The potential of rice husk-derived biochar as a bio-silica source in the agricultural area of Tuban, East Java

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Abstract. Rice husk, accounting for about 20% of total paddy biomass, remains an underutilized agricultural residue despite its abundance. This study explores the conversion of rice husk into biochar through pyrolysis under limited oxygen conditions, focusing on biomass yield and physicochemical characteristics for agronomic use. Biochar is valued for its carbon content, soil-enhancing ability, and contribution to sustainable agriculture. Biomass analysis of rice showed an aboveground yield of 95.06 g per plant (grain: 43.20 g; straw: 51.86 g) and belowground biomass of 39.06 g (root). Soil nutrients included nitrogen (0.41%), phosphorus (53.8 mg/100 g), potassium (137.40 mg/100 g), and organic carbon (4.54%), influencing biomass accumulation and plant physiology. Pyrolysis at 250 °C was conducted using a controlled furnace, and the resulting biochar's composition was analyzed via X-Ray Fluorescence (XRF). The biochar contained high silica (SiO_2: 80.03%), with P_2O_5 (3.07%), K_2O (10.38%), CaO (5.16%), and trace elements such as MnO, Fe_2O_3, CuO, ZnO, and ZrO_2. It also exhibited a water holding capacity of 81.09% and a pH of 6.23, indicating its potential as a soil amendment and nutrient carrier. These results demonstrate the dual role of rice husk biochar as a bio-silica source and soil enhancer, promoting sustainable residue-based agriculture in East Java.

1 Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops and a top priority in the agricultural sector. As a major food commodity, rice plays a vital role as a staple food source for most of the Indonesian population and throughout the Asian region. In 2024, Indonesia's rice production reached 53,142,726 tons, with East Java Province being the largest contributor, producing approximately 9,270,435 tons. One of the regions that contributed significantly to this production is Tuban, with a total yield of 523,067 tons in the same year [1]. This achievement indicates that Tuban possesses strong agricultural potential and plays an important role in supporting East Java as a national rice granary.

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The abundant rice production in Tuban has implications for the increasing volume of agricultural waste, particularly rice husks, which account for about 20% of the total grain weight [2]. Generally, farmers still manage rice husk waste through open-field burning, and the resulting ash is rarely utilized further. This practice causes various negative environmental impacts, such as air pollution, increased greenhouse gas emissions, health risks, and damage to beneficial soil microbial communities that play a crucial role in maintaining soil fertility [3]. According to [2], this condition occurs due to a lack of understanding in managing rice husk waste into economically valuable products, such as biochar, which has great potential as a biosilica source. Rice husks are known to contain high amounts of silica after undergoing calcination. The calcination process of rice husks (RH) produces rice husk ash (RHA), which consists mostly of SiO_2 (approximately 93%) along with small amounts of other metal oxides [4].

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass, such as rice husks. In agriculture, biochar has been proven to provide numerous benefits as a soil conditioner, including improving soil quality, nutrient retention, and water-holding capacity, while also contributing to the long-term sustainability of agricultural land [5]. Rice husks used as the main feedstock for biochar are known to have a high silica content. Silica plays an essential role as a vital nutrient for plants, particularly for the *Gramineae* group such as rice, maize, sorghum, and sugarcane, which are known as natural silica accumulators. In these plants, silica is absorbed through the roots and deposited in the epidermal cell walls, enhancing leaf rigidity, strengthening stems, reducing water loss, and increasing resistance to both biotic and abiotic stresses. Moreover, the physical abundance of silicates also plays an essential role in improving plant productivity [6].

Considering this potential, further studies are needed to explore the chemical characteristics and potential of rice husk–based biochar, particularly in agricultural lands of Tuban. Such studies are essential to identify the elemental composition of biochar that could function as a soil conditioner (ameliorant) as well as a sustainable bio-silica source to enhance agricultural productivity and long-term sustainability in the region.

2 Methods

2.1 Sampling Location

This research was conducted in Tuban, East Java, Indonesia, a region known for its extensive rice cultivation and high productivity. Soil sampling was carried out in Jenu District, which represents the typical agricultural soil of Tuban. The sampling site is geographically located at 6°52′02.95″ South latitude and 112°01′26.22″ East longitude.

2.2 Soil Chemical Analysis

Soil samples were air-dried, ground, and sieved through a 2 mm mesh prior to analysis. The chemical parameters analyzed included total nitrogen (N), total phosphorus (P), total potassium (K), and organic carbon (C-organic). Total nitrogen was determined using the Kjeldahl method, total phosphorus was analyzed using the Bray I extraction method followed by spectrophotometric measurement, total potassium was quantified by flame photometry, and organic carbon was determined using the Walkley–Black method. The results were interpreted based on the Balai Perakitan dan Pengujian Tanah dan Pupuk (2023) [7].

2.3 Rice Biomass

Plant biomass was divided into two components, namely aboveground biomass (grains and straw) and belowground biomass (roots). The rice plants were harvested at the physiological maturity stage, then separated into plant components and oven-dried at 80°C until a constant dry weight was achieved. The dry weight values were recorded and expressed in grams per plant, and the ratio between aboveground and belowground biomass was calculated to evaluate the carbon allocation pattern of the plants.

2.4 Characteristics of biochar

Biochar was produced through the slow pyrolysis of dried rice husks under limited oxygen conditions. The process was carried out in a laboratory-scale furnace at a temperature of 250°C for 4 hours. The produced biochar was then cooled, ground, and sieved to obtain particles smaller than 2 mm prior to characterization.

The physical and chemical properties of the rice husk biochar were subsequently analyzed. The pH was measured in a 1:10 biochar-to-water suspension using a calibrated pH meter. The water holding capacity (WHC) was determined gravimetrically to measure the amount of water retained per unit weight of biochar. Elemental composition was analyzed using X-ray Fluorescence (XRF) spectroscopy to determine the oxide contents of major elements, including SiO_2, K_2O, CaO, P_2O_5, MnO, Fe_2O_3, CuO, ZnO, and ZrO_2. The analysis emphasized silica (SiO_2) dominance to evaluate its potential as a bio-silica source for soil improvement and sustainable agricultural applications.

3 Results and Discussion

3.1 Soil Chemical Analysis

The research included an analysis of environmental conditions in Tuban, conducted through testing of soil characteristics, with the results presented as follows.

Table 1. Results of soil chemical analysis

Properties	Results	Criteria
N-total (%)	0,41± 0,08	Moderate*
P-total (mg/100g)	53,8 ± 6,94	High*
K-total (mg/100g)	137,40 ± 16,00	Very High*
C-organic (%)	4,54 ± 0,60	High*

*Balai Perakitan dan Pengujian Tanah dan Pupuk (2023)

Soil analysis in the agricultural area of Tuban indicates that the nutrient content is relatively good to support rice growth. The nitrogen content of 0.41% falls into the moderate category, which is sufficient to sustain the vegetative growth phase of the plant. The phosphorus content of 53.8 mg/100g is classified as high, indicating efficient fertilization and soil pH conditions that favor the availability of this element. The potassium level, measured at 137.40 mg/100g, falls into the very high category, reflecting adequate nutrient availability to support plant physiological processes [8]. In addition, the organic carbon content of 4.54% is also considered high, showing that the soil fertility level is good, with a strong ability to retain moisture and support microbial activity optimally [9].

3.2 Rice Biomass

Plant biomass reflects the plant's ability to absorb and utilize water and nutrients while indicating the efficiency of converting nutrients into stored dry energy. After water loss, biomass represents the final outcome of the plant's metabolic processes. In this study, rice biomass was partitioned into grains, straw, and roots. The following graph illustrates the average dry weight of each component.

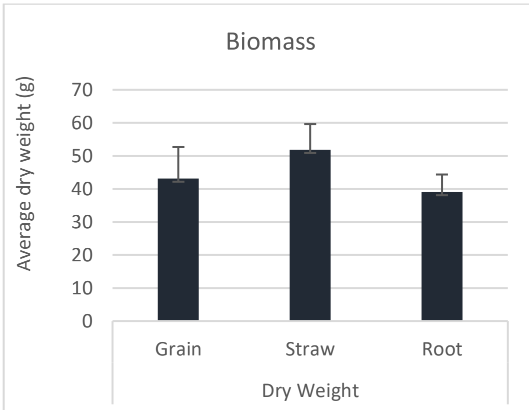

Fig. 1. Average Rice Plant Biomass

Plant biomass can be categorized into two main parts based on growth location: aboveground biomass (plant parts above the soil surface) and belowground biomass (parts below the soil surface). In this study, the aboveground components included straw and grains, while the belowground component was represented by roots. The total dry weight of aboveground biomass reached 95.06 g, while belowground biomass was 39.06 g. The dominance of aboveground biomass reflects the high allocation of photosynthates to the upper plant parts, which is closely related to photosynthetic efficiency, nutrient uptake, and water availability during the growth phase. Straw, as the largest component, indicates optimal vegetative activity in stem and leaf formation, while the significant contribution of grains demonstrates successful resource allocation toward the generative phase. The balance between these components indicates good growth capacity and plant productivity under favorable environmental conditions [10].

3.3 Characteristics of Rice Husk Biochar

3.3.1 pH of Rice Husk Biochar

Rice husk biochar with a pH of 6.23 is slightly acidic to neutral, making it ideal for improving soil chemical properties without causing excessive alkalinization. The pyrolysis process at 250°C preserves –COOH and –OH functional groups that maintain chemical stability. Its low ash content makes it effective in adsorbing heavy metals and retaining nutrients. A moderate pH supports soil microbial activity and enhances water use efficiency. Overall, this biochar is stable, environmentally friendly, and suitable for sustainable agriculture [11].

3.3.2 Water Holding Capacity of Rice Husk Biochar

Rice husk biochar has a water holding capacity (WHC) of 81.09%, indicating a high ability to retain soil moisture. Its wide porosity and hydrophilic functional groups enhance water absorption and retention in the root zone. The porous structure allows water to be stored longer and released gradually according to plant needs. These characteristics make biochar effective in maintaining water availability, especially in sandy or dry soils. With high WHC, rice husk biochar serves as a natural water-binding agent that improves water use efficiency and increases plant tolerance to drought [12].

3.3.3 Chemical Element Components of Rice Husk Biochar

The chemical composition of rice husk biochar was analyzed using the X-Ray Fluorescence (XRF) method to evaluate the content of metal oxides and minerals in the biochar. This analysis aims to determine the potential of biochar in supplying essential nutrients and trace elements that play important roles in soil fertility and improving fertilizer use efficiency. The results of the analysis are presented in the following table.

Table 2. X-Ray Fluorescence (XRF) analysis results of rice husk biochar

Element	**Rice Husk Biochar**
	Percentage (%)
SiO_2	80,03
P_2O_5	3,07
K_2O	10,38
CaO	5,16
MnO	0,29
Fe_2O_3	0,64
CuO	0,23
ZnO	0,03
ZrO_2	0,01

Based on the results of X-Ray Fluorescence (XRF) analysis, rice husk biochar contains nine main oxide compounds SiO_2, K_2O, CaO, P_2O_5, MnO, Fe_2O_3, CuO, ZnO, and ZrO_2, with silica (SiO_2) as the dominant component, reaching approximately 80%. The high silica content reflects the typical characteristics of rice husk biochar rich in amorphous silica and shows great potential as a soil ameliorant to improve the physical, chemical, and biological properties of soil [13]. Silica plays an important role in strengthening plant tissues, enhancing resistance to drought and pathogens, and improving water-use efficiency [14]. In the soil, silica helps reduce the toxicity of heavy metals such as aluminum and iron, improves aeration and pH, and increases cation exchange capacity (CEC). Overall, the high silica content makes rice husk biochar an effective and environmentally friendly soil conditioner that supports sustainable agriculture [15].

4 Conclusion

Rice husk biochar shows great potential as a sustainable bio-silica source. Its dominant SiO_2 content (80.03%), along with K_2O (10.38%), P_2O_5 (3.07%), and CaO (5.16%), enhances the chemical quality of the biochar. This composition contributes to strengthening plant tissues, improving structural integrity and cell turgidity, and increasing nutrient retention in the soil. With a high WHC (81.09%) and pH of 6.23, the biochar functions effectively as a soil ameliorant. Therefore, rice husk biochar has strong potential to support the development of bio-silica-based sustainable agriculture in Tuban, East Java.

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