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The Potential of Various Compost and Biochar Materials as Soil Amendments to Enhance Soil Nitrogen Availability: A Review

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ABSTRACT

Nitrogen is an important nutrient in soil that is often a limiting factor in agricultural practices because it tends to be easily lost from the soil through various natural processes. Maintaining and increasing the availability of Nitrogen in the soil is the main focus in efforts to increase agricultural productivity. The purpose of writing this article is to provide information on the potential of various compost and biochar materials as soil improvers. The method used is a literature review to collect library data related to compost and biochar. Various sources of compost and biochar materials have diverse nutrient content that has the potential to increase the availability of Nitrogen in the soil. The application of compost to the soil contributes to the Nitrogen cycle through the mineralization and immobilization processes, and Nitrogen absorption by biochar can reduce Nitrogen leaching. The provision of various types of compost or a combination with biochar is recommended to maintain nutrient balance and improve soil quality. Future research can explore further to determine the optimal strategy for the application of compost and biochar to support more productive and sustainable agriculture.
Keywords: Ammonium, Fertilization efficiency, Nitrate, Organic waste, Compost, Biochar

ABSTRAK

Nitrogen merupakan unsur hara penting dalam tanah yang sering kali menjadi faktor pembatas dalam praktik pertanian karena cenderung mudah hilang dari tanah melalui berbagai proses alamiah. Mempertahankan serta meningkatkan ketersediaan Nitrogen di tanah menjadi fokus utama dalam usaha untuk meningkatkan produktivitas pertanian. Tujuan dari penulisan artikel ini yaitu untuk memberikan informasi mengenai potensi berbagai bahan kompos dan biochar sebagai pembenah tanah. Metode yang digunakan adalah tinjauan literatur untuk mengumpulkan data pustaka terkait dengan kompos dan biochar. Berbagai sumber bahan kompos dan biochar memiliki kandungan unsur hara beragam yang memiliki potensi untuk meningkatkan ketersediaan Nitrogen di dalam tanah. Aplikasi kompos di tanah berkontribusi pada siklus Nitrogen melalui proses mineralisasi dan imobilisasi, serta adsorpsi Nitrogen oleh biochar dapat mengurangi pencucian Nitrogen. Pemberian berbagai jenis kompos maupun kombinasi dengan biochar disarankan untuk menjaga keseimbangan unsur hara dan meningkatkan kualitas tanah. Penelitian mendatang dapat mengeksplorasi lebih dalam untuk menentukan strategi optimal pada penerapan kompos dan biochar guna mendukung pertanian yang lebih produktif dan berkelanjutan.
Keyword: Amonium; Efisiensi pemupukan; Limbah organik; Nitrat, Kompos, Biochar

1. Introduction

Agricultural systems are highly dependent on external factors, particularly in providing nutrients. Synthetic fertilization in conventional farming systems is often applied intensively to increase crop productivity; however, this practice adversely affects soil quality. The increasing use of synthetic fertilizers, especially Nitrogen, has altered the global Nitrogen cycle over the past few decades (Mahmud et al., 2021). The Nitrogen cycle consists of six processes: ammonification, Nitrogen fixation, nitrification, denitrification, anaerobic ammonium oxidation (anammox), and assimilation (Mosley et al., 2022). Fertilizer application often exceeds plant requirements, leading to Nitrogen losses. Nitrate (NO_3^-) leaching, followed by ammonia (NH_4^+) volatilization, are the dominant forms of Nitrogen loss (Wang et al., 2023). Nevertheless, the use of sustainable organic materials has become increasingly common to ensure optimal crop yields and reduce Nitrogen losses from soils, thereby enhancing Nitrogen availability. Organic soil amendments are often applied directly to the soil surface without additional processing to minimize nutrient leaching.

In recent years, the utilization of organic materials or agricultural residues and other resources as soil amendments has been widely adopted to improve soil physical, chemical, and biological properties, thereby creating optimal conditions for crop production and productivity (Aytenew & Bore, 2020). Organic soil amendments such as compost and biochar can enhance soil physical, chemical, and biological properties, which in turn reduce Nitrogen losses from soil, meeting the needs for plant growth and development (Shinde et al., 2019). Compost is a type of fertilizer derived from the decomposition of organic matter (Suyudi & Kartiwa, 2020). Biochar is a carbon-rich soil amendment produced through the conversion of organic materials—such as agricultural biomass waste—via incomplete combustion or limited oxygen supply, a process known as pyrolysis (Liu et al., 2022).

Soil amendments serve several important functions: they can improve soil physical, chemical, and biological properties; maintain soil pH; increase water-holding capacity, infiltration, percolation, and permeability; create a healthy environment for beneficial microorganisms and earthworms; enhance soil aeration; restore degraded soils due to improper cultivation practices; supply essential nutrients to improve soil fertility and promote healthier plant growth with higher yields; reduce soil compaction; and enhance overall soil productivity (Shinde et al., 2019). Several studies have mentioned that compost, as a soil amendment, can increase the organic matter content in soil, thereby maintaining and improving soil fertility (Nurhayati, 2018). Research by Rubin et al. (2020) reported that biochar can reduce cumulative leaching of ammonium (NH_4^+) and nitrate (NO_3^-).

The purpose of this paper is to analyze the potential of various compost and biochar materials in improving soil quality and enhancing Nitrogen availability effectively. Through a comprehensive literature review, this paper explores the mechanisms and effectiveness of these materials as soil amendments, focusing on efforts to minimize Nitrogen losses that frequently occur in conventional agricultural practices.

2. Materials and Methods

The research method employed in this study is a literature review, which involves collecting library data, reading, analyzing, and synthesizing the results into written form. This paper draws on various literature sources, most of which were published within the last decade, utilizing electronic databases of Indonesian journals indexed in SINTA (Science and Technology Index), as well as international databases with moderate reputations such **as** PubMed and NCBI, and high-reputation databases such as Scopus and ScienceDirect.

The selected journals primarily focus on research in soil science, agriculture, environmental science, and agro-environmental studies. The search keywords were carefully chosen to identify the potential of various raw materials used in the production of compost and biochar as soil amendments.

This study follows a structured literature review approach as described by Snyder (2019), involving three main stages: (1) planning and defining research questions; (2) searching, screening, and selecting relevant studies; and (3) analyzing, synthesizing, and reporting findings. This approach enables a comprehensive understanding of existing research trends, theoretical foundations, and practical applications related to compost and biochar for soil improvement.

3. Result and Discussion.

3.1 Soil Amendments

Soil amendments refer to substances that are added to the soil to improve its quality and have a positive impact on agricultural productivity (Garbowski et al., 2023). A soil amendment product must contain a specific amount of essential nutrients to ensure that it meets the required quality standards necessary for enhancing overall agricultural productivity. In Indonesia, the minimum technical requirements for soil amendments are regulated by the government under the Minister of Agriculture Decree Number 261/KPTS/SR.310/M/4/2019**.** The composition of compost products used as soil amendments includes the following parameters: a minimum solid organic carbon (C-organic) content **of** 15%**,** a C/N ratio ≤ 25**,** moisture content of 8–20%**,** and pH between 4 and 9. For micronutrients, the limits are as follows: total Fe ≤ 15,000 ppm**,** available Fe **≤** 500 ppm**,** Zn ≤ 5,000 ppm, and for heavy metals: As ≤ 10 ppm**,** Hg ≤ 1 ppm**,** Pb ≤ 50 ppm**,** Cd ≤ 2 ppm**,** Cr **≤** 180 ppm**,** and Ni ≤ 50 ppm**.** The quality standard for biochar, on the other hand, requires a total carbon content between 30% and >60%, and a pH range of 7–12**.**

3.2 Compost as a Soil Amendment

Compost is the final product of the composting process. Composting is a biological process that converts degradable organic materials under aerobic conditions by microorganisms into a stable product that is safe for use in agricultural cultivation (Ho et al., 2022). The application of compost as a soil amendment can increase the organic matter content in the soil, enhance water-holding capacity, improve nutrient availability for plants, and promote soil microbial population growth (Lim et al., 2018). Various types of organic materials can be used as feedstock for compost production (Table 1).

Table 1. Nutrient Composition of Compost from Various Organic Sources

Type of Compost	Organic C (%)	Total N (%)	C/N Ratio	Total P_2O_5 (%)	Total K_2O (%)	Reference
Water hyacinth (*Eichhornia crassipes*)	26.10	1.13	23.31	0.50	1.45	Ismayanti et al., 2020
Cattle manure	36.21	1.06	24.16	1.27	0.34	Rosniawaty et al., 2021
Azolla microphylla	42.95	3.94	11.00	1.21	4.88	Lestari et al., 2019
Rice straw	27.84	1.69	16.50	0.23	5.04	Muliarta, 2020
Leaf litter	7.45	0.50	15.00	0.23	0.13	Rosniawaty et al., 2017
Guano	24.45	4.89	5.00	1.65	1.89	Hayanti et al., 2014

Table 1 presents the nutrient composition of compost derived from various organic materials. The composition varies significantly depending on the source material. Compost derived from *Azolla microphylla* shows the highest organic carbon content (42.95%) and total Nitrogen (3.94%) with a relatively low C/N ratio (11), indicating rapid decomposition and high nutrient availability. Guano compost also contains high Nitrogen (4.89%) and phosphorus (1.65%), making it a rich nutrient source, though its very low C/N ratio (5) suggests a fast mineralization rate and potential Nitrogen loss if not properly managed.

In contrast, compost from leaf litter contains the lowest nutrient values, particularly in total Nitrogen (0.50%) and potassium (0.13%), implying limited fertilization potential unless combined with other organic sources. Cattle manure and rice straw represent more balanced compost materials, providing moderate C/N ratios (16–24) that are suitable for maintaining soil organic matter and ensuring gradual nutrient release.

Water hyacinth compost offers a medium C/N ratio (23.31) and moderate levels of phosphorus and potassium, making it beneficial as a supplementary organic amendment. Overall, these results indicate that combining different organic feedstocks can optimize compost nutrient profiles to improve soil fertility and structure, as also supported by previous studies (Garbowski et al., 2023; Lim et al., 2018).

Table 2. Effects of Compost on Soil Nitrogen Availability and Plant Growth

Type of Compost	Effect on Soil Nitrogen Availability	Effect on Plants	Reference
Rice straw compost	Increased soil Nitrogen content from 0.093% to 0.111%.	Enhanced Nitrogen uptake and increased rice plant height from 87.10 cm to 93.62 cm.	Kaya, 2013
Aleurites moluccanus (candlenut) leaf compost	Increased total Nitrogen from low status (1.16%) to (2.12%).	–	Puspita et al., 2023
Oil palm empty fruit bunch (EFB) compost	Increased total soil Nitrogen compared to the control (1.82%) at a 15 ton/ha application rate (1.99%), and increased total population of *Azotobacter* sp.	Produced higher *pakcoy* (Brassica rapa L.) biomass compared to untreated control.	Setiawati et al., 2022
Azolla compost	Compost containing 3–5% Nitrogen provided readily available Nitrogen during the early vegetative growth stage.	Increased plant height and yield in long bean (*Vigna unguiculata*) plants.	Ramadhani et al., 2020
Sugarcane bagasse compost	Increased total soil Nitrogen compared to control (1.82%) with 20 ton/ha application (1.90%).	Increased Nitrogen uptake from 26.44 mg/plant (control) to 30.44 mg/plant.	Setiawati et al., 2022

Table 2 summarizes the effects of different compost materials on soil Nitrogen availability and plant growth. The data indicate that compost application generally enhances soil Nitrogen content and improves plant performance. The application of rice straw compost significantly increased soil Nitrogen and plant height, demonstrating its potential as a Nitrogen source for cereal crops. Candlenut leaf compost also improved soil Nitrogen content, suggesting its suitability for use in organic farming systems rich in lignocellulosic residues. Meanwhile, oil palm empty fruit bunch (EFB) compost and sugarcane bagasse compost not only elevated total soil Nitrogen but also enhanced microbial populations such as *Azotobacter sp.*, which play a vital role in biological Nitrogen fixation. Similarly, Azolla compost, with its high Nitrogen content (3–5%), effectively supported Nitrogen availability during the vegetative phase, promoting vigorous growth and higher yields in legume crops. Overall, these findings indicate that compost derived from agricultural residues can substantially contribute to Nitrogen cycling in the soil–plant system, reducing the need for synthetic Nitrogen fertilizers and supporting sustainable agricultural productivity (Kaya, 2013; Setiawati et al., 2022; Puspita et al., 2023).

The results presented in Table 2 demonstrate that compost application plays a crucial role in enhancing soil Nitrogen availability and improving plant growth performance. This improvement is primarily attributed to the mineralization of organic Nitrogen compounds contained in compost materials, which are gradually converted into inorganic forms—ammonium (NH_4^+) and nitrate (NO_3^-)—that can be readily absorbed by plants (Saha et al., 2008). The decomposition process of compost releases Nitrogen through microbial activity, particularly by heterotrophic microorganisms that decompose complex organic matter such as proteins and amino acids. This process not only increases available Nitrogen but also improves soil microbial diversity and enzymatic activity, contributing to more efficient nutrient cycling (Liu et al., 2022).

Composts with a balanced C/N ratio (10–25), such as rice straw, cattle manure, or sugarcane bagasse compost, provide a slow and steady Nitrogen release pattern, which minimizes Nitrogen losses through leaching or volatilization (Shinde et al., 2019). Conversely, composts with a very low C/N ratio (e.g., guano or Azolla compost) release Nitrogen rapidly, which may benefit short-term plant growth but could lead to nutrient losses if not managed properly.

Furthermore, the presence of beneficial microorganisms such as *Azotobacter sp.* in compost-treated soils enhances biological Nitrogen fixation, contributing additional Nitrogen to the soil–plant system (Setiawati et al., 2022). These microorganisms convert atmospheric Nitrogen into plant-available forms, thereby reducing dependence on synthetic Nitrogen fertilizers (Zhang et al., 2020). Improved Nitrogen availability has a direct effect on plant physiological performance. Higher Nitrogen levels stimulate chlorophyll synthesis, enhance photosynthetic efficiency, and promote vegetative growth, as observed in rice, pakcoy, and long bean plants treated with compost (Kaya, 2013; Ramadhani et al., 2020). Moreover, compost also enhances soil structure and moisture retention, which further supports root development and nutrient uptake efficiency (Aytenew & Bore, 2020).

Overall, the integration of compost derived from agricultural residues such as rice straw, oil palm empty fruit bunches, and sugarcane bagasse represents a sustainable strategy to improve Nitrogen management in agricultural systems. By optimizing the decomposition rate and microbial balance, compost application can sustain soil fertility, reduce environmental Nitrogen losses, and enhance crop productivity in the long term. Biochar is a product that does not directly supply nutrients to plants but plays a significant role in enhancing the plant's ability to absorb water and nutrients (Garbowski et al., 2023). In general, biochar possesses a highly porous structure (Figure 1) and a large specific surface area, which contribute to its high water-holding capacity and cation exchange capacity (CEC). These properties enable biochar to adsorb soil cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and ammonium (NH_4^{+}), thereby improving nutrient availability and supporting plant growth (Mehmood et al., 2020).

The incorporation of biochar into agricultural soils can improve soil physical and chemical properties by enhancing soil aggregation, porosity, and moisture retention. Biochar also reduces water evaporation from the soil surface, thus maintaining soil moisture for longer periods. Furthermore, biochar creates a favorable habitat for soil microorganisms, promoting microbial colonization and biological activity that are essential for nutrient cycling and soil fertility (Lehmann & Joseph, 2015). Consequently, biochar application is recognized as an effective strategy for improving soil water and nutrient retention, enhancing plant productivity, and supporting the sustainability of agricultural systems, especially in degraded or nutrient-poor soils (Zhao et al., 2022).

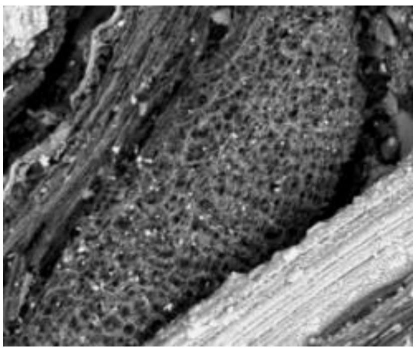

Figure 1. Surface morphology of rice straw biochar under Scanning Electron Microscope (SEM) (Source: Selvarajh et al., 2023)

The image shows the microstructural morphology of rice straw biochar observed under a Scanning Electron Microscope (SEM). The biochar exhibits a highly porous and irregular surface structure, characterized by a network of interconnected pores and cavities. These pores are remnants of the original plant tissue and cellular architecture of rice straw that were preserved during the pyrolysis process. The porous structure significantly increases the specific surface area of the biochar, providing abundant sites for water and nutrient adsorption, as well as serving as a habitat for beneficial soil microorganisms. Such characteristics are essential for improving soil aeration, water retention, and cation exchange capacity (CEC).

The rough and layered texture seen in the image also indicates a heterogeneous carbon matrix, which contributes to biochar's high stability and slow decomposition rate in soil, making it an effective and long-lasting soil amendment for enhancing soil fertility and Nitrogen retention (Selvarajh et al., 2023; Mehmood et al., 2020).

Table 3. Sources of Biochar and Their Response to Soil Nitrogen

Biochar Source	Temperature (°C)	pH	Elemental Composition	Specific Surface Area (m^2 g^{-1})	Response	Reference
Rice straw	300–400	9.52	–	–	Increased NH_4^+ and NO_3^- content at a depth of 20–60 cm	Feng et al., 2021
Rice husk	600	–	C: 40.97%, N: 0.47%, C/N: 109	179	Adsorbed NO_3^- up to 2.1 mg g^{-1} and NH_4^+; reduced NH_4^+ leaching by 11% and NO_3^- by 23%	Pratiwi et al., 2016
Corn straw	450	9.2	C: 66%, N: 1.27%, C/N: 51.96	8.87	Enhanced nitrate reductase activity, decreased urease activity, and increased soil C/N ratio	Wang et al., 2024
Wood	550	8.21	C: 50.80%, N: 0.13%, C/N: 390.7	–	Increased NO_3^- concentration and decreased NH_4^+ concentration	Bai et al., 2015
Tobacco stalk	450	9.98	C: 21.52%, N: 0.69%, C/N: 34.21	145.21	Enhanced soil N retention (0–20 cm depth) by promoting ammonia assimilation, reducing NO_3^- leaching, and improving N uptake	Yang et al., 2024

The data presented in Table 3 demonstrate that the physicochemical properties of biochar, such as pyrolysis temperature, pH, carbon-to-Nitrogen (C/N) ratio, and specific surface area, strongly influence its effectiveness in regulating soil Nitrogen (N) dynamics.

Biochar derived from rice straw at relatively low temperatures (300–400°C) exhibits moderate alkalinity and enhances NH_4^+ and NO_3^- concentrations in the subsoil layer (20–60 cm), suggesting its potential to reduce Nitrogen leaching losses (Feng et al., 2021). Meanwhile, rice husk biochar, produced at higher temperatures (600°C), shows a large surface area (179 m^2 g^{-1}) and strong adsorption capacity for nitrate and ammonium, reducing Nitrogen leaching by up to 23% for NO_3^- and 11% for NH_4^+ (Pratiwi et al., 2016).

Corn straw biochar (450°C) improves enzyme-mediated Nitrogen transformation by increasing nitrate reductase and reducing urease activity, which contributes to higher Nitrogen efficiency in soils (Wang et al., 2024). Biochar from woody materials tends to have high stability and a relatively high C/N ratio, enhancing NO_3^- retention while decreasing NH_4^+ concentration, reflecting its slow mineralization and long-term soil amendment potential (Bai et al., 2015).

Furthermore, tobacco stalk biochar demonstrates strong Nitrogen retention capacity, particularly in the topsoil (0–20 cm), through enhanced ammonia assimilation and reduced nitrate leaching, thereby promoting plant N uptake (Yang et al., 2024).

Overall, the table indicates that biochar's source material and production temperature critically determine its performance in Nitrogen retention, transformation, and availability in agricultural soils.

3.3 Future Prospects

In future projections, the potential use of various soil amendments such as compost and biochar in enhancing Nitrogen availability is highly promising. Alongside technological advancements and ongoing research, there are growing opportunities for the discovery of new natural resources that can serve as effective soil amendment materials. Innovations in composting techniques and biochar production processes are expected to improve the efficiency and quality of the final products, thereby providing greater and more sustainable impacts on soil Nitrogen availability.

Moreover, the integration of diverse technologies and management approaches in soil and agricultural **systems** may lead to more optimal outcomes. Combining various types of compost is recommended to maintain nutrient balance, while the combined application of compost and biochar has shown potential in further enhancing Nitrogen availability. This is supported by Lim et al. (2018), who reported that compost application increases overall soil organic carbon and dissolved Nitrogen contents, whereas biochar addition helps reduce nutrient leaching and improve nutrient retention within the soil matrix.

Conclusion

Compost and biochar play crucial roles in improving soil Nitrogen availability and soil fertility. Compost enhances soil organic matter, microbial activity, and nutrient supply, thereby supporting plant growth and Nitrogen uptake. Meanwhile, biochar—through its porous structure and high surface area—effectively retains ammonium and nitrate, reduces Nitrogen leaching, and improves soil structure.

The combination of compost and biochar provides synergistic benefits by balancing nutrient availability and enhancing Nitrogen cycling efficiency. Future agricultural practices should focus on optimizing composting and biochar production technologies to achieve sustainable Nitrogen management and long-term soil productivity.

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