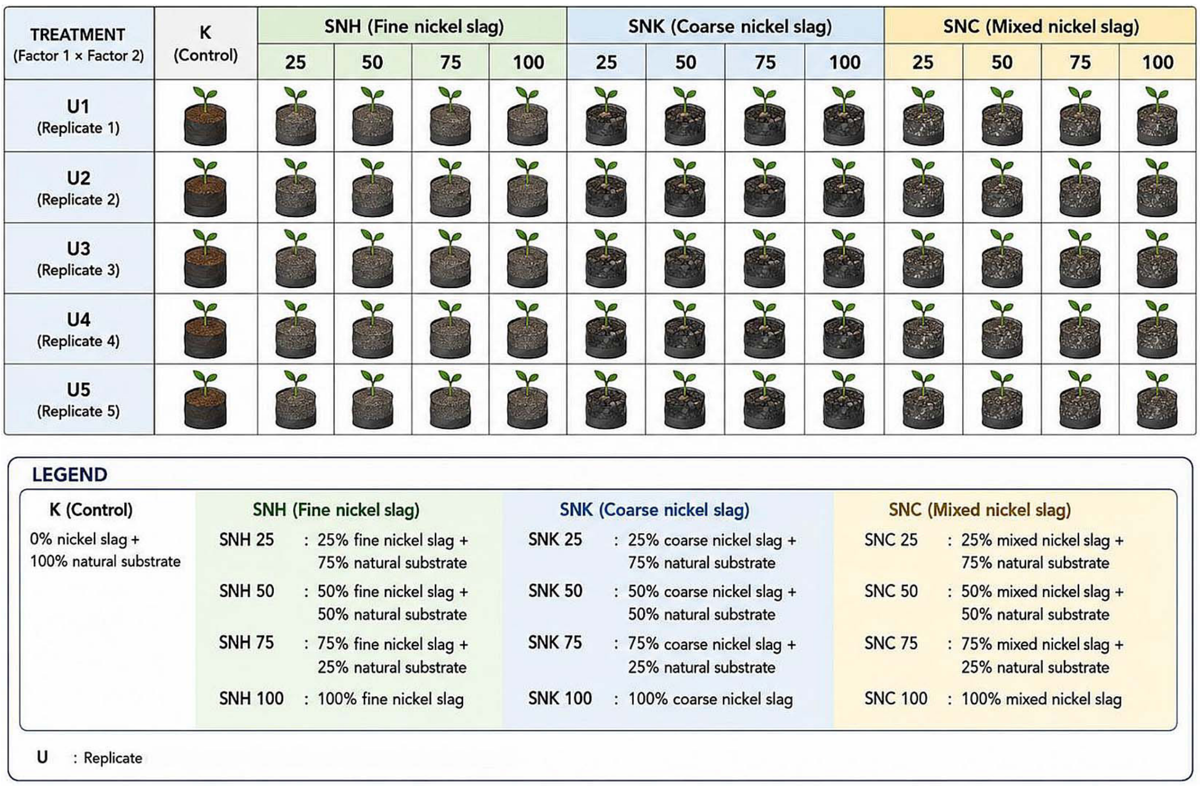

Figure 2. Experimental design showing the treatment combinations of nickel slag particle size and concentration

height, leaf number, chlorophyll content, and root condition. Seedling survival rate was determined based on the number of surviving seedlings in each treatment throughout the observation period. Seedling height was measured using a ruler from the base of the stem to the highest growing point. Leaf number was determined by direct counting of the leaves on each observed seedling. Leaf chlorophyll content was measured using a SPAD-502 Plus chlorophyll meter. Soil plant analysis development (SPAD) values were used as a relative indicator of leaf chlorophyll content, reflecting the physiological status and photosynthetic capacity of the plants (Wu et al., 2007). SPAD values were obtained from several sample leaves within each treatment, and the average value was subsequently calculated. Root condition was assessed at the end of the experiment after the seedlings had been carefully removed from the substrate and cleaned. The observed parameter was the number of fibrous roots formed. The number of fibrous roots was used as an indicator of root system development because fine roots play a crucial role in water and nutrient uptake and contribute significantly to the ecological functioning and productivity of mangrove ecosystems (Arnaud et al., 2021).

Substrate analysis and laboratory procedures

Substrate pH and N, P, and K were measured at the beginning and end of the experiment. Calcium (Ca), magnesium (Mg), and silicon dioxide (SiO_2) concentrations were analyzed using substrate samples collected at the end of the experiment. The analyzed parameters included substrate pH, nutrient contents of nitrogen (N), phosphorus (P), and potassium (K), as well as calcium (Ca), magnesium (Mg), and silicon dioxide (SiO_2) concentrations. The relative concentrations of pH, N, P, and K were estimated using a portable soil nutrient checker. Substrate samples were collected from each treatment, stored in zip-lock plastic bags, and subsequently transported to the laboratory for analysis. Calcium and magnesium concentrations were determined using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP–OES), whereas SiO_2 concentration was analyzed using a UV–Visible spectrophotometric method in accordance with the procedures described by the American Public Health Association (2017) and the U.S. Environmental Protection Agency (1996).

Data analysis

The seedling survival rate was calculated using the formula specified in the Regulation of the Minister of Forestry of the Republic of Indonesia No. P.70/Menhut-II/2008 as follows:

$$Survival\ Rate\ (\%) = \frac{Number\ of\ Surviving\ Seedlings}{Number\ of\ Seedlings\ Planted} \times 100\% \quad (1)$$

Seedling height growth was determined based on the average increase in seedling height using the equation proposed by Kusmana and Rifana (2023), as follows:

$$Average\ Height\ Growth = \frac{Total\ Height\ Growth}{Number\ of\ Seedlings\ Planted} \quad (2)$$

The average leaf growth was calculated based on the total number of leaves produced by each seedling and subsequently averaged according to the total number of seedlings observed (Kusmana and Rifana, 2023). The calculation was performed using the following equation:

$$Average\ Leaf\ Growth = \frac{Total\ Number\ of\ Leaves}{Number\ of\ Seedlings\ Planted} \quad (3)$$

Chlorophyll content was determined based on the average SPAD readings obtained for each treatment. In addition, the number of fibrous roots observed at the end of the experiment was calculated as the mean value per seedling for each treatment to assess root system development in response to nickel slag application in the nursery media. The number of fibrous roots was used as an indicator of the growing medium's ability to support root growth and nutrient uptake by mangrove seedlings. Seedling growth and root parameters were analyzed using Analysis of Variance (ANOVA) at a 95% confidence level to evaluate the effects of nickel slag particle size and concentration on the observed variables. When significant differences among treatments were detected, Tukey's honestly significant difference (HSD) test was performed at the 5% significance level. Substrate pH and N, P, and K were analyzed descriptively by comparing their initial and final values, whereas Ca, Mg, and SiO_2 concentrations were described based on their final concentrations at the end of the experiment. The results were presented in tables and graphs to facilitate the interpretation of changes in nursery substrate quality resulting from nickel slag treatments.

RESULTS AND DISCUSSION

Results

Growth performance of Rhizophora mangrove seedlings

Growth of *Rhizophora mangrove* seedlings was monitored for 12 weeks to evaluate plant responses to different particle sizes and concentrations of nickel slag applied to the nursery media. The observed parameters included seedling survival rate, height growth, leaf production, and leaf chlorophyll content. The results showed that all treatments maintained a 100% survival rate throughout the experimental period (Figure 3). No seedling mortality was observed in either the control treatment or the treatments amended with nickel slag. These findings indicate that all seedlings were able to survive and establish successfully during the nursery period. With respect to seedling height growth, the SNC 50 treatment produced the highest average height increase, reaching 18.6 cm, whereas the control treatment exhibited the lowest growth, with an average increase of 7.4 cm (Figures 4, 5 and 6). ANOVA performed at the 95% confidence level revealed that nickel slag treatments had a significant effect on seedling height growth. Tukey's HSD test further showed that SNC 50 belonged to the highest significance group (b) and differed significantly from the lowest group (a), which included the control (K), SNH 100, SNK 100, and SNC 100 treatments. The remaining treatments were classified within the intermediate group (ab) and did not differ significantly from either group. Leaf production also varied among treatments. The SNC 50 treatment resulted in the highest average number of leaves, with 3.2 leaves per seedling, while the control treatment produced the lowest average number of leaves, with 1.4 leaves per seedling (Figure 7). Treatments SNK 50, SNC 25, and SNC 75 also exhibited relatively higher leaf numbers compared with the other treatments. However, ANOVA results indicated that nickel slag treatments did not have a statistically significant effect on the number of leaves produced by *Rhizophora* seedlings. Leaf chlorophyll content, measured using a SPAD meter, also differed among treatments. The highest chlorophyll content was recorded in the SNC 50 treatment, with an average value of 64.36 SPAD units, whereas the control treatment exhibited the lowest value, averaging 44.40 SPAD units (Figure 8). Tukey's HSD test showed that SNC 50 belonged to significance group c and differed significantly from the control treatment, which was classified in group a. Several other treatments, including SNH 100, SNK 75, SNC 25, and SNC 100, also exhibited higher chlorophyll contents than the control treatment.

Nursery substrate conditions and root development

Nursery substrate conditions were evaluated to determine the effects of nickel slag application on substrate chemical characteristics and root development. The pH measurements showed that all treatments experienced an increase in pH during the study period (Figure 9). The pH of the control treatment increased from 6.0 to 6.5 by week 12 (Figure 10). Treatments with high nickel slag concentrations, namely SNH 100, SNK 100, and SNC 100, exhibited the highest and most stable pH values, remaining close to 7.0. In general, increasing nickel slag concentration resulted in a gradual increase in substrate pH toward neutral conditions. In general, nitrogen, phosphorus, and potassium showed decreasing trends in most treatments (Table 1). At the end of the experiment, silicon dioxide, calcium, and magnesium concentrations varied among treatments (Table 2). In the SNC 50 treatment, nitrogen content decreased from 235.0 mg/kg to 49.7 mg/kg, phosphorus from 668.7 mg/kg to 154.7 mg/kg, and potassium from 642.3 mg/kg to 152.7 mg/kg. Silicon dioxide concentrations were relatively high at the end of the experiment. Magnesium concentrations differed among treatments, with the highest concentration observed in SNH 50 (825.6 mg/kg). Calcium concentrations differed among treatments, with the highest concentration observed in control (325.2 mg/kg). The SNC 50 treatment produced the highest average number of fibrous roots (19.8 roots per seedling), followed by SNC 75 (15.8 roots per seedling) and SNK 50 (15.6 roots

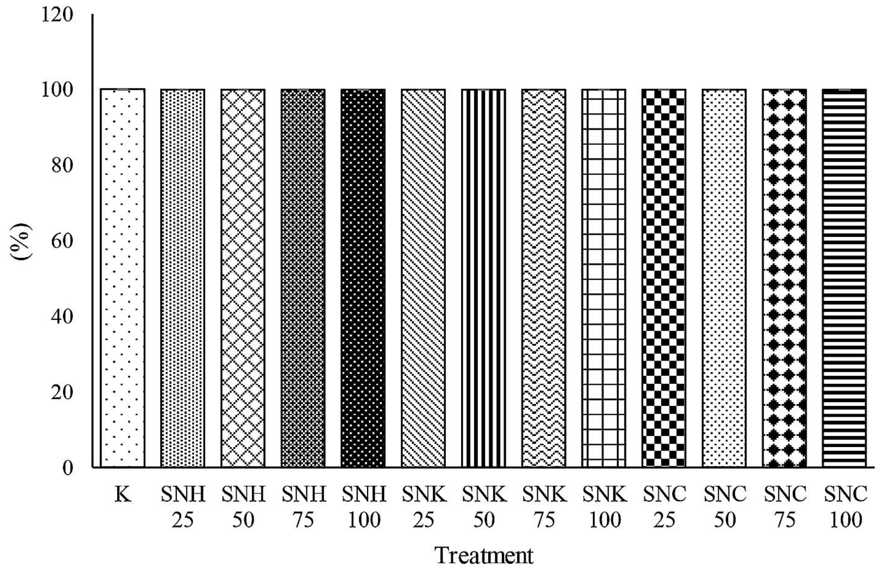

Figure 3. Survival rate of *Rhizophora* mangrove seedlings after 12 weeks of observation

Figure 4. *Rhizophora* seedlings during the experimental period

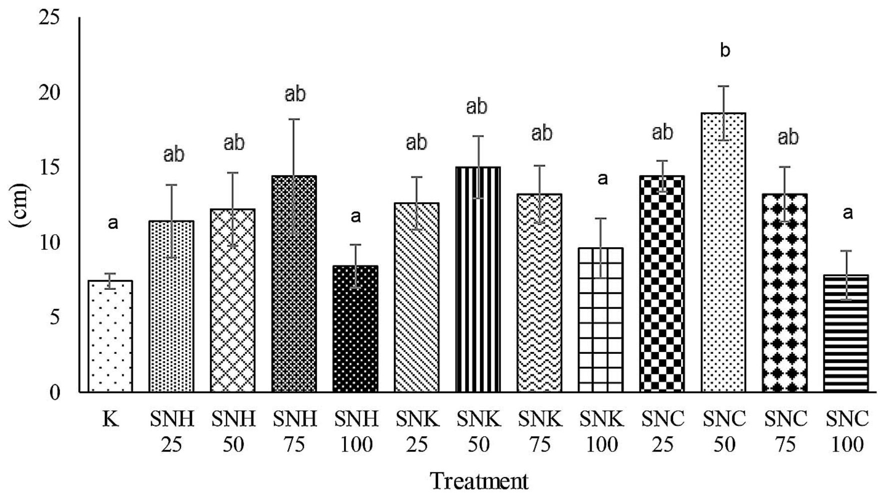

Figure 5. Average final height of *Rhizophora mangrove* seedlings after 12 weeks of observation

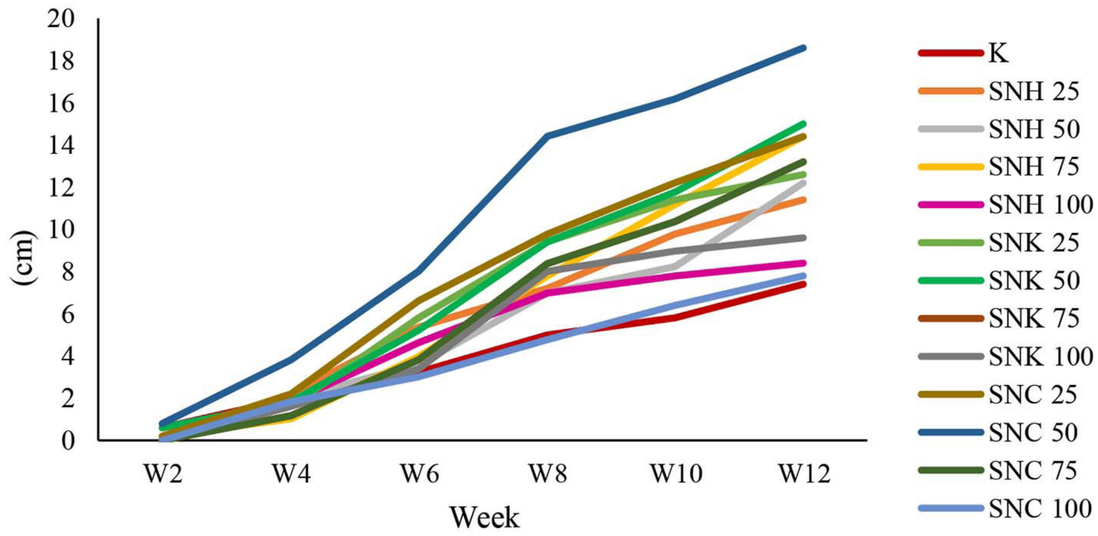

Figure 6. Average height growth of *Rhizophora mangrove* seedlings

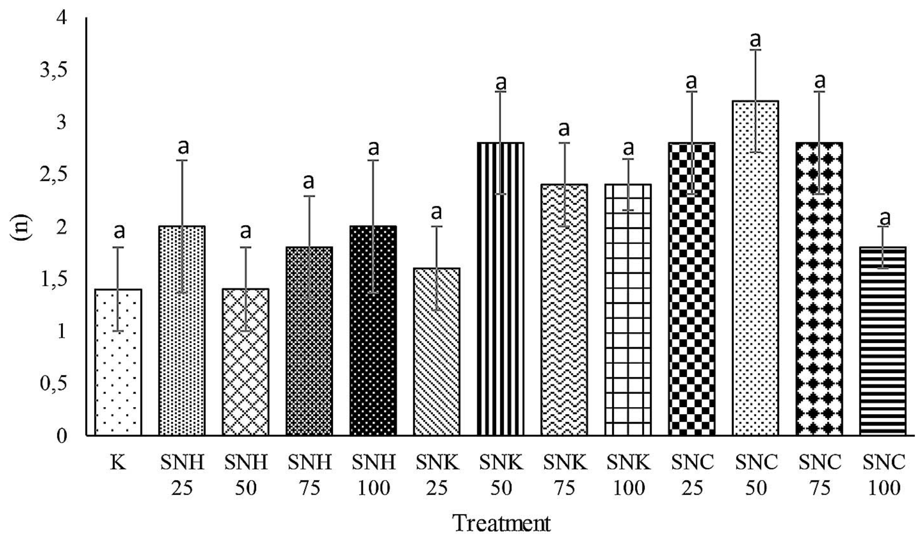

Figure 7. Average number of leaves of *Rhizophora mangrove* seedlings after 12 weeks of observation

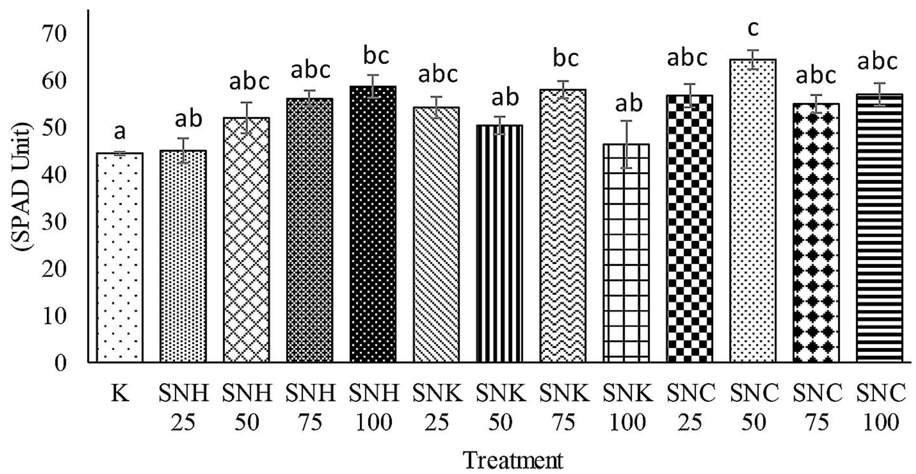

Figure 8. Average leaf chlorophyll content (SPAD) of *Rhizophora mangrove* seedlings after 12 weeks of observation

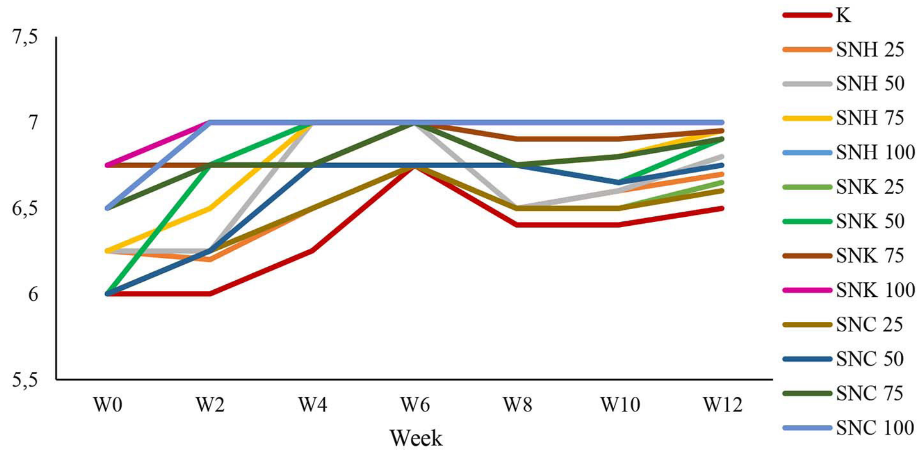

Figure 9. pH of mangrove seedling growing media

Table 1. Results of nitrogen, phosphorus, and potassium analyses in the growing media at the beginning (Week 0) and end (Week 12) of the experiment

Treatment	Nitrogen (mg/kg)		Phosphorus (mg/kg)		Potassium (mg/kg)	
	Week 0	Week 12	Week 0	Week 12	Week 0	Week 12
K	554.7	222.3	1310.3	592.3	1365.7	561.3
SNH 25	303.0	40.0	740.3	161.7	760.3	126.3
SNH 50	163.3	32.3	421.7	143.0	449.0	126.0
SNH 75	43.0	23.3	143.7	100.7	143.3	93.0
SNH 100	0.0	18.7	23.3	89.7	14.0	88.0
SNK 25	243.7	97.3	653.3	281.3	676.3	271.7
SNK 50	145.7	85.7	346.3	257.7	361.7	255.0
SNK 75	45.3	22.7	177.7	113.3	156.7	106.0
SNK 100	0.0	2.3	5.3	65.7	0.3	50.3
SNC 25	278.3	76.0	662.7	211.7	650.7	204.7
SNC 50	235.0	49.7	668.7	154.7	642.3	152.7
SNC 75	31.7	36.3	124.0	131.7	133.7	147.3
SNC 100	0.0	0.0	0.0	51.0	0.3	35.7

Table 2. Results of silicon dioxide, calcium, and magnesium analyses in the growing media at the end of the experiment (Week 12)

Treatment	Silicon Dioxide (mg/kg)	Calcium (mg/kg)	Magnesium (mg/kg)
K	2305.1	325.2	227.6
SNH 25	1694.8	195.9	583.2
SNH 50	972.3	141.6	825.6
SNH 75	800.9	113.5	626.8
SNH 100	521.3	54.0	623.6
SNK 25	2006.5	151.2	234.5
SNK 50	1580.6	101.7	257.0
SNK 75	1352.1	51.9	233.2
SNK 100	906.1	12.0	343.3
SNC 25	2009.2	114.4	282.0
SNC 50	1429.3	88.9	397.0
SNC 75	1318.0	47.7	390.3
SNC 100	957.2	32.5	753.0

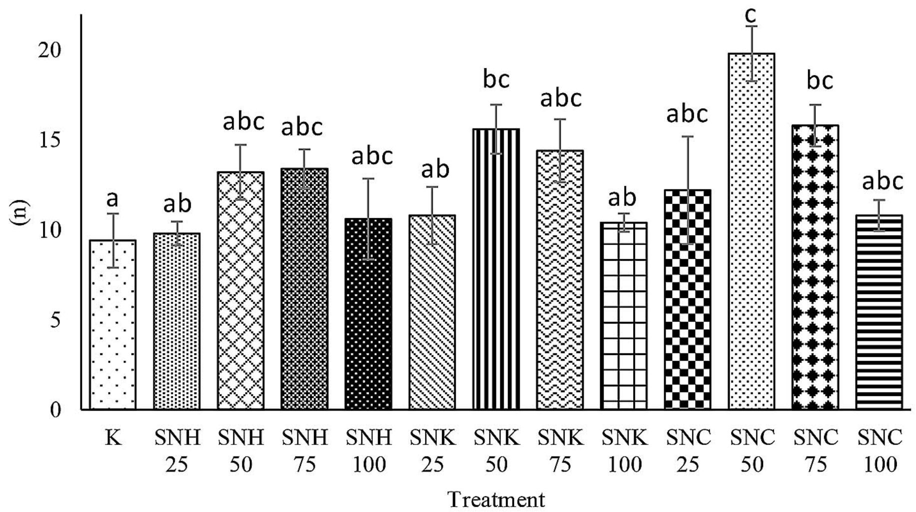

Figure 10. Average number of fibrous roots of *Rhizophora* seedlings after 12 weeks of observation

per seedling). The control treatment produced an average of 9.4 fibrous roots per seedling. Tukey's HSD test indicated that SNC 50 belonged to the highest significance group (c) and differed significantly from the control treatment, which was classified in group (a).

Discussion

Seedling survival is one of the most important indicators for evaluating the suitability of nursery substrates and the tolerance of mangrove seedlings to environmental modifications. In the present study, the incorporation of nickel slag into the nursery media did not adversely affect seedling survival, indicating that the amended substrates remained suitable for supporting seedling establishment and growth. This finding was reflected by the 100% survival rate of *Rhizophora* seedlings across all treatments, regardless of slag particle size (coarse, fine, or mixed) and concentration. The absence of seedling mortality suggests that nickel slag application at the tested concentrations did not impair the seedlings' ability to adapt to the nursery environment. This condition may be associated with the relatively stable characteristics of nickel slag and its low potential for metal release. Yan et al. (2025), reported that nickel slag exhibits good environmental stability, thereby reducing the risk of adverse environmental impacts. Consequently, the seedlings were able to maintain essential physiological processes required for survival, growth, and development throughout the experimental period. Mangroves are known for their high adaptability to a wide range of environmental and substrate conditions (Aiken et al., 2021). Similarly, Richards et al. (2021) reported that *Rhizophora* seedlings possess a strong capacity to adapt to dynamic and complex coastal environments. This observation is consistent with the findings of Rangkuti et al. (2024), who demonstrated that *Rhizophora apiculata* and *Rhizophora mucronata* are capable of adapting to environmental pressures and changes in land use.

Differences in seedling growth responses among treatments were likely influenced more by changes in the physical characteristics of the growing media resulting from nickel slag application, particularly media porosity. The porous structure of nickel slag, combined with the granulation and rapid cooling processes that produce sand-like granular particles, may increase the interparticle spaces within the growing medium, thereby improving aeration and drainage (Gultom, 2024). These characteristics allow roots to obtain a more optimal supply of oxygen and water, thereby supporting root system development and overall seedling growth. Root aeration is known to play an important role in promoting plant growth through increased soil nitrification, nitrate (NO_3^-) formation, and enhanced uptake of NH_4^+ and NO_3^- by plants (Zhao et al., 2019). In mangrove species, oxygen availability within the root zone is also essential for maintaining root respiration and preventing hypoxic conditions that may inhibit plant growth (Inoue, 2026). Cheng et al. (2020)

reported that mangrove species with higher root porosity exhibit greater tolerance to inundation because they are able to enhance oxygen diffusion toward root tips through the development of aerenchymatous tissues within the root system. Furthermore, Wu et al. (2020) stated that nickel slag possesses high porosity and low bulk density, indicating its potential to improve the physical properties of growing media.

The improvement in the physical properties of the growing media was reflected in root system development. The SNC 50 treatment produced the highest average number of fibrous roots (19.8 roots per seedling), followed by SNC 75 (15.8 roots per seedling) and SNK 50 (15.6 roots per seedling). In contrast, the control treatment and treatments with the highest nickel slag concentrations (SNH 100, SNK 100, and SNC 100) exhibited relatively lower numbers of fibrous roots. These findings suggest that the application of nickel slag at moderate concentrations provided a more favorable balance between porosity, aeration, and water-holding capacity for root development than either lower or higher slag concentrations. These results are consistent with the findings of Santos et al. (2024) on pre-sprouted sugarcane seedlings, which demonstrated that substrates containing excessively high proportions of slag could inhibit early plant development, whereas appropriate proportions created more suitable conditions for root growth. Furthermore, Zhou et al. (2021) reported that soil macroporosity plays a major role in root system development by providing pathways for root penetration, improving aeration, and enhancing water availability.

Better root development in the SNC 50, SNC 75, and SNK 50 treatments was also associated with differences in nutrient concentrations among treatments. The decrease in nitrogen, phosphorus, and potassium concentrations observed in most treatments may reflect nutrient utilization by the seedlings during growth, although changes in nutrient dynamics within the growing medium may also have contributed to the observed patterns. Nitrogen and phosphorus are essential nutrients that regulate mangrove productivity, whereas potassium plays an important role in various plant metabolic processes. The availability of these nutrients is a key factor influencing vegetative growth and root system development in coastal environments, which are generally characterized by low nutrient availability (Moslehi et al., 2021; Ishfaq et al., 2025). Nitrogen also plays a crucial role in plant tissue formation and root growth, as demonstrated by the relationship between root structure and function and enhanced nitrogen acquisition in mangroves (Cheng et al., 2020). In the present study, the SNH 50, SNK 50, and particularly the SNC 50 treatments exhibited substantial reductions in nitrogen content by the end of the experiment, which were accompanied by improved root development and seedling growth compared with the other treatments. Calcium concentrations at the end of the experiment also differed among treatments. Wang et al. (2024) reported that calcium plays a vital role in cellular signaling regulation and in maintaining plant growth balance through the regulation of intracellular Ca^{2+} homeostasis.

Magnesium concentrations differed among treatments, with the highest concentration observed in the SNH 50 treatment. Magnesium is the central atom of the chlorophyll molecule and functions as an activator of various enzymes involved in photosynthesis (Santoso et al., 2021). Akpovwovwo (2020) reported that magnesium in sediments is one of the factors contributing to variations in mangrove growth. Furthermore, Nur-Hafiza et al. (2023) demonstrated that the growth of *Rhizophora* spp. is positively associated with exchangeable magnesium concentrations in sediments. Nevertheless, high magnesium concentrations did not directly correlate with superior root development, as treatments with the highest Mg contents did not consistently produce the greatest numbers of fibrous roots or the highest seedling growth.

Although several nutrients, including N, P, K, Ca, and SiO_2, exhibited higher concentrations in the control treatment, these values do not necessarily reflect nutrient availability to plants. This condition may be related to the inert nature of nickel slag and its relatively low chemical activity, which results in the gradual release of mineral elements over time (Kasikov et al., 2022; Kasikov et al., 2023). Therefore, the improved root development observed in treatments with moderate concentrations of nickel slag was likely influenced more by improvements in the physical characteristics of the growing medium than by a direct increase in nutrient concentrations. These findings suggest that successful mangrove seedling growth is not solely determined by high nutrient concentrations in the growing medium, but also by the medium's ability to support root system development and enhance the efficiency of nutrient utilization by plants.

The improvement in substrate conditions was further reflected in seedling growth performance. The SNC 50 treatment produced the highest height growth, reaching 18.6 cm, and differed significantly from several other treatments based on ANOVA and Tukey's HSD tests at the 95% confidence level. The SNC 50 treatment was classified within the highest significance group, whereas the control, SNH 100, SNK 100, and SNC 100 treatments were classified within the lowest group. These results indicate that mixed nickel slag at a concentration of 50% created the most favorable substrate conditions for seedling growth. In contrast, increasing the nickel slag concentration to 100% did not necessarily enhance plant growth. This condition may be associated with changes in substrate structure that resulted in a less balanced physical environment, thereby reducing water-holding capacity and limiting the optimal distribution of pore spaces. Consequently, water and oxygen uptake by roots may have been restricted, leading to less favorable vegetative growth. These findings are consistent with those reported by Usman et al. (2022), who demonstrated that specific substrate combinations produced greater increases in plant height and stem diameter than the dominant use of a single substrate type. Nutrient uptake is known to be strongly influenced by processes occurring within the rhizosphere, including interactions between plant roots and soil microorganisms that enhance nutrient-use efficiency (David and Rengel, 2024).

A relatively similar pattern was also observed for leaf production. The SNC 50 treatment produced the highest average number of leaves, with 3.2 leaves per seedling, whereas the control treatment exhibited the lowest average, with 1.4 leaves per seedling. Although the statistical analysis indicated that nickel slag application did not have a significant effect on leaf number, an increasing trend in leaf production was observed in treatments that exhibited greater height growth. This finding suggests that improvements in substrate conditions resulting from nickel slag application still elicited a positive response in canopy development, although the differences were not statistically significant.

For chlorophyll content, the SNC 50 treatment produced the highest value, reaching 64.36 SPAD units, and differed significantly from the control treatment according to Tukey's HSD test at the 5% significance level. This value was comparable to the average leaf chlorophyll content of *Rhizophora apiculata* reported by Li et al. (2023), which reached 66.57 SPAD units, indicating that the physiological condition of the seedlings remained within an optimal range. The higher chlorophyll content suggests a greater photosynthetic capacity compared with the other treatments. This condition was likely associated with more favorable root development, which enabled more efficient uptake of water and nutrients. Chai et al. (2023) reported that changes in the physical properties of growing media, such as porosity and bulk density, can influence root growth, chlorophyll content, and photosynthetic efficiency in mangroves. Therefore, the increased chlorophyll content observed in the SNC 50 treatment was likely a physiological response to substrate conditions that were more conducive to root system development and plant metabolic activity.

The results of this study demonstrated that the application of nickel slag in coarse, fine, and mixed forms influenced the growth of *Rhizophora* mangrove seedlings, primarily through improvements in the physical characteristics of the growing media. The SNC 50 treatment produced the most favorable response, as it provided a more optimal balance of porosity, aeration, drainage, and water-holding capacity. These conditions promoted root development, enhanced nutrient-use efficiency, maintained high chlorophyll content, and resulted in superior seedling growth compared with the other treatments. These findings are consistent with those reported by Gultom et al. (2024) and Handayani et al. (2025), who found that the use of nickel slag as a soil amendment improved the physical properties of growing media and enhanced plant growth through improvements in substrate conditions.

CONCLUSIONS

Based on the results of this study, the application of nickel slag in nursery media was shown to support the sustainability of mangrove ecosystems by improving substrate conditions and enhancing the growth of *Rhizophora mangrove* seedlings. All treatments maintained a 100% seedling survival rate throughout the experimental period, indicating that the use of nickel slag was able to support seedling establishment and growth during the nursery stage. The SNC 50 treatment (50% mixed nickel slag) produced the best growth response, resulting in a seedling height growth of 18.6 cm, an average of 3.2 leaves per seedling, a chlorophyll content of 64.36 SPAD units, and an average of 19.8 fibrous roots per seedling. The SNC 75 and SNK 50 treatments also exhibited relatively favorable growth responses compared with the other treatments. In general, moderate nickel slag concentrations (50–75%) promoted more optimal seedling growth than either lower or higher concentrations. Nickel slag application improved substrate conditions through enhanced porosity, aeration, and drainage, thereby creating a more favorable environment for root development and seedling growth. In addition, nickel slag influenced the chemical properties of the substrate, as indicated by an increase in pH toward a near-neutral range (6.0–7.0) and changes in pH and N, P, and K throughout the nursery period, while differences in the final concentrations of Ca, Mg, and SiO_2 were observed among treatments. In contrast, treatments containing 100% nickel slag generally exhibited lower growth performance, although seedling survival remained unaffected. Overall, the findings demonstrate that nickel slag has considerable potential for use as a soil amendment in mangrove nursery media. Its application can support coastal ecosystem rehabilitation while simultaneously promoting the sustainable reuse of industrial by-products.

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