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Improving water use efficiency and yield in shallot (*Allium cepa* L.) cultivation using rice husk biochar application

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ABSTRACT

Biochar is considered a potential eco-friendly organic amendment to enhance soil characteristics, increase water holding capacity, and improve water use efficiency (WUE) in agricultural land with limited water conditions. Rice straw, a main residue of rice milling, has significant promise for biochar production. This study aimed to (1) examine the potential of rice husk biochar (RHB) application in increasing water holding capacity (WHC) and improving water use efficiency (WUE); (2) determine the optimal dosage of RHB to improve shallot yields. Conducted through a controlled greenhouse experiment in Kuningan Laboratory, Universitas Gadjah Mada, Yogyakarta, the soil samples of the study were collected from hilly areas in Nawungan Village, Selopamioro, Bantul Regency, Yogyakarta. This study used RHB with a pyrolysis temperature of 550 °C in four application doses, namely without RHB, B5 (5 ton ha^{-1}), B10 (10 ton ha^{-1}), and B15 (15 ton ha^{-1}). RHB characteristics were analyzed using SEM-EDX, while water distribution and percolation were evaluated using visual and volumetric methods. The results of this study found that RHB can provide mesopores with the potential to enhance the soil's ability to hold water through capillary force, thereby preventing water from easily percolating and moving vertically into the soil profile. RHB doses of up to 15 ton ha^{-1} reduced water percolation by 25.9%, increased water holding capacity in the soil at various pF, increased yield by 91.78% compared to without RHB application, and improved actual water use efficiency (WUE), irrigation water use efficiency (IWUE), crop water use efficiency (CWUE) values by 87.44%, 92.87%, 92.37% respectively compared to without RHB application. Overall, the application of RHB improved water use efficiency and yield in shallot (*Allium cepa* L.) cultivation, suggesting its potential for ecologically sustainable agriculture on rainfed agricultural land.

Keywords: drip irrigation, rice husk biochar, shallot, soil, water use efficiency.

INTRODUCTION

Rainfed agricultural land in hilly areas often poses threats of water limitations during the dry season for irrigation purposes. Global warming has exacerbated the problem of water shortages in several areas, including hilly regions (Salehi, 2021). The lack of water irrigation sources often has a significant impact on agricultural practices, resulting in suboptimal yields and even crop failure (Mondol et al., 2022). Although farmers have implemented adaptation strategies by storing water reserves in small reservoirs for irrigation purposes, maintaining the availability of irrigation water throughout the cultivation season and anticipating prolonged droughts to fulfill plant water needs is very important (Mioduszewski, 2012; Casadei et al., 2019). Increasing water use efficiency is an effective strategy to overcome the challenges faced by agricultural water use.

Utilizing local agricultural waste, such as rice husk, as a raw material for making biochar as a soil amendment is a promising alternative to improve water use efficiency in an environmentally friendly manner. Biochar derived from rice husk has the potential to increase water holding capacity (WHC) and improve actual water use efficiency (WUE) in agricultural practices. Studies by Wu et al. (2022) and Wang et al. (2022) found that biochar application increases crop water use efficiency (CWUE) by 4.7% and irrigation water use efficiency (IWUE) by 2–9.43%. Biochar can enhance soil structure by promoting the formation of macroaggregates and mesopores, which play a crucial role in retaining water (Kim et al., 2021). Research by Liu et al. (2020) also reported that the application of biochar as an organic amendment contributed to increasing the biomass and yield of horticultural crops.

Several studies have investigated the potential of biochar in increasing the physical, chemical, and biological properties of various types of soils used for different crops. To our knowledge, this is among the first studies evaluating RHB impacts on shallot WUE and yield under controlled conditions. In addition to utilizing environmentally friendly local materials, the application of rice husk biochar (RHB) was chosen due to its effectiveness in holding water, attributed to its less hydrophobic characteristics (Zhang et al., 2014). This study aims to (1) examine the potential of RHB in increasing WHC and improving WUE; (2) determine the optimal dosage of RHB to improve shallot yields. The assessment of RHB potential was conducted through several stages, including: (1) analyzing the characteristics of RHB, (2) measuring water percolation during cultivation, (3) observing soil wetting patterns, and (4) measuring the increase in soil moisture content at several water status (pF = 2.00, pF = 2.54, and pF = 4.2), and (5) calculate the actual WUE, IWUE, and CWUE. The findings provide insight for farmers on the utilization of local organic materials, especially risk husk materials, to increase WHC and improve actual WUE, IWUE, and CWUE in areas with water-limited problems.

RESEARCH METHODS

Study location and experimental design

A pot experiment in this study was conducted in a greenhouse at Universitas Gadjah Mada from April 1 to June 15, 2024 (73 days). Each pot contained 5 kg of soil with a depth of 25 cm. Soil samples were collected from Nawungan Village, Selopamioro, Bantul. D.I. Yogyakarta (Lat: 7°57’45.508”, Long: 110°24’41.475”). Shallot bulbs (*Allium cepa* L.) of the “Bima Brebes” variety were used in this experiment. This study used a Completely Randomized Design (CRD) with varying doses of RHB (without RHB, 5 ton ha^{-1}, 10 ton ha^{-1}, and 15 ton ha^{-1}) and three replications for each treatment (Figure 1).

Fertilization was carried out 3 times during shallot cultivation. The first fertilization used cow manure as the base fertilizer, with a dose of 3750 kg ha^{-1}, and Super Phosphate 36% (SP36) at 400 kg ha^{-1} was applied before planting. The second fertilization, at 14 days after planting, used NPK blue fertilizer 16–16–16 at 40 kg ha^{-1} and NPK Complex Fertilizer 15–15–15 at 120 kg ha^{-1}. The third fertilization, 35 days after planting, utilized potassium chloride (KCl) at 120 kg ha^{-1}. The logger was used to record microclimate data (soil temperature, air temperature, and humidity) from the sensor, as well as to measure the volume of water irrigation and monitor water pressure and flow for irrigation systems. Initial soil properties for the experiment were presented in Table 1.

Rice husk biochar (RHB) characterization

RHB derived from pyrolysis at a temperature of 550 °C was analyzed with scanning electron microscopy energy dispersive x-ray (SEM-EDX). Observation using SEM-EDX not only provides a morphological picture of RHB in terms of structure, shape, and pore size, but also reveals data on the elemental content of RHB. RHB at a temperature of 550 °C was chosen based on previous studies by Ghorbani et al. (2022). Biochar production using the pyrolysis method at a temperature of 550 °C was detected as the most efficient treatment to increase porosity, water-stable

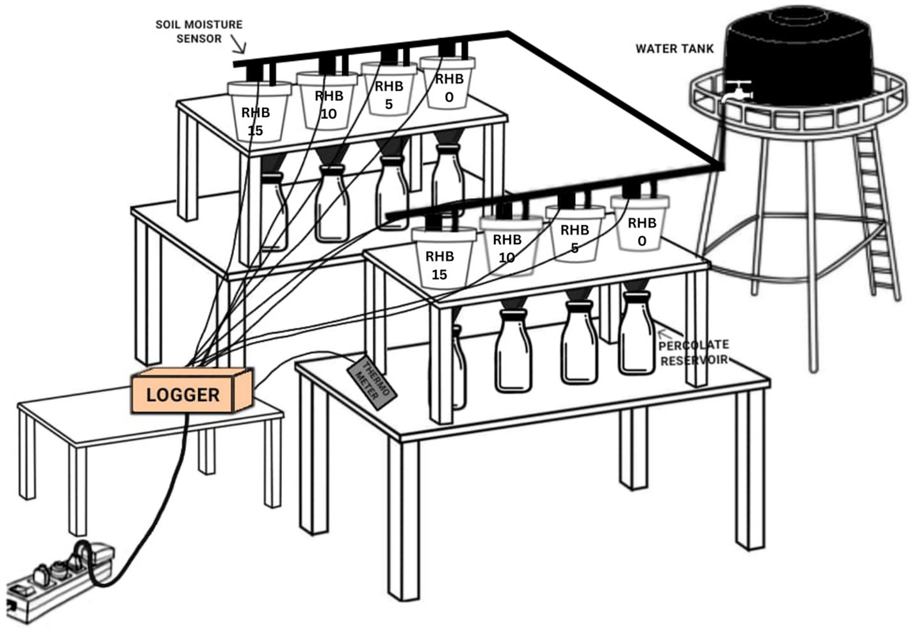

Figure 1. Illustration of research design

Table 1. Initial soil sample properties

Soil texture	Silt (%)	Clay (%)	Sand (%)	Particle density (g cm^{-3})
Clay	20.26	66.77	12.97	1.89
pH H_2O	CEC (cmol(+)/kg)	OC (%)	pF 4.2	pF 2.54
7.31 (neutral)	53.52 (very high)	1.77	48.11	38.21

Note: CEC – cation exchange capacity; OC – organic carbon.

aggregates, and available soil water content (Ghorbani et al., 2022). The pH measurement of RHB samples was carried out using a pH meter with a ratio of RHB 1:1 distilled water.

Determination of irrigation water requirements for shallot plants

Watering of shallots using SDI was maintained at available water conditions based on the automatic soil moisture sensor. Soil samples were prepared and measured using a pressure plate apparatus at pF 2.54 (1/3 bar pressure) to determine field capacity and pF 4.2 (15 bar pressure) to determine wilting point. The pF value is a representation of the water tension in the soil, which shows how strongly water is retained in soil particles. Measurement of soil samples at a pF value of 2.54 produced a soil water content of 48.40%, and a pF of 4.2 produced a soil water content of 38.21%. The sensor will trigger the valve to flow irrigation water for watering when the soil moisture condition approaches the wilting point, or a soil moisture content of 38.21%.

Previously, SDI systems calibration was performed on all installed emitters by determining the uniformity of the discharge. These results indicate that the soil moisture condition used as a reference for the SDI sensor systems must be maintained at available water conditions. The SDI system applied 150% of the available water to meet water requirements, anticipating higher evaporation conditions due to the potential of higher temperatures in the greenhouse (Priatri, 2023). Calculation of actual evapotranspiration (ETc) and potential evapotranspiration (ETo) was used to meet the water requirement for shallots. The Penman-Monteith method is used to calculate ETc and ETo with Equations 1 and 2 as follows: (Allen et al., 1998)

$$ETc = ETo \times Kc \quad (1)$$

where: ET_c – plant evapotranspiration (mm day^{-1}),
ET_o – constant evaporation (mm day^{-1}),
K_c – crop coefficient.

$$ET_o = \frac{\left[\begin{array}{c} 0.408\,\Delta\,(Rn - G) + \\ \left\{\frac{\gamma 900}{T + 273}\right\} U_2(ea - ed) \end{array} \right]}{[\Delta + \gamma(1 + 0.34U_2)]} \quad (2)$$

where: Rn – net radiation equivalent to evaporation (mm day^{-1}), G – soil heat flux (MJ/m^{-2}day^{-1}), γ – psychometric constant (kPa °C^{-1}), T – average temperature (°C), U_2 – wind speed (m s^{-1}), $(ea – ed)$ – difference between saturated and actual vapor pressure (kPa).

Effectiveness of RHB application in increasing water holding capacity

Wetting pattern simulation by flowing water into a glass box was conducted to observe water movement and distribution in the soil after RHB application. Each glass box was treated with RHB at different doses (without RHB, 5 ton ha^{-1}, 10 ton ha^{-1}, and 15 ton ha^{-1}). Wetting pattern simulations were observed for 10 minutes through watering from emitters installed on the soil. Wetting pattern visualization was illustrated manually with colorful line patterns every 30-second record. Additionally, measurements of soil moisture content at several pF values (pF = 4.2, pF = 2.54, and pF = 2.00) using the pressure plate apparatus method were conducted to determine the effectiveness of RHB for increasing WHC (Figure 2).

Water use efficiency and water percolation measurements

Actual WUE was calculated to assess the efficiency of water use that was absorbed by plants into yield using the following formula:

$$WUE = \frac{Y}{I - P} \quad (3)$$

where: Y – crop yield (kg m^{-2}), I – amount of water irrigation (L m^{-2}), P – water percolation (L m^{-2}).

In addition, irrigation water use efficiency (IWUE) and crop water use efficiency (CWUE) are calculated to assess the efficiency of water use during every growth phase during shallot cultivation to produce yield using the following formula:

$$WUE = \frac{Y}{I - P} \quad (4)$$

where: Y – crop yield (kg ha^{-1}), I – amount of water irrigation (L m^{-2})

$$CWUE = \frac{Y}{ET} \quad (5)$$

where: Y – crop yield (kg ha^{-1}), ET – evapotranspiration (Giriappa, 1983).

The yield of shallot plants in kilograms (kg) was measured after harvest, and percolation was measured throughout the shallot cultivation period. The volumetric method was used to measure water percolation with a measuring cup installed under the pot as a reservoir. Water flowed into the measuring cup after the watering process. The volume of water in the measuring cup was measured periodically as part of the water percolation data.

Statistical analysis

One-way ANOVA statistical test with Duncan's Multiple Range Test (DMRT) was used to determine the difference in average among three repetitions in each treatment at a significance level of $p < 0.05$. IBM SPSS Statistics 27 software was used to analyze the statistical test.

RESULTS AND DISCUSSION

Weather conditions in the greenhouse and plant water requirements for shallot plants

Weather data in the greenhouse during shallot cultivation were used to calculate Et_o and ET_c. In the development stage, shallot plants require more water for metabolic activities related to cell development, photosynthesis, and nutrient transport (Gimenez et al., 2005). Shallot plants require a substantial amount of water to support their growth (Robbins and Dinneny, 2018). The average air temperature was relatively stable, ranging from 30.61 °C to 33.34 °C, and the average air humidity ranged from 81.98% to 94.28% (Table 2).

The potential of rice husk biochar (RHB) in increasing water holding capacity

Characteristics of rice husk biochar (RHB)

Micro and meso pores are formed in the size range of 0.33–8.8 µm in RHB 550 °C through

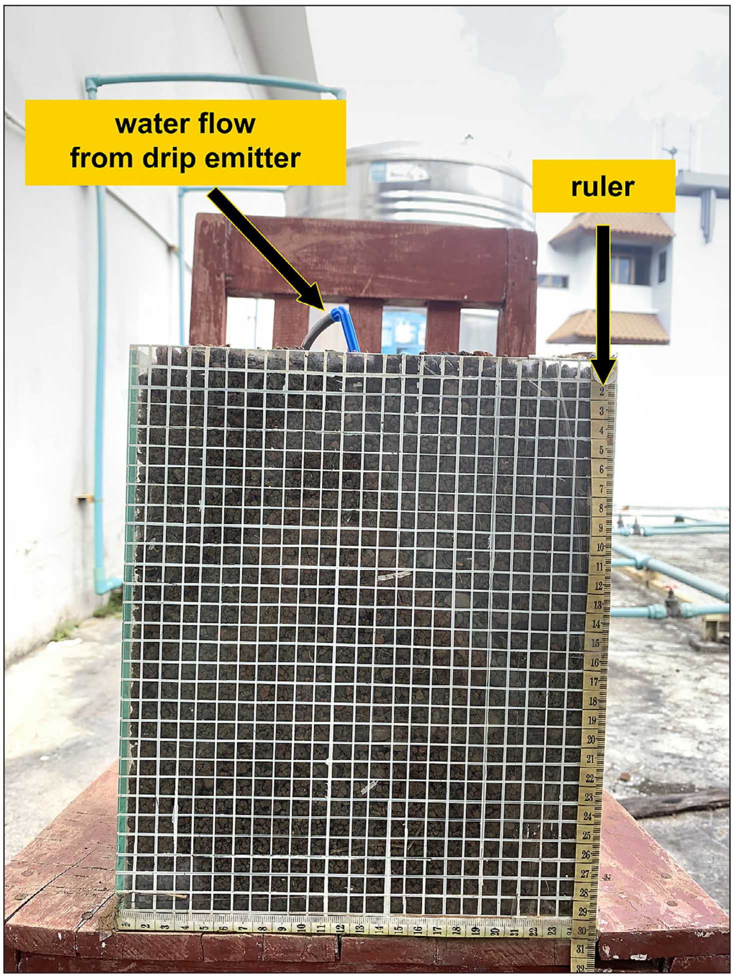

Figure 2. Visual observation of wetting pattern simulation after rice husk biochar (RHB) application

pore formation observation using SEM-EDX (Figure 3) and quantification of several elements in the form of C, O, Si, and K detected through qualitative analysis of SEM-EDX (Figure 4). Application of RHB with pH 8.71 (very alkaline) as an organic amendment mixed with soil has a positive effect on nutrient availability and the growth of shallot plants (Widowati et al., 2024). RHB production with the pyrolysis process increases the number of soil pores and the larger surface area of RHB. Based on the International Union of Pure and Applied Chemistry (IUPAC) classification, biochar pores can be divided into three categories: micro pores (< 2 μm), meso pores (2–50 μm), and macro pores (> 50 μm) (Yaashikaa et al., 2020). Meso pores in biochar play a significant role in retaining water in the soil through the capillary force mechanism, thereby maintaining soil moisture and enhancing water availability for plants (Mengistu et al., 2018; Luo et al., 2023).

Irrigation water volume and water percolation evaluation during shallot cultivation

Under the same volume of water irrigation addition, water percolation was observed in all treatments during the development phase. However, the treatment without RHB application showed the highest water percolation compared to the other treatments with RHB application. The reduction in water percolation volume with increasing RHB dose suggests that RHB plays a crucial role in retaining water. Biochar enhances the soil's ability to hold water and increases WHC due to its highly porous structure (Wang et al., 2014). A previous study by Wu et al. (2022) found that biochar increases the available water content, reaching an average of 26.8%. The reduction in water percolation of RHB at 15 ton ha^{-1} was the most optimal, reaching 25.91% compared to without RHB application (Table 3).

Table 2. Weather conditions and plant water requirements in the greenhouse during shallot cultivation

Variables	Growth phase			
	Initial	Development	Mid-season	End-season
Age (days)	25	22	13	12
T min (°C)	29.66	29.35	29.66	25.50
T max (°C)	38.48	32.38	33.45	32.08
T mean (°C)	33.44	31.37	31.74	30.61
Rh min (%)	57.38	94.97	84.88	95.00
Rh max (%)	95.00	95.00	95.00	95.00
Rh mean (%)	81.98	95.00	94.28	95.00
ETo (mm day^{-1})	2.70	2.25	1.99	1.97
Kc	0.7	1.05	1.05	0.75
ETc (mm day^{-1})	1.89	2.36	2.09	1.47

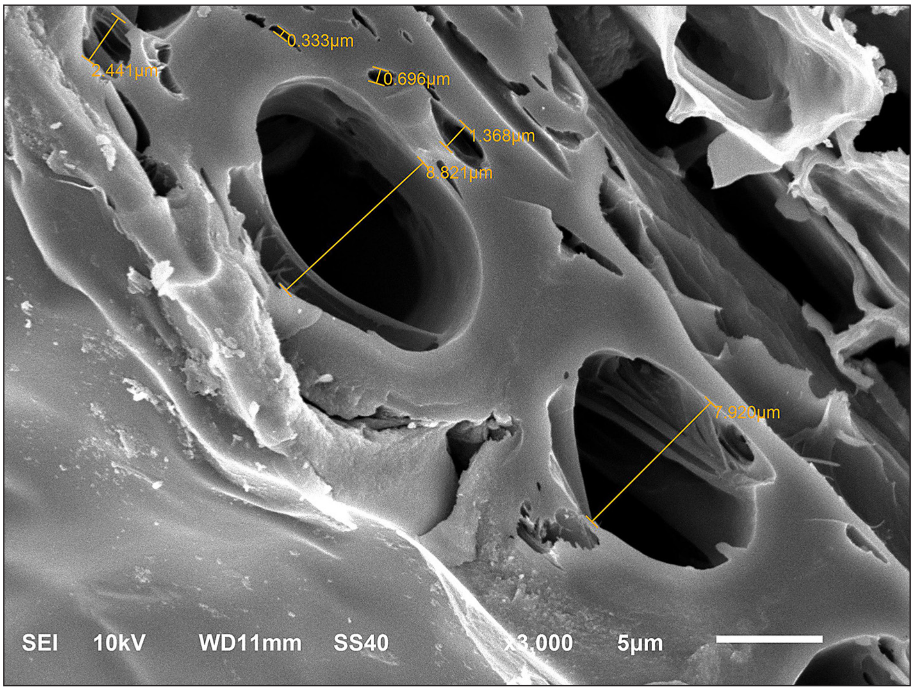

Figure 3. Pore formation in rice husk biochar (RHB) after the pyrolysis process at a temperature of 550 °C

Effectiveness of rice husk biochar (RHB) application in increasing water holding capacity

Water easily moves vertically downwards and horizontally sideways without RHB application, while water movement is relatively stable in the root zone area with RHB application. During the 10 minutes of wetting pattern simulation in the glass box, the water absorption process was rapid at the beginning of watering time, and slowed down towards the end of the watering time. This indicates that RHB slows down vertical water movement downward through water storage in large pore spaces and reduces saturated hydraulic conductivity in the soil (Chen et al., 2018; Edeh et al., 2020). This process reduces water loss from the rhizosphere through percolation, making it available to plants. RHB application up to 15 ton ha^{-1} was the most optimum in maintaining a more stable water surface and slowing down vertical water movement in the soil profile compared to RHB doses below this level (Figure 5).

The soil water content at pF 2.54 and pF 2.00 significantly increased in all doses of RHB application compared to without RHB application, while the soil water content at

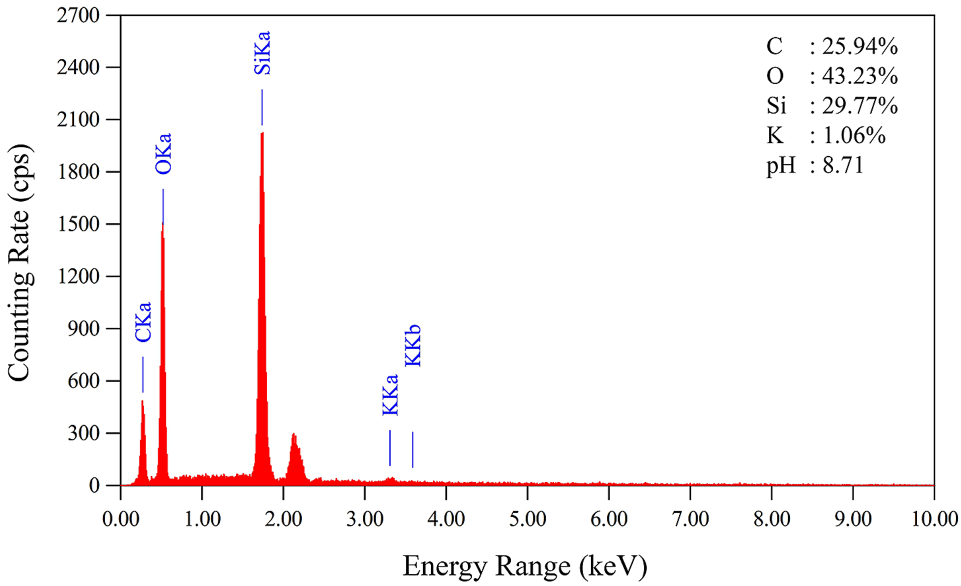

Figure 4. Elemental quantification of rice husk biochar (RHB) at 550 °C

Table 3. Irrigation water volume and water percolation during shallot cultivation at several doses of RHB

Variables	Growth phase	Without RHB	RHB5	RHB10	RHB15
Volume of water irrigation (L m^{-2})	Initial	44.58	44.58	44.58	44.58
	Development	77.53	77.53	77.53	77.53
	Mid-season	36.47	36.47	36.47	36.47
	End-season	33.43	33.43	33.43	33.43
Total water irrigation (L m^{-2})		192.01	192.01	192.01	192.01
Volume of water percolation (L m^{-2})	Initial	-	-	-	-
	Development	22.45	20.38	19.10	17.83
	Mid-season	-	-	-	-
	End-season	-	-	-	-
Total water percolation (L m^{-2})		22.45	20.38	19.10	17.83

pF 4.2 showed no differences between all the treatments. Soil with a high clay content tends to have a higher WHC due to the predominance of small pores that hold water, inhibiting plant roots from absorbing the water (Ghanbarian-Alavijeh and Millán, 2009). The increase in soil moisture content at each pF value indicates that RHB application enhances the soil's ability to retain water, thereby increasing its water holding capacity (WHC). RHB application with increasing RHB dose up to 15 ton ha^{-1} optimally increased soil moisture compared to biochar doses below it, reaching 6.17% at pF 2.00, 5.88% at pF 2.54, and 1.24 % at pF 4.2 (Table 4).

The effect of varying RHB dose on shallot growth and yield

A significant increase in yield along with the increasing RHB dose application was observed by calculating the amount of fresh root weight, fresh shoot weight, and fresh shallot bulb weight. A similar study from Qodarrohman et al. (2024) reported that the combination of RHB with compost or manure as an organic amendment may improve soil characteristics by increasing nutrient uptake by plants. Additionally, RHB enhances the soil's ability to hold water, thereby supporting water availability for plants and promoting better growth and

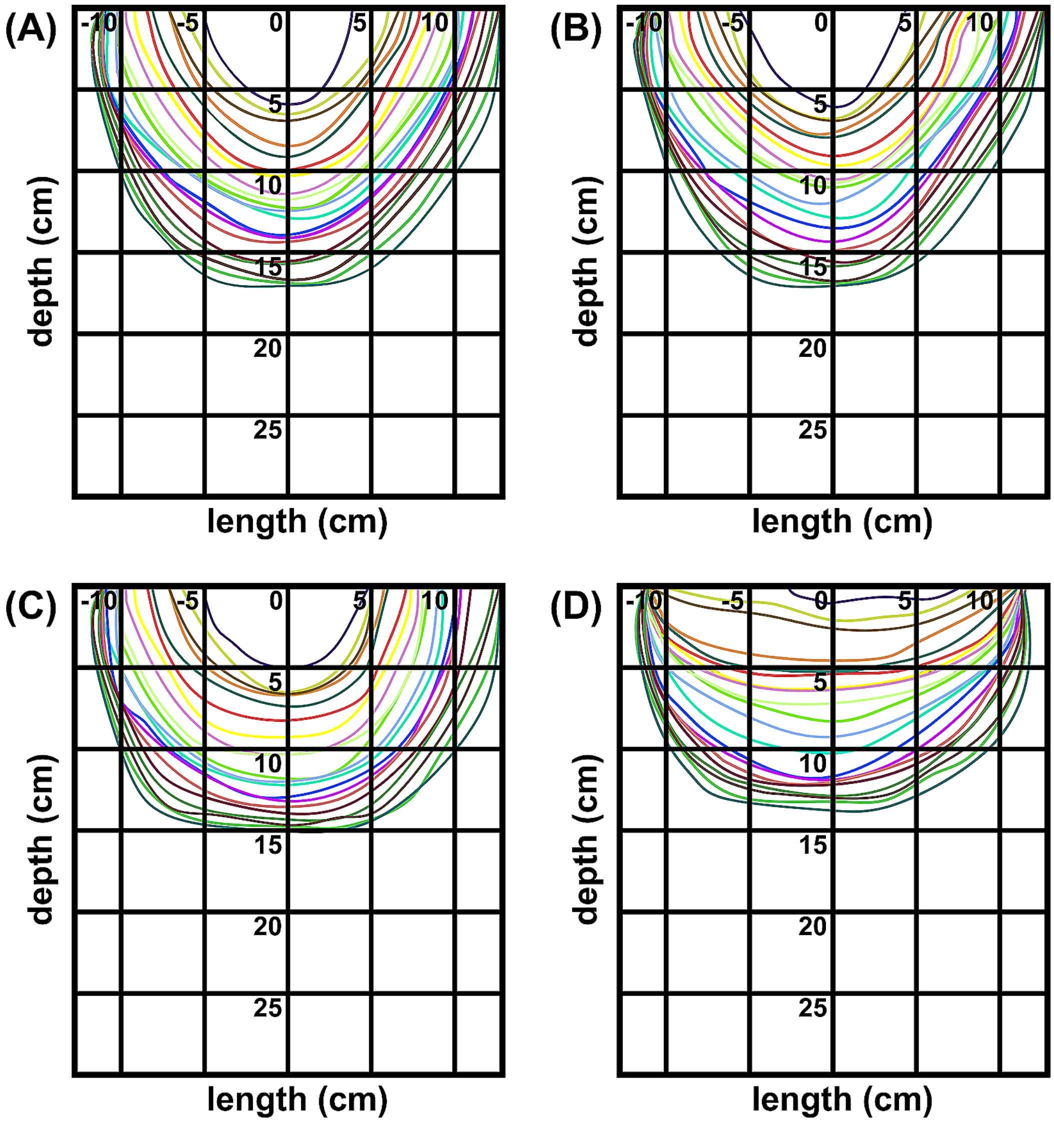

Figure 5. Visualization of soil wetting patterns simulation at various rice husk biochar (RHB) doses. (A) Without RHB, (B) RHB 5 ton ha^{-1}, (C) RHB 10 ton ha^{-1}, and (D) RHB 15 ton ha^{-1}

Table 4. Soil moisture content after RHB application at various pF values

Treatment	Soil moisture content (%)		
	pF 2.00	pF 2.54	pF 4.2
Without RHB	60.73 ± 0.42^{b}	48.66 ± 0.77^{c}	37.02 ± 0.89
RHB5	63.02 ± 0.47^{a}	50.02 ± 0.88^{bc}	37.76 ± 1.55
RHB10	63.71 ± 1.07^{a}	51.02 ± 0.50^{ab}	37.35 ± 1.42
RHB15	64.48 ± 0.84^{a}	51.52 ± 0.80^{a}	37.48 ± 0.77

Note: Data are presented as the average value of each treatment (n = 3), and different letters indicate significant differences ($p < 0.05$) between treatments of varying fertilizer doses in each irrigation treatment.

yield (Manickam et al., 2015). RHB application up to 15 ton ha^{-1} significantly increased biomass and yield, reaching 91.78% compared to without RHB application (Table 5).

The effect of biochar application on WUE, IWUE, and CWUE values

Actual WUE, IWUE, and CWUE values increased with increasing doses of RHB application

Table 5. Effect of varying doses of RHB application on total biomass and yield

Treatment	Root weight (g)	Shoot weight (g)	Bulb weight (g)	Total biomass (g)	Yield (kg m^{-2})
Without RHB	1.80 ± 0.26^{b*}	14.50 ± 3.15^{c}	7.20 ± 0.43^{b}	23.50 ± 3.47^{c}	0.73 ± 0.10^{c}
RHB5	1.80 ± 0.10^{b*}	21.57 ± 0.66^{b}	8.27 ± 0.49^{b}	31.63 ± 1.00^{bc}	0.98 ± 0.03^{bc}
RHB10	2.70 ± 0.69^{a*}	21.83 ± 1.62^{b}	9.77 ± 0.89^{ab}	34.30 ± 2.42^{b}	1.06 ± 0.07^{b}
RHB15	3.17 ± 0.51^{a*}	30.23 ± 4.66^{a}	11.87 ± 2.69^{a}	45.27 ± 7.83^{a}	1.40 ± 0.24^{a}

Note: Data are presented as the average value of each treatment (n = 3), and different letters indicate significant differences ($p < 0.05$) between treatments of varying fertilizer doses in each irrigation treatment.

Table 6. WUE, IWUE, and CWUE during shallot cultivation at varying doses of RHB

Treatment	WUE (kg m^{-3})	IWUE (kg m^{-3})	CWUE (kg m^{-3})
Without RHB	4.30	3.79	4.98
RHB5	5.71	5.11	6.69
RHB10	6.15	5.54	7.26
RHB15	8.06	7.31	9.58

up to 15 ton ha^{-1}. The actual WUE, IWUE, and CWUE values interpret the number of kilograms of shallot yield per 1 m^3 of irrigation water used, total irrigation water, and total evapotranspiration, respectively. Previous research by Faloye et al. (2019) also argued that biochar application with a dose of 20 ton ha^{-1} effectively increased actual WUE and IWUE and produced optimal yields. The highest actual WUE, IWUE, and CWUE values were in the RHB15, reaching 88.3%, 92.1%, and 92.5% compared to the treatment without biochar (Table 6).

Rice cultivation by farmers during the rainy season generates quantities of rice husks, which are commonly discarded as agricultural waste. Economically, utilizing rice husk from local areas is considered cost-effective for biochar production (Kavitha et al., 2018). Applying 15 ton ha^{-1} of RHB is calculated based on conventional farming methods, where RHB is spread over the entire land area in 1 ha. Implementing shallot's land management through bed creation can reduce RHB application, allowing it to be less than 15 ton ha^{-1}. Additionally, small-scale biochar production requires further study due to economic considerations associated with implementing pyrolysis technology.

Biochar plays a role in enhancing soil characteristics by maintaining soil moisture and increasing WHC. Biochar has hydrophilic functional groups such as carboxyl and hydroxyl, which play a role in binding water molecules (H_2O) (Dengxiao et al., 2023). Initially, the hydrophobic properties of biochar made it less able to absorb water. However, after being mixed into the soil under humid conditions, biochar undergoes a hydrophilic transformation, increasing the WHC and improving actual WUE, IWUE, and CWUE values (Liu et al., 2017; Reuling et al., 2023). The application of organic amendments, such as biochar, has been shown to increase WUE effectively (Jayakumar et al., 2021).

CONCLUSIONS

Implementing RHB application for shallot cultivation can be a promising strategy to reduce water loss and increase WHC. RHB has excellent potential to improve water holding capacity by providing micro- and mesopores. In addition, mesopores have a crucial role in holding water in the soil through the capillary force mechanism. RHB up to 15 ton ha^{-1} on shallot cultivation is the most optimal compared to the dosage below, to significantly increase actual WUE, IWUE, and CWUE by 87.44%, 92.87%, and 92.37% compared to without RHB application. RHB application not only improves water holding capacity and water use efficiency by improving the values of actual WUE, CWUE, and IWUE, but also leads to better yields on RHB doses of 15 ton ha^{-1} by 91.78% compared to without RHB application.

This experiment was limited to a small-scale greenhouse setup and a short duration, only one season of shallot cultivation. On a broader level, further studies are also needed to investigate the long-term impact of RHB application and conduct a field-based experiment to improve WUE, IWUE, and CWUE values and yield in shallot (*Allium cepa* L.) cultivation. Biochar application for agriculture has great potential to support policies for reducing water consumption and utilizing agricultural waste for environmental sustainability.

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