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Research Article

Change of soil chemical properties and the growth of *Pogostemon cablin* Benth on nickel-mined soil amended with rice husk charcoal

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Abstract

Nickel is an important main resource mineral in Southeast Sulawesi, which has deposited around 97.4 billion tons, and undoubtedly, nickel exports emerged in national and regional economic growth. Mining activities were carried out through topsoil and subsoil stripping, resulting in damage to the soil ecosystem and making it difficult for soil to recover. A study was performed to evaluate the changes in soil chemical properties and the growth of patchouli (*Pogestemon cablin* Benth) on nickel-mined soil treated with rice husk charcoal (RHC). A randomized block design was applied in this study, including six treatments of RHC with three replications. The treatments were without RHC (control), 1.5%, 3.0%, 4.5%, 6%, and 7.5% of soil weight. Data were analyzed descriptively for soil chemical properties; meanwhile, ANOVA was applied for plant growth. The results revealed that RHC increased soil pH, organic C, CEC, and available P, and conversely, the application of 4.5% of RHC decreased soil Ni and Fe content by 65.43% and 40.47%, respectively. The application of RHC up to 6% increased significantly the plant height and number of leaves as well as the dry weight of patchouli. The present study concluded that the use of carbon-rich soil conditioners such as rice husk charcoal is an imperative measure to restore the nickel-mined soil.

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Introduction

Nickel (Ni) ore is one of the important mineral resources in Southeast Sulawesi Province, with around 97.4 billion tonnes of deposits spread over 595 locations (BPS, 2019). Nickel is a rare and non-renewable natural resource with a high economic value as a raw material for the steel, automotive, electroplating, and new metal industries. Nickel mining activities significantly contribute to state revenues, create new jobs, and spur the growth of new economic sources such as trade, hotels, restaurants, transportation, and others. Nickel mining activities, which are carried out openly, begin with land clearing, stripping topsoil, and then subsoil to a depth of several meters to exploit nickel ore. The mining process certainly has an impact on damage to the soil ecosystem. Open land conditions cause extreme erosion, which has affected the transport of soil particles and sedimentation on agricultural land or coastal areas. As a result, it will demolish the aquaculture activities of fishermen in coastal areas. After the mining was completed, the land was abandoned, resulting in the land being largely exposed to the rain directly, and so they remained only the parent materials that formed the soil. Furthermore, the surrounding societies in a given area face a catastrophic menace due to severe environmental conditions. As pointed out by Widiatmaka et al. (2010), the unfavorable chemical characteristics such as organic C (0.26-3.3%), total N (0.03-0.2%), and CEC is low (13.3-36.9 me 100 g^{-1}), and dissolved Ni levels reach 8,970.31 ppm (Aprilianti et al., 2021). The hydrological conditions changed drastically and led to more frequent flooding.

The restoration of nickel-mined soil remains difficult due to the destruction of soil physical properties and the loss of soil chemical attributes (Prematuri et al., 2020). Therefore, the rehabilitation of nickel-mined soil should first focus on improving the soil physical properties that allow tree growth to grow quickly. The addition of organic manure might also be considered to replace the nutrient losses across the nickel mining process. This mechanism allows the plants to grow properly and cover the land surface quickly to prevent soil erosion and sedimentation of heavy metals such as Ni, Fe, and Cr. This is intended to avoid the negative effects of trace elements on human health. Soil amendment carbon-rich such as biochar is one of the useful alternative solutions to restore soil carbon losses due to nickel ore mining.

Biochar or black carbon has been well-known for its potential to enhance soil quality, carbon sequestration, climate change mitigation (Laird et al., 2008), and improve the capacity of the soil to immobilize the heavy metals contaminated soils. Other authors have demonstrated that black carbon can improve soil physical properties, such as soil aggregate stability, porosity, and decrease bulk density, and, in turn, improve water holding capacity of the soil (Lehmann et al., 2011; Alburquerque et al., 2014). In addition, it has the ability to influence biochemical processes as well as function, abundance, composition, and microbial activity and also become a preferred habitat and protect it from predators. Biochar can be made from agricultural wastes such as manure, straw and rice husks, and other materials. Rice husk waste is abundant, which so far has only been used as chicken coop bedding, mushroom media, or compost mixing material. Biochar or charcoal from rice husks has been extensively studied; however, there is still little information on its effect on soil chemical properties and plant growth in former nickel-mined soils.

The restoration of nickel-mined soil must also pay attention to the plants used. Wherever possible, they use plants or herbs that are not consumed (non-edible plants) because it is feared that they will cause toxic effects on humans. One type of plant that can be developed for the utilization of nickel-mined soil is patchouli (*Pogostemon cablin* Benth). Patchouli is a plant that produces essential oil as a raw material for making perfume. The local community has widely developed patchouli plants because they have high economic value.

This study aimed to evaluate the changes in several soil chemical properties and the growth of patchouli plants on nickel-mined soil treated with rice husk charcoal.

Materials and Methods

Soil collection

The soil sample in this study was collected from the nickel-mined site of PT. Sulemandara Konawe, Dunggua Village, Amonggedo District, Konawe Regency, and approximately 50 km from the Faculty of Agriculture, Halu Oleo University in Kendari City. Prior to the commencement of the experiment, surface soil (0-20 m depth) samples were randomly collected from five different points in the nickel-mined site. They were brought to the experimental farm air-dried, the debris and plant residues were removed, homogenized to form a composite sample, sieved to 2 mm, and analyzed for the initial soil chemical characteristics. The basic soil chemical properties indicated a low soil pH (5.76), and very low organic C as well as available P by 0.2% and 4.71 mg kg$^{-1,}$ respectively. The cation exchange capacity (CEC) was medium level by 22.79 cmol kg^{-1}, with a high concentration of Ni and a high concentration of Fe by 776.10 and 6,433.53 mg kg^{-1}, respectively.

Experimental setup and procedures

The study was conducted at the Experimental Farm of the Faculty of Agriculture, Halu Oleo University, Kendari located between 4°0'21.62" S and 122°31'46.83" E with an altitude of 19 masl. The study used a randomized block design with three replications. The treatment consisted of 6 levels of rice husk charcoal (RHC), such as without RHC serving as control, 1.5%, 3%, 4.5%, 6%, and 7.5% of the soil weight. The RHC was obtained from a local producer in Amoitosiama village, South Konawe Regency. The rice husk charcoal was produced via slow pyrolysis using a medium thermal process (300-350 °C) in the absence of O_2. The particle size of the rice husk charcoal used was 2-4 mm; therefore, to guarantee a more homogeneous application, the rice husk charcoal was ground and sieved to 25 mesh and thoroughly mixed with the nickel-mined soil for the study. This study used a polybag of 20 x 20 cm in which 5 kg of nickel-mined soil was mixed homogeneously with RHC, before incubating for 7 days. Cow manure at the dose of 15 t ha^{-1} as basal fertilizer was applied before the seedling of patchouli was transplanted. One-month-old healthy seedlings of patchouli were transplanted into the experimental polybags with three replications. In case of a lack of rain, the plants were watered daily with 200 mL of deionized water to avoid the plant water stress.

Plant measurement and soil analysis

The plant height was recorded by measuring the base of its root to the highest point of the stem at 14 days after transplanting (DAT); meanwhile, the number of leaves was noted at 30 and 60 days DAT. The plant dry matter was assessed at 60 days after the measurement of the number of leaves. The plants were removed from the polybag carefully, cleaned with water, and then placed in a sample collection bag. The total biomass of the whole plant was measured after drying in the oven at 75 ºC. After the measurement of all plant growth parameters, the soil in each unit of treatment was prepared with the same procedure as described before for analysis of soil properties. The soil pH was measured using a glass electrode pH meter in a 1:2 soil-water ratio. Soil organic C was analyzed by Walkley and Black procedure (Nelson and Sommers, 1982). Total N content was determined by the Kjeldhal method (Bremner and Mulvaney, 1982), available P by the Bray I method (Bray and Kurtz, 1945), cation exchange capacity (CEC) was extracted with 1M NH_4OAc (buffered at pH 7.0). Total Ni and Fe concentrations in the soil were analyzed using flame atomic absorption spectrophotometry as described by Vahedi et al. (2022).

Data analysis

The plant growth components were subjected to the analysis of variance (ANOVA) using a statistical package, SPSS 16.0 version, and the mean difference between treatments was separated by Tukey's HSD test ($p<0.05$). Meanwhile, the chemical characteristics of the soil were performed descriptively using the criteria of the BPT (2009).

Results and Discussion

Soil chemical properties

The results revealed that the application of rice husk charcoal affected some of the chemical properties of nickel-mined soils (Table 1). The increasing rate of rice husk charcoal consistently increased soil pH from 4.96 in the treatment without rice husk charcoal to 6.57 or increased by 1.61 units at the 7.5% of RHC. It was attributed that the charcoal released basic cations such as oxides Ca^{2+}, Mg^{2+}, and K^+ from the ashes of the rice husk charcoal and led to a decrease in dissolved Al^{3+} ion in the soil (Steiner et al., 2007; Yuan and Xu, 2010; Chintala et al., 2014; Palansooriya et al., 2019). Glaser et al. (2002) suggested that biochar has a broad adsorption surface to adsorb basic cations that improve soil pH. As reported by Adekiya et al. (2019), the addition of black carbon up to 50 t ha^{-1} increased soil pH to 6.30 as well as the organic C and available P by 3.30% and 7.2 mg kg^{-1} respectively, compared to without the addition of ameliorants. Palmeggiani et al. (2021) stated that the application of biochar to As-contaminated soil increased soil pH. It was further described that the increase was attributed to the alkalinity of the biochar, the release of metal oxides, hydroxides, and carbonates, and the presence of surface functional groups that act as H^+ binding sites.

The increasing rate of RHC consistently increased soil organic C. The addition of 4.5% of RHC increased organic C by 66.67%, and the highest organic C was recorded by the application of 7.5% RHC by 350% over the control. This increase occurred as a contribution to the application of rice husk biochar, as it is known that biochar is a carbon substrate that is difficult to degrade in the soil, so it is very suitable for improving the physical condition of degraded soil. Lehmann et al. (2006) stated that the estimated residence time of organic C from biochar in soil is in the range of hundreds to thousands of years, while the plant residues are only in the range of decades. Windeatt et al. (2014) demonstrated that rice husk charcoal is an important source of organic matter because it contains 51% of organic C. Another study reported that the application of 10 t ha^{-1} of biochar increased soil organic C content by up to 20.7% and soil water content by up to 11.8% (Amendola et al., 2017). The results revealed that the available P also consistently increased with the increasing rate of biochar applied (Table 1). Application of 4.5% and 7.5% of RHC increased the available P by 47.50% and 150.77% respectively. The results of this study demonstrated a linear relationship between the addition of RHC and available P in soil (r=0.943) (Figure 1).

Table 1. The soil chemical properties after the application of RHC on nickel-mined soil.

Chemical properties	Rice Husk Charcoal (%)					
	0	1.5	3	4.5	6	7.5
Soil pH (H_2O)	4.96(A)	5.61(A)	5.98(MA)	6.28(MA)	6.37(MA)	6.57(MA)
Organic C (%)	0.24(VL)	0.36(VL)	0.38(VL)	0.40(VL)	0.50(VL)	1.08(L)
Avail P (mg kg^{-1})	5.20(VL)	5.90(VL)	5.99(VL)	7.67(VL)	11.02(L)	13.04(L)
CEC (cmol kg^{-1})	31.31(H)	34.49(H)	35.44(H)	35.56(H)	37.84(H)	39.36(H)
Ni (mg kg^{-1})	679.51(H)	442.79(H)	386.98(H)	234.93(H)	456.39(H)	545.95(H)
Fe (mg kg^{-1})	5797.13(VH)	5274.76(VH)	4994.07(VH)	3450.85(VH)	5300.93(VH)	5636.61(VH)

Note: A = acidic, MA = moderately acidic, VL = very low, L = low, H = high, VH = very high.

In line with the results reported by Chan et al. (2007), the application of biochar up to 100 t ha^{-1} increased soil pH, organic C, available P, exchangeable K, and Ca, but on the contrary, decreased exchangeable Al^{3+}. It was shown that black carbon was the most efficient soil conditioner in adsorbing soil nutrients, improving soil organic matter and soil pH as well as nutrients availability (Thies and Rilling, 2009; Nielssen et al., 2012; Zhang et al., 2013; Adekiya et al., 2019; Adekiya et al., 2020; Li et al., 2021). Trupiano et al. (2017) stated that the application of biochar can increase the carbon content, total soil N and P, as well as the soil microbial community. As reported by Gao et al. (2019), biochar addition significantly increased surface soil available P by 45%. It was observed that the application of RHC improved the cation exchange capacity (CEC) of nickel-mined soil (Table 1). Table 1 reveals that the soil CEC consistently increased with the increase of RHC applied. The addition of 4.5% of RHC improved the CEC by 35.56 cmol kg^{-1}, and the highest of CEC was recorded by the application of 7.5% of RHC (39.36 cmol kg^{-1}) over the control. A positive relationship was found between the rate of RHC and soil CEC up to 7.5% of the soil weight (r=0.968) (Figure 2). This is presumably because the black carbon has a large surface area, which allows the basic cations such as Ca^{+2}, Mg^{+2}, and K^{+} to be adsorbed. Another study has shown a positive relationship between the black carbon rate added and soil CEC (Liang et al., 2006). The application of biochar at 50 to 100 t ha^{-1} significantly improved soil pH, organic C, available P, and CEC (Chan et al., 2007). The carboxyl (-COOH) groups of biochar have been well documented in their ability to retain nutrients, thereby increasing the availability of nutrients for plants and adsorbing metals through ion exchange mechanisms (Jia et al., 2015; Ho et al., 2017).

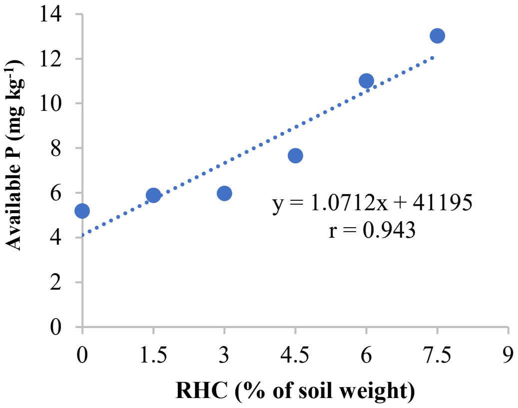

Figure 1. Relationship between soil available P and the rate of RHC on nickel-mined soil.

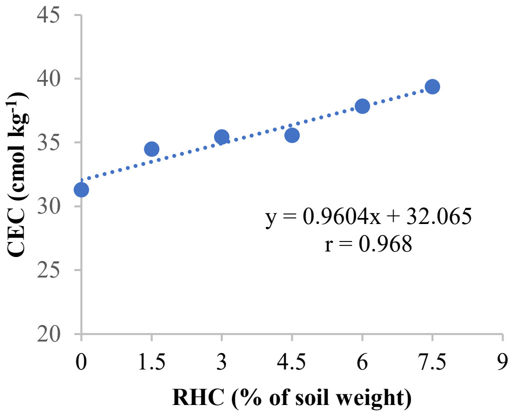

Figure 2. Relationship between soil CEC and the rate of RHC on nickel-mined soil.

Salawati et al. (2016) stated that the increase in CEC value due to the addition of black carbon can occur through two mechanisms: the first is a higher surface area on the surface of biochar for cation adsorption, the second is a higher charge density which causes a higher degree of oxidation. From various studies, Singh et al. (2022) concluded that the addition of biochar is able to increase CEC both at the laboratory scale, in pots, and on agricultural land and varied from 19 to 41%. The application of rice husk charcoal reduced dissolved Ni and Fe levels in the soil (Table 1). The highest reduction in Ni and Fe levels was recorded in the application of 4.5% rice husk charcoal by 65.43% and 40.47%, respectively. Figures 3 and 4 illustrate the decreasing Ni and Fe contents in soil across the experiment. This is probably due to the high CEC and the large surface area of RHC allowed to immobilize Ni and Fe (Rizwan et al., 2015). Windeatt et al. (2014) revealed that rice husk charcoal has a very wide surface area of 114.9 m^{2} g^{-1}, so it has the potential to absorb cations in the soil.

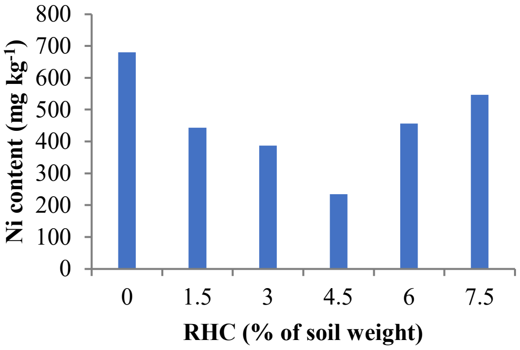

Figure 3. Change of soil Ni content after application of RHC on nickel-mined soil.

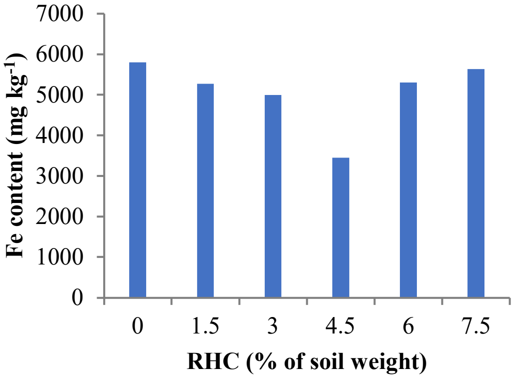

Figure 4. Change of soil Fe content after application of RHC on nickel-mined soil.

As noted by He et al. (2019), a reduction in soil heavy metal content may involve direct (e.g., electrostatic adsorption, ion exchange, complexation, and precipitation) and indirect interactions (i.e., through modifying soil properties, e.g., pH, CEC, minerals content, and organic carbon contents, and thus metal-soil bindings) between biochar and heavy metals. Ahmad et al. (2014) explained that the biochar would interact with metals such as Ni and Fe, adsorb these ions on the adsorption surface, and possibly be transformed into hydroxyl, carbonate, or precipitation with phosphate. Heavy metal ions can also be adsorbed by biochar through cation exchange mechanisms such as basic cations· which are associated with functional groups on the biochar surface (Fidel et al., 2018). This will have a good impact on the availability of basic cations and reduce the solubility of acid cations (H^+). Another study showed that the application of 120 g of rice husk biochar reduced the concentrations of trace elements such as Cd, Ni, and Mn but increased the concentration of Pb and Zn (Ndor et al., 2016). Pandey et al. (2022) reported that the application of 3% biochar from *Lantana camara* and *Tanacetum parthenium* plants can reduce the solubility of micronutrients in the soil as well as avoid the toxic effects on plants. Similarly, the addition of biochar enhances the ability of soil to absorb and solidify nickel ions and reduces the bioavailability of nickel ions Gao et al. (2023).

Table 2. The plant height, number of leaves, and plant dry weight of patchouli after the application of RHC on nickel-mined soil.

RHC (%)	**Plant height (cm)**	**Number of leaves**		**Plant**
	14 DAT	**30 DAT**	**60 DAT**	**dry weight (g)**
0	10.67 a	2.00 a	9.00 a	2.67 a
1.5	10.67 a	3.00 a	11.33 a	3.00 ab
3	14.00 bc	5.33 a	10.00 a	3.00 ab
4.5	12.67 ab	5.33 a	11.00 a	3.67 ab
6	15.33 c	11.00 b	24.67 b	5.33 c
7.5	18.00 c	9.67 b	15.67 b	5.67 c
HSD 5 %	4.09	4.26	9.53	2.48

Note: Different letters indicate significant differences among the treatments at $p<0.05$, RHC = rice husk charcoal, DAT = day after transplanting.

The growth of patchouli

The application of rice husk charcoal significantly affected the plant height, the number of leaves as well as the plant dry weight of patchouli ($p<0.05$). Table 2 illustrates the effect of RHC on plant growth components. It was observed that the application of rice husk charcoal significantly affected the plant height ($p<0.05$). The addition of RHC at the rate of 6% was significantly different compared to the control (without RHC), 1.5% and 4.5% of RHC, except the rate of 3% and 7.5% of RHC. The highest plant was recorded at the addition of 7.5% and 6 of RHC by 18.00 cm and 15.33 cm, respectively, in line with the observation of the number of leaves and plant dry matter weight at 60 DAT. The highest number of leaves was noted at the rate of 6% of RHC (24.67) and, significantly different from the other treatments except for the addition of 7.5% of RHC. It was also observed that the addition of 7.5% (5.67 g) of RHC significantly affected the plant dry weight compared to the control (2.67 g) and other treatments, except for the addition of 6% of RHC. The results indicated that the effect of nickel and iron in soil is important. The Ni and Fe concentrations initially in nickel-mined soil were 776.10 and 6,433.53 mg kg^{-1}, respectively. The soil used was classified as polluted soil. As documented by Sreekanth et al. (2013), the Ni^{+2} concentration of polluted soil varied between 200 to 26,000 mg kg^{-1}. Iron and nickel play a crucial role in biochemistry and are essential micronutrients for plants and humans alike, despite it remaining a controversial element because of debate on their essentiality or non-essentiality in plants (Abou-Seeda et al., 2020). At high concentrations, Ni and Fe could have a negative effect on soil fertility, soil microbial activity, diversity, crop yields, and even human health (Ma et al., 2015). As pointed out by Hannan et al. (2021), Ni is required in small quantities for optimum plant growth; however, excessive bioavailability of Ni could have certain devastating effects on plant growth and development. The toxicity index of Ni is different in sensitive and tolerant crop species.

Some studies demonstrated that Ni toxicity symptoms including low nutrient uptake (Fabiano et al., 2015), reduced root and shoot growth (Hassan et al., 2019), decreased chlorophyll in the leaves of coffee and soybean (Sirhindi et al., 2016); and decreased stomatal conductance (Velikova et al., 2011). Another author has also explained the reduction in plant height and root length as well as chlorophyll formation due to Ni toxicity in rice seedlings (Hasanuzzaman et al., 2019). The slowing of plant growth (height, number of leaves, and dry weight), especially in the control treatment reported here, may indicate that Nickel and Iron have a negative effect at high concentrations. Therefore, the use of soil amendments such as RHC is important in nickel-contaminated soil. Some authors reported the positive impact of biochar on reducing the mobility of heavy metals and further increasing plant growth (Lahori et al., 2017; Bashir et al., 2018; Meng et al., 2018), although its effectiveness is strongly influenced by the source of biochar, the manufacturing process and time exposed to soil. Some authors demonstrated that iron toxicity in plants affected the primary root growth by decreasing both cell elongation and division due to direct contact of the root tip with external Fe, and in turn, the growth stunted (Becker et al., 2005; Zhang et al., 2012; Li et al., 2015; Reyt et al., 2015).

Conclusion

The present study clearly exhibits the beneficial aspect of rice husk charcoal (RHC) in improving soil chemical properties and, contrary, reducing Ni and Fe concentration in soil and, in turn, enhancing plant growth. The addition of RHC up to 6% of soil weight increased soil pH, organic C, available P, and CEC and significantly improved the patchouli growth. The RHC decreased the dissolving of Ni and Fe in soil by 65.43% and 40.47%, respectively. This result suggests that incorporating carbon-rich amendments is considered a less expensive cost and environmentally friendly strategy to restore nickel-mined soil; however, further study is needed to quantify the effectiveness of rice husk charcoal in field conditions.

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References

Abou-Seeda, M.A., EL-Sayed, A.A., Yassen, AA., Abou El-Nour, EAA., Zaghloul, S.M. and Gad-Mervat, M. 2020. Nickel, iron and their diverse role in plants: A review, approaches and future prospective. *Middle East Journal of Applied Sciences* 10(2):196-219, doi:10.36632/mejas/2020.10.2.21.

Adekiya, A.O., Agbede, T.M., Aboyeji, C.M., Dunsin, O. and Simeon, V.T. 2019. Effects of biochar and poultry manure on soil characteristics and the yield of radish. *Scientia Horticulturae* 243:457-463, doi:10.1016/j.scienta.2018.08.048.

Adekiya, A.O., Agbede, T.M., Olayanju, A., Ejue, W.S., Adekanye, T.A, Adenusi, T.T. and Ayeni, J.F. 2020. Effect of biochar on soil properties, soil loss, and cocoyam yield on a tropical sandy loam Alfisol. *Scientific World Journal* 9391630, doi:10.1155/2020/9391630.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S. and Ok, Y.S. 2014. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* 99:19-33, doi:10.1016/j.chemosphere.2013.10.071.

Alburquerque, J.A., Calero, J.M., Barrón. V., Torrent, J., del Campillo, M.C., Gallardo, A. and Villar, R. 2014. Effects of biochars produced from different feedstocks on soil properties and sunflower growth. *Journal of Plant Nutrition and Soil Science* 177(1):16-25, doi:10.1002/jpln.201200652.

Amendola, C., Montagnoli, A., Terzaghi, M., Trupiano, D., Oliva, F., Baronti, S., Miglietta, F., Chiatante, D. and Scippa, G.S. 2017. Short-term effects of biochar on grapevine fine root dynamics and arbuscular mycorrhizae production. *Agriculture Ecosystems & Environment* 239:236-245, doi:10.1016/ j.agee.2017.01.025.

Aprilianti, N., Darwis, S., Resman, Namriah, Ginting, S. and Anas, A.A. 2022. The effect of chicken manure bokashi on available P and K and the growth of cayenne pepper (*Capsicum frutescens* L.) on nickel-mined soil. *Berkala Penelitian Agronomi* 10(1):96-105, doi:10.33772/bpa.v10i1 (*in Indonesian*).

Bashir, S., Shaaban, M., Mehmood, S., Zhu, J., Fu, Q. and Hu, H. 2018. Efficiency of C3 and C4 plants derived-biochar for Cd mobility, nutrient cycling, and microbial biomass in contaminated soil. *Bulletin of Environmental Contamination and Toxicology* 100(6):834-838, doi:10.1007/s00128-018-2332-6.

Becker, M. and Asch, F. 2005. Iron toxicity in rice-conditions and management concepts. *Journal of Plant Nutrition and Soil Science* 168:558-573, doi:10.1002/jpln.200520504.

BPS. 2019. Nickel Potential in Southeast Sulawesi. Report of the Mining and Energy Office of Southeast Sulawesi Province. https://sultra.bps.go.id/subject/10/pertambangan.html (*in Indonesian*).

BPT. 2009. Chemical Analysis of Soil, Plants, Water and Fertilizers. Technical Instructions 2nd Edition. p 203. http://balittanah.litbang.deptan.go.id (*in Indonesian*).

Bray, R.H. and Kurtz, L.T. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Science* 59:39-45.

Bremner, J.M. and Mulvaney, C.S. 1982. Nitrogen Total p. 595-624. In: Page, A.L. (ed.) *Methods of Soil Analysis*. Part 2. 2nd Eds. Agronomy Monograph. 9. ASA and SSSA. Madison, WI.

Chan, K.Y., Van-Zwieten, E.L., Meszaros, I., Downie, A. and Joseph, S. 2007. Agronomic values of green waste biochar as a soil amendment. *Australian Journal of Soil Research* 45:629-634, doi:10.1071/SR07109.

Chintala, R., Mollinedo, J., Schumacher, T.E., Malo, D.D. and Julson, J.L. 2014. Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science* 60(3):393-404, doi:10.1080/03650340.2013.789870.

Fabiano, C.C., Tezotto, T., Favarin, J., Polacco, J.C. and Mazzafera, P. 2015. Essentiality of nickel in plants: a role in plant stresses. *Frontiers in Plant Science* 6:754, doi:10.3389/fpls.2015.00754.

Fidel, R.B., Laird, D.A. and Spokas, K.A. 2018. Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. *Scientific Reports* 8:17627, doi:10.1038/s41598-018-35534-w.

Gao, S., DeLuca, T.H. and Cleveland, C.C. 2019. Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of the Total Environment* 654:463-472, doi:10.1016/j.scitotenv.2018.11.124.

Gao, W., He, W., Zhang, J., Chen, Y., Zhang, Z., Yang, Y. and He, Z. 2023. Effects of biochar-based materials on nickel adsorption and bioavailability in soil. *Scientific Reports* 13:5880, doi:10.1038/s41598-023-32502-x.

Glaser, B., Lehmann, J. and Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biology and Fertility of Soils* 35:219-230, doi:10.1007/s00374-002-0466-4.

Hanan, F., Huang, Q., Farooq, M.A., Ayyaz, A., Ma, J., Zhang, N., Ali, B., Deyett, E., Zhou, W. and Islam, F. 2021. Organic and inorganic amendments for the remediation of nickel-contaminated soil and its improvement on Brassica napus growth and oxidative defense. *Journal of Hazardous Materials* 416:125921, doi:10.1016/j.jhazmat.2021.125921.

Hasanuzzaman, M., Alam, M.M., Nahar, K., Mohsin, S.M., Bhuyan, M.B., Parvin, K., Hawrylak-Nowak, B. and Fujita, M. 2019. Silicon-induced antioxidant defense and methylglyoxal detoxification work coordinately in alleviating nickel toxicity in *Oryza sativa* L. *Ecotoxicology* 28:261-276, doi:10.1007/s10646-019-02019-z.

Hassan, M.U., Chattha, M.U., Khan, I., Chattha, M.B., Aamer, M., Nawaz, M., Ali, A., Khan, M.A.U. and Khan, T.A. 2019. Nickel toxicity in plants: reasons, toxic effects, tolerance mechanisms, and remediation possibilities—a review. *Environmental Science and Pollution Research* 26(13):12673-12688, doi:10.1007/s11356-019-04892-x.

He, L., Zhong, H., Liu, G., Dai, Z., Brookes, P.C. and Xu, J. 2019. Remediation of heavy metal contaminated soils by biochar: Mechanisms, potential risks and applications in China. *Environmental Pollution* 252:846-855, doi:10.1016/j.envpol.2019.05.151.

Ho, S.H., Zhu, S. and Chang, J.S. 2017. Recent advances in nanoscale-metal assisted biochar derived from waste biomass used for heavy metals removal. *Bioresources Technology* 246:123-134, doi:10.1016/j.biortech.2017.08.061.

Jia, X., Yuan, W. and Ju X. 2015. Short report: effects of biochar addition on manure composting and associated N_2O emissions. *Journal of Sustainable. Bioenergy System* 5:56-61, doi:10.4236/jsbs.2015.52005.

Lahori, A.H., Guo, Z., Zhang, Z., Li, R., Mahar, A., Awasthi, M.K., Shen, F., Sial, T.A., Kumbhar, F., Wang, P. and Jiang, S. 2017. Use of biochar as an amendment for remediation of heavy metal-contaminated soils: prospects and challenges. *Pedosphere* 27(6):991-1014, doi:10.1016/S1002-0160(17)60490-9.

Laird, A.D. 2008. The charcoal vision: a win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal* 100:178-184, doi:10.2134/agrojnl2007.0161.

Lehmann, J., Gaunt, J. and Rondon, M. 2006. Biochar sequestration in terrestrial ecosystems: a review. *Mitigation and Adaptation Strategies for Global Change* 11:403-427, doi:10.1007/s11027-005-9006-5.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C. and Crowley, D. 2011. Biochar effects on soil biota - A review. *Soil Biology and Biochemistry* 43(9):1812-1836, doi:10.1016/j.soilbio.2011.04.022.

Li, G.J., Xu, W.F., Kronzucker, H.J. and Shi, W.M. 2015. Ethylene is critical to the maintenance of primary root growth and Fe homeostasis under Fe stress in Arabidopsis. *Journal of Experimental Botany* 66:2041-54, doi:10.1093/jxb/erv005.

Li, S., Li, Z., Feng, X., Zhou, F., Wang, J. and Li, Y. 2021. Effects of biochar additions on the soil chemical properties, bacterial community structure and rape growth in an acid purple soil. *Plant, Soil and Environment* 67(3):121-129, doi:10.17221/390/2020-PSE.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J. and Neves, E.G. 2006. Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal* 70:1719-1730, doi:10.2136/sssaj2005.0383.

Ma, L., Zhong, H. and Wu, Y.G. 2015. Effects of metal-soil contact time on the extraction of mercury from soils. *Bulletin of Environmental Contamination and Toxicology* 94:399-406, doi:10.1007/s00128-015-1468-x.

Meng, J., Tao, M., Wang, L., Liu, X. and Xu, J. 2018. Changes in heavy metal bioavailability and speciation from a Pb-Zn mining soil amended with biochars from co-pyrolysis of rice straw and swine manure. *Science of The Total Environment* 633: 300-307, doi:10.1016/j.scitotenv.2018.03.199.

Ndor, E., Jayeoba, O.J. and Ogara, J.I. 2016. Effect of biochar amendment on heavy metals concentration in dumpsite soil and their uptake by amaranthus (*Amaranthus cruentus*). *Journal of Applied Life Sciences International* 9(1):1-7, doi:10.9734/JALSI/2016/29948.

Nelson, D.W. and Sommers, L.E. 1982. Total carbon, organic carbon and organic matter. p. 539-579. In: Page, A.L. (ed) *Methods of Soil Analysis*. 2nd Eds. ASA Monograph 9(2). American Society of Agronomy. Madison, WI.

Palansooriya, K.N., Wong, J.T.F., Hashimoto, Y., Huang, L.B., Rinklebe, J., Chang, S.X., Bolan, N., Wang, H. and Ok, Y.S. 2019. Response of microbial communities to biochar-amended soils: a critical review. *Biochar* 1:3-22, doi:10.1007/s42773-019-00009-2.

Palmeggiani, G., Lebrun, M., Simiele, M., Bourgerie, S. and Morabito, D. 2021. Effect of biochar application depth on a former mine technosol: impact on metal (loid)s and *Alnus* growth. *Environments* 8(11):120, doi:10.3390/environments 8110120.

Pandey, B., Suthar, S. and Chand, N. 2022. Effect of biochar amendment on metal mobility, phytotoxicity, soil enzymes, and metal-uptakes by wheat (*Triticum aestivum*) in contaminated soils. *Chemosphere* 307(2):135889, doi:10.1016/j.chemosphere.2022. 135889.

Prematuri, R., Turjaman, M., Sato, T. and Tawaraya, K. 2020. The impact of nickel mining on soil properties and growth of two fast-growing tropical tree species. *International Journal of Forestry Research* 2020: 8837590, doi:10.1155/2020/8837590.

Reyt, G., Boudouf, S., Boucherez, J., Gaymard, F. and Briat, J.F. 2015. Iron and ferritin-dependent ROS distribution impact Arabidopsis root system architecture. *Molecular Plant* 8:439-53, doi:10.1016/j.molp.2014.11.014.

Rizwan, M., Ali, S., Qayyum, M.F., Ibrahim, M., Zia-ur-Rehman, M., Abbas, T. and Ok, Y.S. 2015. Mechanisms of biochar-mediated alleviation of toxicity of trace elements in plants: a critical review. *Environmental Science and Pollution Research* 23(3):2230-2248, doi:10.1007/s11356-015-5697-7.

Salawati, Basir, M., Kadekoh, I. and Thaha, A.R. 2016. Potential of rice husk biochar on changes in pH, CEC, organic C, and available P in Inceptisol soil. *Agroland* 23(2):101-109 (*in Indonesian*).

Singh, H., Northup, B.K., Rice, C.W. and Prasad, P.V. 2022. Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar* 4(8):1-17, doi:10.1007/s42773-022-00138-1.

Sirhindi, G., Mir, M.A., Abd-Allah, E.F., Ahmad, P. and Gucel, S. 2016. Jasmonic acid modulates the physiobiochemical attributes, antioxidant enzyme activity, and gene expression in *Glycine max* under nickel toxicity. *Frontiers in Plant Science* 7:591, doi:10.3389/fpls.2016.00591.

Sreekanth, T., Nagajyothi, P., Lee, K. and Prasad, T. 2013. Occurrence, physiological responses and toxicity of nickel in plants. *International Journal of Environmental Science and. Technology* 10:1129-1140, doi:10.1007/s13762-013-0245-9.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macêdo, J.L.V., Blum, W.E.H. and Zech, W. 2007. Long-term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil* 291(1): 275-290, doi:10.1007/s11104-007-9193-9.

Thies, J.E. and Rillig, M.C. 2009. Characteristics of biochar: biological properties. In: Lehmann, J. and Joseph, S. (eds.), *Biochar for Environmental Management: Science and Technology*, pp. 85–105, *Earthscan*, London, UK.

Trupiano, D., Cocozza, C., Baronti, S., Amendola, C., Vaccari, F.P., Lustrato, G., Lonardo, S.D., Fantasma, F., Tognetti, R. and Scippa, G.S. 2017. The effects of biochar and its combination with compost on lettuce (*Lactuca sativa* L.) growth, soil properties, and soil microbial activity and abundance. *International Journal of Agronomy* 3158207, doi:10.1155/2017/3158207.

Vahedi, R., Rasouli-Sadaghiani, M.H., Barin, M. and Vetukuri, R.R. 2022. Effect of biochar and microbial inoculation on P, Fe, and Zn bioavailability in a calcareous soil. *Processes* 10(2):343, doi:10.3390/pr10020343.

Velikova, V., Tsonev, T., Loreto, F. and Centritto, M. 2011. Changes in photosynthesis, mesophyll conductance to CO_2, and isoprenoid emissions in Populus nigra plants exposed to excess nickel. *Environmental Pollution* 159:1058-1066, doi:10.1016/j.envpol.2010.10.032.

Widiatmaka, Suwarno and Kusmaryandi, N. 2010. Pedology characteristics and revegetation management of post-Pomalaa nickel mine land, Southeast Sulawesi. *Jurnal Tanah dan Lingkungan* 12(2):1-10, doi:10.29244/jitl.12.2.1-10 (*in Indonesian*).

Windeatt, J.H., Ross, A.B., Williams, P.T., Forster, P.M., Nahil, M.A. and Singh, S. 2014. Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. *Journal of Environmental Management* 146:189-197, doi:10.1016/j.jenvman.2014.08.003.

Yuan, J.H. and Xu, R. 2010. The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol. *Soil Use and Management* 27:110-115, doi:10.1111/j.1475-2743.2010.00317.x.

Zhang, X.D., Hang, X., Wang, D., Jiang, C.C., Zhu, P., Lei, J. and Peng, S.A. 2013. Effect of biochar on physicochemical properties of red and yellow-brown soils in the South China Region. *Chinese Journal of Eco-Agriculture* 21(8):979-984, doi:10.3724/SP.J.1011.2013.00979.

Zhang, Y., Wang, Y.P., Liu, P., Song, J.M., Xu, G.D. and Zheng, G.H. 2012. Effect of toxic Fe^{2+} level on the biological characteristics of rice root border cell. *Russian Journal of Plant Physiology* 59:766-71, doi:10.1134/S1021443712060209.