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Research Article

The use of chitosan-coated biochar for the improvement of heavy metals-contaminated soil and healthy food products

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Abstract

Soil health is a global concern related to food health issues, and the intensity of using agrochemicals contributes greatly to contamination by Pb (lead), Cd (cadmium), Cu (copper), Zn (zinc), and other heavy metals. Land contaminated with heavy metals is absorbed by plants and transferred to tissue, causing food to be unhealthy for consumption. Soil improvers such as biochar and chitosan have been widely used for improvement, but the use remains partial. In this context, granular coating technology is the right choice for overcoming soil problems. Chitosan-coated biochar technology is an effort to combine biochar and chitosan, which are made into granules and function as soil amendments. Therefore, this study aimed to obtain oil amendments that are effective in reducing heavy metals in soil. The target was for the soil to be healthy as well as produce healthy and safe food products. A completely randomized design was used with three replications. The production of granular chitosan biochar was then investigated on vegetable plants. Growth observations were carried out every week until the plants were about to be harvested, while soil and heavy metal analysis was conducted before and after planting. The observed data were analyzed using an Analysis of Variance (ANOVA) and Least Significant Difference (LSD) tests. The results showed that a chitosan-coated biochar dose of 20 t/ha increased plant growth in all observed parameters. The use of chitosan-coated biochar reduced Pb from 10.77 mg/kg to 6.73 mg/kg, Cd from 5.01 mg/kg to 2.56 mg/kg, and Cu from 71.22 mg/kg to 25.65 mg/kg.

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Introduction

Contamination of agricultural land is currently a serious problem, and one significant indicator of unhealthy soil is the accumulation of heavy metals exceeding the limit. Hg (mercury), Pb (lead), Cd (cadmium), and Cu (copper) are heavy metals often found in agricultural land. Globally, more than 20 million ha of land is contaminated with heavy metals, including As (arsenic), Cd, Cr (chromium), Hg, Pb, Co (cobalt), Cu, Ni (nickel), Zn, and Se (selenium). This problem is considered very serious because the concentration of heavy metals has exceeded the threshold value (Dhaliwal et al., 2020; Liu et al., 2024). According to Hamzah and Priyadarshini (2023), several agricultural centers in Indonesia have been reportedly contaminated with Pb and Cu. The figures obtained in agricultural centers in East Java Province are relatively large, with Pb of 16.95 mg/kg and Cu of 89.71 mg/kg, indicating that the land needs to be monitored because the value has exceeded the threshold. The limit levels of heavy metals in soil are set differently for each country; for example, in Europe, the limit levels set for Pb and Cu are 300 and 140 mg/kg, respectively. WHO (World Health Organization), on the other hand, set the limit levels of heavy metals in soil for Pb of 0.3-10 mg/kg and Cu of 1-12 mg/kg. This shows that agricultural lands need serious attention for immediate remediation.

Amendment materials have been widely used for soil improvement but are still limited due to finite costs and technology. Coating technology between biochar and chitosan is an option that can be carried out for soil improvement. Biochar is a product produced from agricultural waste processed by pyrolysis. It is rich in carbon (C) and porous, has several functional groups and has a good physicochemical adsorption capacity. In recent years, several studies have formulated biochar with other materials to accelerate soil improvement. One of the coated formula technologies between biochar and humic acid was carried out by Hamzah et al. (2022) and Hamzah and Priyadarshini (2023).

Biochar coating technology with chitosan is another option for soil amendment. The formulation is made in the form of granules using granulation technology. This formula is considered very effective because biochar has been proven crucial in improving soil properties and crop yields. Biochar also has good adsorption capacity and the potential as a carrier for slow-release fertilizers (Liyuan et al., 2016; Leng et al., 2020). Meanwhile, chitosan is a natural, non-toxic polycationic polymer with great prospects as an adsorbent due to its biocompatibility, biodegradability, harmlessness, and chemical flexibility. Studies on the use of these two materials have been widely carried out but remain limited, while the combination of these materials is rarely performed. Both biochar and chitosan materials used simultaneously with coating technology will improve the environment, including degrading heavy metals in soil (Xi et al., 2020; Issahaku et al., 2023).

Biochar plays a role in influencing the nutrient cycle in soil through retention and absorption as well as increasing bioavailability while reducing leaching (Schmidt et al., 2021). The application of biochar to acidic and alkaline soils significantly increases the release of K, P, and Mg by about 40-50 times, with the release being significantly higher in alkaline soil (Shi et al., 2019). Xu et al. (2023) stated that biochar amendment increases the total amount of heavy metals in soil, but 43-97% of heavy metals in the improved soil are concentrated in the remaining fraction of less bioavailability. Therefore, the addition of biochar can significantly reduce the accumulation of heavy metals in biomass by up to 50%. This shows that biochar is a potential regulator for improving soil (Gonzaga et al., 2019). Another study showed that forming biochar nanocomposites is an innovative way to achieve greater efficacy in controlling contamination (Taraqqi-A-Kamal et al., 2021). Chitosan is an effective adsorbent that eliminates Zn toxicity in contaminated soil (Tripathi et al., 2017). The application of chitosan, together with mono calcium phosphate, reduces Zn bioavailability and plant uptake. Furthermore, chitosan has great potential as a heavy metal reducer in soil contaminated with Pb, As, and P (phosphorus) (Padilla-Rodríguez and Codling, 2016). Soil treated using chitosan solution remediated As, Pb, and P by 17%, 1.8%, and 31%, respectively. Remediation by chitosan and derivatives greatly supports the restoration of degraded agricultural land (Arabyarmohammadi et al., 2018). Heavy metals in soil cannot experience biodegradation, making cleaning contaminants difficult and expensive. Cleaning contaminants conventionally (removal) requires high costs. Hence, it is necessary to develop cheap alternative technologies. In other cases, most soil contaminated with heavy metals has very low fertility.

Biochar and chitosan are materials used to improve soil fertility, including controlling heavy metals. According to previous studies, both materials are mostly used separately (Taraqqi-A-Kamal et al., 2021; Xu et al., 2023). The dispersed and separated use increases the potential for significant material loss. Both materials can be modified with a granular coating method (Utari et al., 2014) to obtain an effective soil conditioner in controlling heavy metals. The coating formulation that combines biochar and chitosan in a granular form will be more efficient. The method is expected to be a way forward to help solve soil problems. Therefore, this study aimed to increase the absorption capacity of chitosan-coated biochar granules by plants and reduce metals in contaminated soil.

Materials and Methods

Preparation of chitosan-coated biochar granules

Modification of chitosan-coated biochar was carried out in two steps. First, biochar was produced using a pyrolyzer from raw materials from straw biomass, and combustion was carried out at 400 °C with limited oxygen. This process produced porous and C-rich materials. Biochar was ground and sieved to a size of 100 mesh, then mixed and blended with 20 g starch as a binder to facilitate the formation of granules. The mixture was granulated using a pan granulator. The granulation process was carried out for 10 minutes until granules were formed.The materials were sieved with an average diameter of 2 to 5 mm to obtain uniform granules. Second, chitosan powder, a biopolymer derived from chitin, up to 20 g was gradually dissolved in a 1% acetic acid solution by stirring until completely dissolved, then the solution was filtered and ready to use. Biochar was then mixed and coated with a chitosan solution to ensure even coverage through mechanical agitation. The coated biochar was dried at moderate temperatures, between 60 and 80 °C. The drying procedure was continued until the moisture content of granules was in the range of 9% to 12%. This step removed excess solvent and secured a strong bond between the chitosan and biochar surface. The modification also improved the surface properties of biochar, increasing the ability to adsorb various pollutants, including heavy metals and organic contaminants (Tripathi et al., 2017).

Soil and chitosan-coated biochar characteristics

The soil used in this study was classified as low, moderate, and high, while heavy metals Pb and Cd were classified as quite high. A planting medium was prepared by using soil obtained from rice fields imported from Karangploso Village, Malang Regency. Soil characteristics included pH = 6.34 (neutral), organic C = 2.66% (moderate), total N = 0.27% (moderate), K_2O = 0.725 cmol/kg (very low), P_2O_5 = 58.77 mg/kg (high), Pb = 13.73 mg/kg (critical value), and Cu = 80.23 mg/kg (very high) (Hamzah et al., 2022). Soil analysis was carried out in the laboratory of Universitas Tribhuwana Tunggadewi and the soil laboratory of Universitas Pembangunan Nasional Veteran, East Java Veteran. The chitosan used was an organic compound in chitin powder form produced from the marine waste of shrimp and crab groups. The composition included 12.29% water content, 13.13% fat content, 2.20% total N, and 81.39% carbohydrates (Cahyono, 2018).

In this study, soil samples were air-dried and sieved with a 2 mm sieve. About 2.5 g each of soil proportions was acid-digested in a microwave-assisted Kjeldahl digester by adding 5 mL concentrated nitric acid, 2 ml hydrochloric acid, and 1 ml hydrofluoric acid. The containers were tightly closed and heated in a microwave unit at 800 W to a temperature of 210 °C for 20 minutes at a pressure of 40 bar. The digested samples were analyzed for heavy metals, including Pb, Cd, and Cu, using the Atomic Absorption Spectrophotometer model UNICAM 919 (Srikanth et al., 2013). Soil analysis included texture, pH (H_2O), organic C (Walkley and Black), N (Kjeldahl), total P (Olsen), total K, and CEC (ammonium acetate pH 7.0). Samples were taken at the beginning and end of the experiment to measure heavy metal content and the decrease in the percentage due to the addition of chitosan-coated biochar.

Pot experiment

The experiment was carried out by using 5 kg of soil and two treatment factors. The first factor was biochar doses (B) of 0, 5, 10, 15, and 20 t/ha. Meanwhile, the second factor was plant types (T), namely T1: spinach, T2: mustard greens, and T3: water spinach. The fifteen treatments were arranged in a completely randomized design with three replicates. The treated soil was maintained at field capacity, and each pot was covered with plastic in a greenhouse for four weeks with an incubation period of one month. The objective was to evaluate the effectiveness of chitosan-coated biochar in responding to the growth and mobilization of heavy metals. Plants were observed weekly until harvest, specifically for height, leaf area, and wet weight. After harvest, the roots and upper part of the plants were separated, washed, and oven-dried at 60 ºC for 72 hours. Heavy metal analysis was carried out on soil and plants, including Pb, Cd, and Cu, using the AAS method.

Pb, Cd, and Cu Absorption

Pb, Cd, and Cu absorption by plants was calculated by multiplying the percentage of concentration in each part by the dry weight. Heavy metal content was calculated by weighing 2 g of the mashed plant sample. The sample was dissolved with 10 mL of HNO_3 and $HClO_4$, then heated until the remaining volume was 2 mL. The liquid was reheated with distilled water until it became clear (pure white), then mixed with distilled water and filtered using the 3050 EPA method. Pb, Cd, and Cu content was measured using an atomic absorption spectrophotometer with a wavelength between 190 and 800 nanometers (Maurya et al., 2018; Jin et al., 2020).

Statistical analysis

The data obtained were analyzed using a One-Way Analysis of Variance (ANOVA). A Least Significant Difference (LSD) test at a significance level of $p<0.05$ was carried out to determine the effect of chitosan-coated biochar doses and plant types on Pb, Cd, and Cu absorption and plant growth.

Results and Discussion

Effect of chitosan-coated biochar application on soil improvement

Soil analysis results showed that chitosan-coated biochar application significantly improved nutrient content. This was indicated by the analysis results before and after incubation, specifically the considerable differences in values between the parameters analyzed (Table 1).

As shown in Table 1, the initial soil pH before incubation was 5.75, which increased to 6.10 after chitosan-coated biochar application. Similar results were observed in the elements of organic C, total N, available P, K-exch, Ca-exch, and Mg-exch, which increased from the initial to the final soil. This indicates a very significant improvement after chitosan-coated biochar application due to improvement in soil pH. The improvement can be attributed to the application of chitosan-coated biochar as an organic material closely related to the mineralization process, which causes the release of nutrients. The increase in nutrients occurs due to the release process, specifically from chitosan. A significant function of chitosan is to act as a long-term nutrient coating. Aside from preventing waste, chitosan contributes to plant defense against disease attacks. In this study, the function of each chitosan-coated biochar material was observed separately. Chitosan caused an increase in nutrient content and expression of various genes. This shows that plant defenses work very effectively, implying that the activation of proteins related to pathogenicity and phytoalexins function properly. According to Riseh et al. (2023), chitosan contributes significantly to the formation of the plant defense system. This combination can improve plant physiological properties and resistance.

Table 1. Chemical properties of the soil before and after incubation.

Soil	pH H_2O	Org C (%)	N (%)	P (ppm)	K-exch cmol/kg)	CEC (me/100 g)	Pb (ppm)	Cd (ppm)	Cu (ppm)
Before Incubation	5.75	1.94	0.32	23.17	0.48	20.12	10.77	5.01	71.22
After Incubation	6.10	2.47	0.39	45.58	0.73	25.05	9.51	4.01	60.57

Furthermore, chitosan functions as a major source of nutrients, including C (47.9-54.4%), oxygen (O_2) (30.19-42.3%), nitrogen (N) (5.8-7.6%), and phosphorus (P) (3.4-6.1%). Studies based on agriculture are trying to reduce the negative impact of conventional chemical fertilizers on the environment. As an organic soil conditioner, chitosan-coated biochar is very effective for improvement. The provision of organic materials will provide nutrients for soil. The decomposition of organic materials can produce organic acids and bind H^+ ions, thereby increasing soil pH. Organic acids bind H^+ ions through negatively charged carboxyl groups. Fluctuations in soil pH in soil are highly dependent on H^+ and OH^- ions. Organic acids also bind Al^{3+} and $Fe^{2+,}$ which form complex compounds (chelates); hence, Al^{3+} and Fe^{2+} are not hydrolyzed (Haghighi et al., 2012).

The positive effect of using chitosan-coated biochar was in line with previous studies that combined biochar with humate to reduce soil acidity. Additionally, chitosan-coated biochar can increase soil buffer capacity, total C, soil CEC, available nutrients, water retention, and soil aggregate stability (El-Naggar et al., 2019; Ampong et al., 2022; Meng et al., 2023). Biochar is also used to improve soil pH, as the results showed that incubation for 180 days increased soil pH from 5.33 to 8.75. This implies that biochar is very effective for improving soil pH. The results showed that chitosan-coated biochar can increase soil pH from 5.75 to 6.10. Therefore, it is very effective for improving soil pH.

Aside from increasing soil fertility, the use of chitosan biochar can reduce heavy metal levels in soil. Based on the results, heavy metal parameters such as Pb, Cd, and Cu showed a decrease. In the initial soil, Pb (10.77 mg/kg), Cd (5.01 mg/kg), and Cu (71.22 mg/kg) decreased to Pb (9.51 mg/kg), Cd (4.01 mg/kg), and Cu (60.57 mg/kg). Two heavy metals were found to be at critical limits, namely Cd and Cu, while Pb fell in the normal range. The decrease in heavy metals is presumably due to biochar. The normal limit of Pb in the soil is 2-300 mg/kg, Cd is 0.01-2.0 mg/kg, and Cu is 2-250 mg/kg (Alloway, 1995). The decrease in Pb, Cd, and Cu in this study indicates that the use of chitosan-coated biochar is very effective. According to Liu et al. (2022), biochar has better performance after modification, providing higher surface area and more functional groups, and has sufficient binding sites to combine heavy metal ions.

Biochar is a promising candidate for removing heavy metals in the environment. Furthermore, some high-valent metal ions can be reduced to low-valent metals, such as Cr (VI) to Cr (III), and form deposits on biochar in situ. The use of biochar not only functions as a nutrient provider but also as a heavy metal controller. Chitosan can effectively reduce heavy metals, radioactive metals, dyes, as well as oil and fat wastes from contaminated sources. This shows that chitosan-coated biochar can function as a potential regulator to improve soil (Pal et al., 2021; Hamzah and Priyadarshini, 2023).

Application of chitosan-coated biochar on plant growth

The analysis results of plant height with various chitosan-coated biochar doses indicate differences in plant growth. The dose of 20 t/ha demonstrated significant plant height growth (Figure 1). The use of chitosan-coated biochar at various doses given to vegetable plants, including mustard greens, spinach, and water spinach, provides a very good growth response. This was reflected in the increased plant growth at each observation period. In general, the use of chitosan-coated biochar at a dose of 20 t/ha provided better plant height growth compared to 0, 5, 10, and 15 t/ha. A dose of 20 t/ha for mustard greens provided plant growth of 23.65 cm, while the highest was found in spinach and water spinach at 81.12 and 51.75 cm, respectively. The lowest plant height was found in the control treatment (without chitosan-coated biochar) for the three plants at 7 weeks after planting (WAP), namely mustard greens at 10.70 cm, spinach at 36.17 cm, and water spinach at 35.05 cm. This suggested that the use of chitosan-coated biochar provided a significant growth response for the three plants.

The chitosan-coated biochar dose of 20 t/ha produced the best treatment in terms of height parameters for the three plants compared to others. The increase in plant height studied using single biochar without other materials on spinach plants was estimated at 27.50 cm (Sapanca et al., 2024). This shows that the use of single biochar did not provide a response to plant growth, underscoring the need for a combination with other materials, including chitosan. According to Anggara et al. (2017), the use of chitosan for soil improvement increased the height of corn plants to 189.46 cm. This is because chitosan contains gibberellin, which can support plant height growth. The higher the chitosan-coated biochar dose, the greater the effect on plant growth. Hence, B4 treatment (chitosan-coated biochar 20 t/ha) was more effective and efficient in increasing plant height growth.

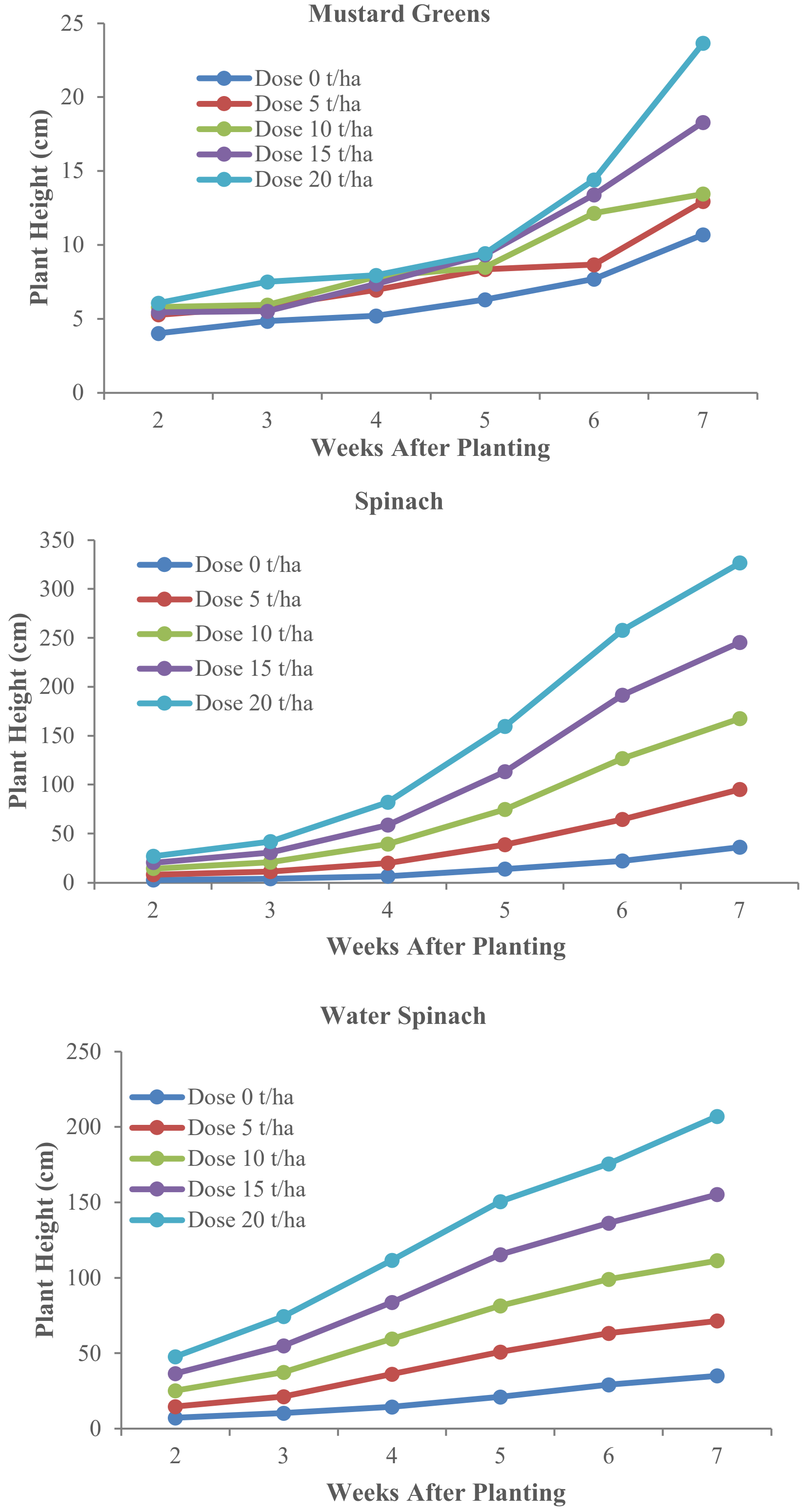

Figure 1. Application of chitosan-coated biochar on plant growth.

The plant height results are relatively the same as the leaf area parameter (Figure 2). The use of various chitosan-coated biochar doses increased leaf area growth up to 7 WAP. The pattern of leaf area increase is the same as in the plant height parameter (Figure 1). The chitosan-coated biochar dose that produced the highest leaf area growth response was 20 t/ha, while plants in the control treatment (not given chitosan-coated biochar) had relatively small leaf area growth. The results showed that the 20 t/ha chitosan-coated biochar treatment increased plant vegetative growth, specifically height and leaf area, with taller plants having greater leaf area. Chitosan-coated biochar plays a significant role in plant growth due to its ability to provide nutrients. Sufficient nutrients during the growth period stimulate physiological processes.

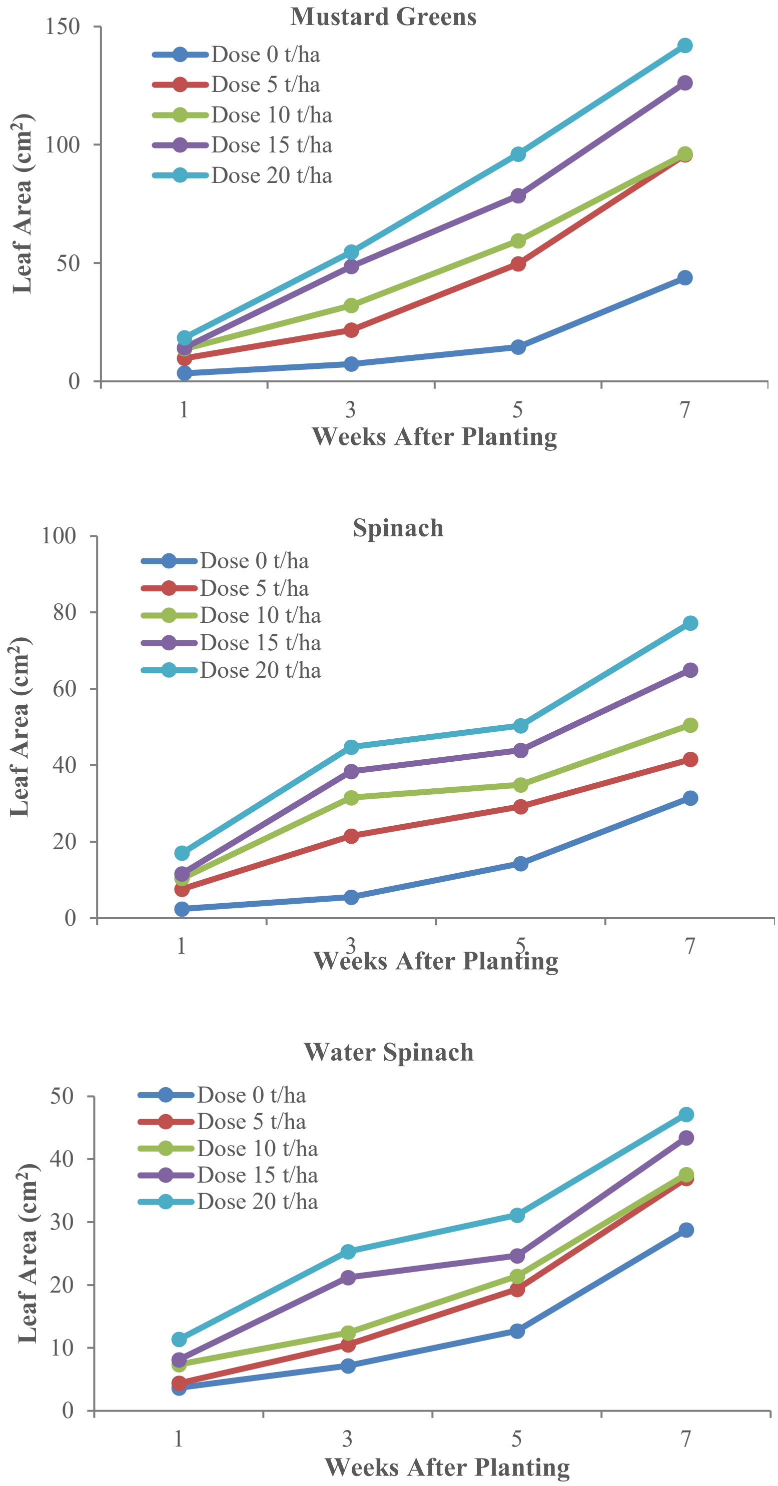

Figure 2. Application of chitosan-coated biochar on plant leaf area.

For example, the photosynthesis process will run perfectly when supported by a wide leaf area capable of capturing sufficient sunlight (Akmal and Simanjuntak, 2019). Furthermore, the availability of nutrients in plants helps increase leaf area. The provision of biochar increased the availability of nutrients N, P, and K (potassium), thereby expanding the leaf area. Another study (Sapanca et al., 2024) stated that increasing the biochar dose in spinach plants can increase leaf area. The use of chitosan also increased the average leaf area of mustard greens to 410.83 cm^2 (Letahiit et al., 2022).

Chitosan-coated biochar dose of 20 t/ha provided a higher leaf area for mustard greens, spinach, and water spinach than other doses. The use of chitosan-coated biochar can provide macronutrients, making it effective for plants. One role of biochar is acting as a habitat for beneficial microorganisms, including pseudomonas bacteria (P fixers) and acetobacter bacteria (N fixers), facilitating the availability of macronutrients in soil (Verdiana et al., 2016). According to Karamina and Fikrinda (2020), biochar has a large number of micropores that function as a habitat for microorganisms. The higher the number of microorganisms in the soil, the greater the availability of nutrients, making it easier for plants to absorb in sufficient quantities. This is proven by the performance of the three plants tested, which showed very good growth. The use of chitosan-coated biochar is highly effective for plant growth because it plays an important role in providing nutrients.

The availability of nutrients in sufficient quantity will help the formation of vegetative parts. Plants with a wide leaf area have better chlorophyll formation, which enhances the photosynthesis process. A good photosynthesis process produces high plant biomass. In this study, improvements in the physical and chemical properties of soil were supplied with biochar. Biochar also provides several elements that trigger plant growth. Vegetative growth, including plant height and leaf area, is the absorption result of nutrients provided by chitosan-coated biochar. Additionally, chitosan-coated biochar provided N, further enhanced by the addition of a base fertilizer.

Table 2. Average results of wet weight, dry weight, root weight, and root length.

Treatment	**Wet Weight (g)**	**Root Weight (g)**	**Root Length (cm)**
B0T1 (Without chitosan-coated biochar + Mustard Greens)	25.38 e	0.48 e	11.64 e
B1T1 (Chitosan-coated biochar 5 t/ha + Mustard Greens)	93.70 d	1.36 d	12.14 de
B2T1 (Chitosan-coated biochar 10 t/ha + Mustard Greens)	109.02 c	2.76 c	13.43 c
B3T1 (Chitosan-coated biochar 15 t/ha + Mustard Greens)	120.57 b	2.86 bc	15.63 b
B4T1 (Chitosan-coated biochar 20 t/ha + Mustard Greens)	141.25 a	4.04 a	18.42 a
LSD (5%)	1.75	0.65	0.86
B0T2 (Without chitosan-coated biochar + Spinach)	22.94 e	1.62 e	13.61 e
B1T2 (Chitosan-coated biochar 5 t/ha + Spinach)	62.59 d	3.54 d	22.09 d
B2T2 (Chitosan-coated biochar 10 t/ha + Spinach)	92.06 c	4.96 cd	22.54 cd
B3T2 (Chitosan-coated biochar 15 t/ha + Spinach)	107.78 b	11.12 b	24.78 b
B4T2 (Chitosan-coated biochar 20 t/ha +Spinach)	119.57 a	12.24 a	27.34 a
LSD (5%)	1.92	0.79	0.85
B0T3 (Without chitosan-coated biochar + Water Spinach)	36.20 e	9.24 e	20.86 e
B1T3 (Chitosan-coated biochar 5 t/ha + Water Spinach)	60.39 d	10.10 d	21.39 de
B2T3 (Chitosan-coated biochar 10 t/ha + Water Spinach)	64.67 cd	13.43 c	23.24 c
B3T3 (Chitosan-coated biochar 15 t/ha + Water Spinach)	71.81 b	13.55 b	26.90 b
B4T3 (Chitosan-coated biochar 20 t/ha + Water Spinach)	78.79 a	16.55 a	29.19 a
LSD (5%)	4.55	1.52	1.16

The addition of N will promote better vegetative growth. During the vegetative period, plants need N in large quantities compared to P and K (Sa'adah, 2019). Additionally, the use of chitosan-coated biochar also increased plant yields, evidenced by the parameters of wet weight, dry weight, root weight, and root length (Table 1). This study suspects that the role of biochar and chitosan in granular form complement each other to support plant growth. The combined application enhanced plant growth by increasing water-holding capacity, providing nutrients, improving soil structure, stimulating growth, and increasing disease resistance. Biochar is rich in minerals important for plants, such as calcium, magnesium, and iron. These minerals will be released slowly into the soil; hence, plants are more guaranteed to be available. Chitosan has the properties of a plant growth stimulator, stimulating cell division, root elongation, and the production of growth hormones. It also helps regulate soil pH, thereby creating optimal conditions for plant growth. Chitosan-coated biochar functions as a biostimulant, stimulating plant growth and increasing yields when applied to the roots by mixing into the soil or adding to other materials. Suwanchaikasem et al. (2024) also used chitosan in spray form, with periodic spraying of 0.0125-0.1% w/v on strawberry leaves for 2 months before flowering, causing a significant increase in plant height, leaf size, as well as individual, and total fruit weight. Based on the results, there was a significant difference between various doses of chitosan-coated biochar. The wet weight parameters of mustard greens, spinach, and water spinach in the 20 t/ha chitosan-coated biochar treatment produced the highest average results for mustard greens (141.25 g), spinach (119.57 g), and water spinach (78.79 g). Meanwhile, the lowest wet weight was found in the control treatment for mustard greens (25.38 g), spinach (22.94 g), and water spinach (36.20 g). Similar results were observed for the parameters of dry weight, root weight, and root length.

The comparison of plants with and without chitosan-coated biochar is shown in Figure 3. The distribution of roots without chitosan-coated biochar appeared less thick, but plants with 20 t/ha chitosan-coated biochar showed a very dense distribution. This shows that biochar application can affect root growth. A chitosan-coated biochar dose of 20 t/ha showed the highest growth of all observed parameters. The use of chitosan-coated biochar not only increased plant growth but also controlled heavy metals. Hamzah et al. (2022) used biochar coated with humic acid to remediate Pb and Cu-contaminated soil. The use of biochar as an amendment has also been reported to improve soil health and fertility, increase nutrients and C, reduce soil pollutants, improve plant performance for agro-environmental sustainability, as well as contribute to the development of a circular bioeconomy (Rahim et al., 2024).

Without chitosan-coated biochar With chitosan-coated biochar

Figure 3. Plant roots with and without chitosan-coated biochar.

Biochar combined with humic acid was used to reduce pest attacks on land planted with apples (Liu et al., 2024). This combination also increased soil enzyme activity of urease, phosphatase, and catalase. Antioxidant enzyme activity and rooting index of apple seedlings studied can increase plant growth and reduce disease attacks (Liu et al., 2024). Furthermore, the combination of various materials with biochar was studied by Zubair et al. (2021), which used textile waste biochar coated with chitosan for moringa plants. The results showed that the treatment increased the growth parameters of root length (90%), root fresh weight (76%), shoot dry weight (75%), root dry weight (68%), chlorophyll-a content (42%), and chlorophyll-b content (74%). Chitosan-coated biochar given to contaminated soil increased the activity of microbes as well as urease, catalase, and invertase enzymes, thereby improving soil quality and increasing crop yields.

Reduction of heavy metals Pb, Cd, and Cu

The post-planting soil analysis results showed that chitosan-coated biochar not only improved soil conditions but also remediated contamination by heavy metals. Based on the results, the use of chitosan-coated biochar granules as soil amendments reduced Pb, Cd, and Cu (Figure 4). As shown in Figure 4, the use of chitosan-coated biochar at the end of the study led to a significant decrease in the three heavy metals analyzed. Pb of 10.77 mg/kg decreased to 6.73 mg/kg, Cd (5.01) to 2.56 mg/kg, and Cu (71.22) to 25.65 mg/kg. This indicates that the use of chitosan-coated biochar doses can reduce heavy metals, particularly due to biochar content with good functional groups, surface area, and cation exchange capacity. The use of chitosan-coated biochar granules plays an important role in overcoming heavy metal oxidative stress by improving the activity of antioxidant enzymes as well as increasing protein, tannin, lipid, alkaloid, saponin, and flavonoid in plants. These results indicate that chitosan-coated biochar granules have a very large perspective for remediating Pb, Cd, and Cu-contaminated soil while preventing human health risks through contaminated food. The results are consistent with previous studies that used biochar and humic acid to improve Pb-contaminated rice fields. The combination increased rice production by up to 8 t/ha and reduced Pb by >60% (Hamzah et al., 2022).

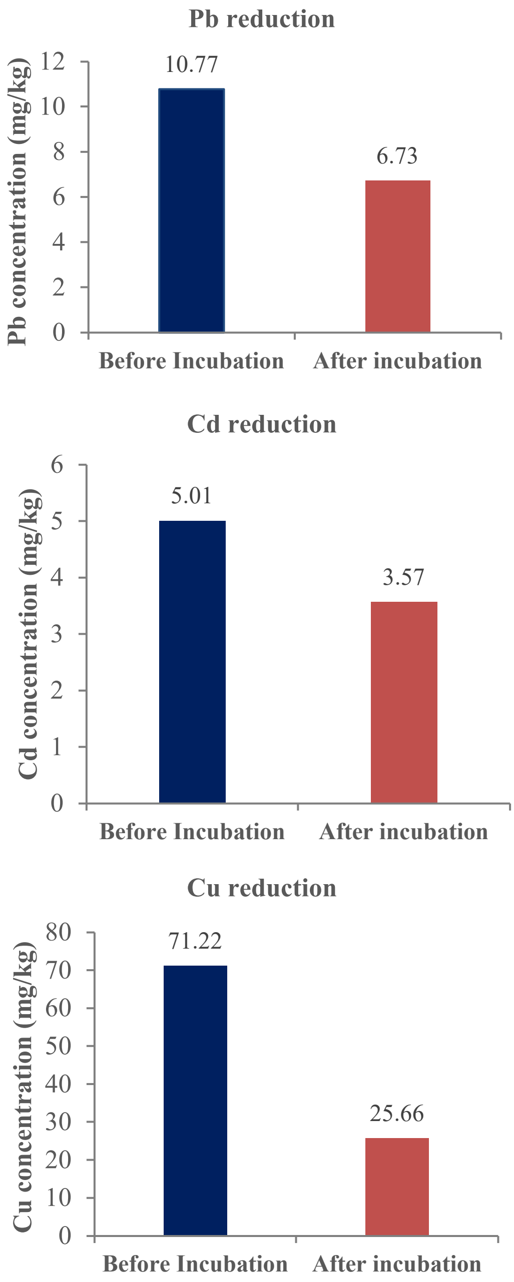

Figure 4. The use of chitosan-coated biochar for heavy metal reduction.

The use of biochar can also remediate Pb between 18.8-77.0% and Cu around 20% (Sizmur et al., 2011; Jiang et al., 2012). As stated by Priyadarshini et al. (2024), biochar can reduce Pb due to the presence of microbes. Furthermore, the use of chitosan plays a significant role in soil productivity. Chitosan is a highly efficient, biodegradable, and environmentally friendly polymer to improve the environment. It is often extracted from various wastes such as marine waste, algae, and housefly larvae (Ai et al., 2012). Chitosan can effectively remove heavy metals, radioactive metals, dyes, as well as oil and fat waste from contaminated resources. It may be combined with other chemical compounds to increase the effectiveness of chitosan or chemical compounds (Pal et al., 2021). Aside from using biochar as a heavy metal detoxifier, chitosan also has the same role in controlling heavy metals, including Pb, Cd, and Cu.

The use of chitosan with other materials reduced heavy metal cadmium by up to 81% (Ahmed and Mohamed, 2023). This shows that chitosan alone is not very effective compared to chitosan mixed with other materials. In particular, chitosan-coated biochar is very effective in changing soil structure. According to Shariatmadari et al. (2020), the use of chitosan as a soil stabilizer is very effective, specifically in sandy and clayey soil. Both have differences in the formation of electrostatic bonds between clay and sandy soil particles due to various surfaces and electrical charges. Chitosan biopolymers in sandy soil remain constant over time, and under field capacity conditions, submerged biochar shows good strength.

Conclusion

In conclusion, the use of chitosan-coated biochar improved soil quality specifically changes in pH, N, P, K, organic C, CEC, and heavy metal reduction. Plant response to the provision of chitosan-coated biochar was reflected in growth. The use of chitosan-coated biochar also reduced heavy metals, including Pb, Cd, and Cu. Based on the results, Pb of 10.77 mg/kg decreased to 6.73 mg/kg. Cd of 5.01 mg/kg decreased to 2.56 mg/kg, and Cu of 71.22 mg/kg decreased to 25.65 mg/kg. There was still a significant amount of heavy metals in the soil; hence, further studies are needed to determine the effectiveness of using chitosan-coated biochar in remediating heavy metals.

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