Effect of Biochar and Hydrochar Concentrations on Enhancing Germination and Seedling Growth in the Exposed Arable Crop Oryza Sativa

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Abstract

As carbon-rich materials, biochar (BC) and hydrochar (HC), the by-products of feedstocks produced through pyrolysis and hydrothermal carbonization, respectively, have demonstrated encouraging promise as soil conditioners that enhance soil fertility and crop development and have recently gained attention as potential products for seed germination improvement, growth, and yield, this research was carried out to evaluate the impact of BC and HC on rice (*Oryza sativa*) seedlings germination and growth under laboratory conditions. conduct the factorial the experiment, five (5) treatments for each of BC and HC, respectively was applied. The results indicated that T1(0%), T2 (1%), T3 (2%), T4 (4%), and T5 (6%) of BC and HC increased germination percentage (GP), mean germination time (MGT), germination rate index (GRI), germination energy (GE), shoot length (cm), fresh and dry shoot weight (g), fresh dry root weight (g), root/shoot ratio, and plant biomass, which GP, GRI, and GE showed increased by 70.2% and MGT by 66.6% in comparison with the control (0%) for BC and HC, respectively. Treatments 1%, 2%, 4%, and 6% of BC and HC significantly increased shoot length by 43.8% and 60.5%, respectively. Fresh and dry shoot weight, fresh and dry root weight, and plant biomass were significantly increased in comparison to the control for BC and HC at lower and higher concentrations, respectively. The findings reveal that lower concentrations of BC and higher concentrations of HC may be used as a viable soil conditioner to enhance rice seed germination and improve growth.

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Introduction

Rice is an important staple food for about half of the world's population; more than a billion people worldwide depend on rice farming for subsistence and livelihood. In developing countries, rice farming serves as the primary source of income for approximately

200 million households, has fed more than 3.5 billion people, and ranks as the second most important food crop due to its relative affordability and nutritional value; it meets the average calorie requirements and protein they need in their diets (Muthayya *et al.,* 2014). Every year, more than 100 countries grow rice on around 162.06 million hectares of land. They grow 495.78 million tonnes of milled rice and 715 million tons of paddy rice (Dorairaj and Govender, 2023). As the Malaysia population is increasing, resulting in the demand for rice as a source of food rising, the rice production capacity is becoming increasingly challenged. Rice is a great source of carbs, with roughly 87% of the grain being carbohydrates. It contains 7 to 8% protein, which is more digestible, biologically valuable, and nutritious, as well as less crude fibre and fat. (1 to 2%) (Anisuzzaman *et al.,* 2022). Rice cultivation has contributed about 2.4 billion RM (2.3%) to gross domestic product (GDP) in 2020 in Malaysia, with a total production of 2,356,000 metric tons. Even though it has a small contribution from the paddy and rice industries to the nation's GDP, it has received much more attention from policymakers given its important relationship with food security, culture, and socio-economic factors (Kamaruddin and Abd. Rashid, 2025).

The global poultry industries have increased, which provides numerous employment opportunities and alleviates poverty, leading to the large amount of waste generated that causes a wide range of complex environmental problems (Hejna *et al.,* 2022). Rising consumption of more animal protein, due to a growing world population, has led to increased poultry litter (PL) from these industries, for which its reuse is common practice, mainly through land application as a source of fertilizer (Mau *et al.,* 2018). It is one of the organic wastes whose management is a challenge because of the large amounts being produced annually. Management of the generated waste, especially those from poultry industries, is complicated in terms of separation, collection, transportation, treatment, and disposal, greatly affecting environmental sustainability and causing several environmental (water, air, and soil pollution), (Mozhiarasi and Natarajan, 2025).

The conversion of Poultry litter into carbon-rich materials BC and HC produced through pyrolysis and hydrothermal carbonization (HTC) have been widely used for their importance in enhancing soil physical and chemical properties. Study has indicated that BC can improve germination rate and early growth of various crops, such as rice, by increasing soil fertility and providing a conducive environment (Fedeli *et al.,* 2024). These have been found most especially when BC is applied at intermediate concentrations (0.5 to 1%) and have been observed to initiate seed germination and improve seedling growth without providing hazardous effects on plant development (Karim *et al.,* 2025). HC has recently also received attention as a promising material for soil amendment. HC, unlike BC, is produced under low temperature through HTC, which yields a carbon-rich material with a higher moisture content and greater concentration of oxygenated functional groups, making it effective in enhancing moisture retention and recycling nutrients that are very important for improving germination (Kumar *et al.,* 2020). Research has shown that HC can improve water-holding capacity, especially in sandy soils, which is important for seedling initiation under dry conditions (Wang *et al.,* 2025). Study conducted by Han *et al.* (2021) reported that application of wheat straw and washed-water HC in paddy fields increased the rice yield at lower and higher application rate for about 17.16% and 20.20% respectively in compared with control.

Sawdust-derived HC has also been reported to increase rice grained yield when applied in a low fertility soil and at a low rate (Hou *et al.,* 2020). HC incorporation with nitrogen fertilizer also increased the rice grain yield by 6.9-8.0%, (Ma *et al.,* 2025). Reaction-finished solution HC application significantly ($P \leq 0.05$) increased rice grain yield by 19.6%-30.0% compared to control (Yi *et al.,* 2022). HC produced from HTC aqueous phase treatments increased rice yield by 6.7-29.2% compared with control (Li *et al.,* 2023).

Carbon-rich materials, such as biochar (BC) and hydrochar (HC), are receiving attention for their influence to improve seedling germination and enhance soil properties, promoting sustainable agriculture. These materials could offer a sustainable solution to challenges faced in rice cultivation, particularly in areas with soil degradation and water scarcity. Since there are little studies about the combination role of BC and HC on rice germination for this reason this research aims to find out the recent effects of the carbon-rich materials BC and HC on rice seed germination, focusing on their influence on the germination rate and early seedling growth. The study aims to find out the mechanisms of action of these materials, providing insights into their potential for rice germination and seedling development effects.

Materials And Methods

Preparation of biochar and hydrochar

The carbon-rich materials (BC and HC) were produced using Poultry litter (PL) and eggshells (ES) collected from D'Khairan poultry farm located at Sungai Besar, Selangor, Malaysia and eggshells from open restaurant respectively. Briefly, BC was produced from slow pyrolysis using the PL alone at 400°C for 17 hr, while HC was produced using the HTC process. For the HC production, the PL and ES were incorporated together and were placed in a 100 mL Teflon plastic container at the solid-to-liquid ratio of 1:3, which was then inserted into a steel autoclave reactor. The sample mixtures were heated in an oven at 240°C for 15 hr under autogenous pressure. The steel autoclave reactor was allowed to cool down before opening, and then the solid product was separated from the liquid phase using Whatman No. 2 filter paper, with washing performed using distilled water. The BC and HC yield was calculated using the relationship below (Sivaprasad *et al.,* 2021).

$$\textit{Biochar yield (\%)} = \frac{biochar\ weight}{biomass\ weight} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\textit{Hydrochar yield (\%)} = \frac{hydrochar\ weight}{biomass\ weight} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Physicochemical analysis

1. **Bulk density** was measured using the standard procedure of calculating the mass-to-volume ratio of a fixed sample in a graduated cylinder (Blake and Hartge, 1986).

2. Moisture content was determined by measuring the mass loss after drying the sample at 105 °C until a constant weight was achieved. **Ash composition** was assessed through which the samples were heated in a muffle furnace at 550°C for 17 hr.

3. The evaluation of pH and Electrical Conductivity (EC) was performed on a 1:10 w/v extract of BC and HC in water (Lee *et al.,* 2013). Approximately 5 grams of BC and HC were combined with 50 mL of distilled water, shaken for 13 hr on an orbital shaker, and allowed to settle for 13 hr before measurement with calibrated pH and EC meters. Dry combustion technique (Dumas method, 1831) with an automated LECO elemental analyzer (TruSpec CN model, LECO Corporation, St. Joseph, MO, USA) was explored to determine the Total Carbon (C), Organic matter (OM), and the Total Nitrogen (N) contents from the sample's materials. Dry ashing method (Cottenie, 1980) was used to measure Total Phosphorus (P), Potassium (K), Calcium (Ca), and Magnesium (Mg). A 1 g of sample was ashed at 550°C, followed by dissolving the ash residue in 2 mL of concentrated HCl and 10 mL of 20% HNO_3. The resulting solution was filtered, mark up to a final volume of 100 mL, and analyzed. Potassium, Calcium, and Magnesium were quantified using an Atomic Absorption Spectrophotometer (AAS), while Phosphorus was determined using an Auto-Analyser (AA) following the ascorbic acid method.

Experimental design

The rice germination test was conducted in a laboratory for the period of 10 days from 5th December, 2025 to 14th December, 2025 at the Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, Five (5) different application rates for BC and HC respectively were established, based on their mass/volume: T1 (0%) Distilled water only without BC and HC, T2(1% from each BC and HC), T3(2% from each BC and HC), T4(4% from each BC and HC), and T5(6% from each BC and HC). Treatments were replicated three (3) times using thirty strong plastic petri dishes. The original stock solution was prepared by mixing BC and HC in a ratio of 1:10 (mass/water volume). Following this preparation, various treatment concentrations were applied to the petri dishes.

Germination test procedure

The germination test of rice seed on the carbon-rich materials, poultry litter biochar (PL-BC) and poultry litter mixed with eggshell hydrochar (PL-ES HC) was performed using the petri dish to determine the impact of the carbon-rich materials produced. Whatman 42 filter papers used as a place where the local rice variety (Hill Rice Kolongkob) were kept and trimmed to fit the plates of petri dish. 5 mL of the distilled water was then added to individual plates. The plates were treated to different concentration of the carbon rich materials, and 10 rice seeds were sown on them. The petri dish plates were then covered and put in the dark environment for 48 hr at 25°C. After that, there were cycles of 16 hr of light and 20 hr of darkness for the next 10 days. The percentage of germination rate was determined by the number of seedlings germinated at each treatment (Al-Swadi *et al.,* 2024). The results were compared to that of control treatment to determine the effect of the carbon-rich materials on the seed germination.

The following germination performance-related parameters were calculated based on the data generated and were all determined according to Fedeli *et al.* (2024):

1. Germination percentage (GP%)

$$GP\ (\%) = \frac{Total\ number\ of\ germinated\ seeds}{Total\ number\ of\ seeds\ sown} \times 100 \ldots\ldots\ldots\ldots\ldots (3)$$

2. Mean germination time (MGT)

$$MGT\ (\%) = \frac{\sum_{i=1}^{j} ni \times di}{N} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Such that n_i total number of seeds germinated on the 1st day, d_i is the i the number of days from the first day of the experiment, N is the complete number of seeds germinated during the last day of the observation, and j is the total number of days of the observation

3. Germination rate index (GRI) is a measure of both the speed and uniformity of seed germination over a specific period, often used to evaluate seed vigor:

$$GRI\ (\%) = \sum \frac{Gn}{Dn} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (5)$$

where G_n is the number of germinated seeds, and D_n is the number of days since the beginning of observations

4. Germination energy (GE) is a seed quality metric that measure the percentage of seeds that sprout quickly and uniformly within a specific, short timeframe:

$$GE\ (\%) = \frac{Number\ of\ germinated\ seeds\ at\ 3\ DAS}{Total\ number\ of\ seeds\ tested} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots .. (6)$$

Such that DAS is the days number after sowing.

Statistical analysis

The experiment was conducted using Completely Randomized Design (CRD). The effects of different treatment concentrations for the BC on the measured germination parameters were analyzed using SAS software (version 9.0). Duncan's multiple range test was carried out to establish significant differences between the means ($p \leq 0.05$).

Results and Discussions

Yield (%) of biochar and hydrochar

The conversion of PL and ES into Carbon-rich materials (BC and HC) revealed a significant difference in the final products resulting in the decreased in the initial weight. This reduction is attributed to the partial degradation of organic components which were released as gaseous phases and process water during pyrolysis and HTC respectively (Masoumi *et al.,* 2021). Biochar that was produced through pyrolysis decomposes the cellulose and hemicellulose first at lower temperatures, with ligneous materials decomposing at higher temperatures. This process releases gaseous compounds (e.g., CO_2, CO) and volatile organic compounds, leading to a reduction in weight and the formation of a carbon-rich product. Hydrochar production through HTC occurs at lower temperatures (180-250 °C) in the presence of water, which affects the decomposition of cellulose and hemicellulose differently. The water facilitates hydrolysis and dehydration reactions, leading to the formation of hydrochar with higher oxygenated functional groups, such as carboxyl and hydroxyl groups, and a more hydrophilic surface compared to biochar.

The HTC process for PL and ES yielded about 68.96% of the final weight, while pyrolysis resulted in 61.2% of the yield. These differences in patterns are related to the varying HTC and pyrolysis temperature and residence time operational conditions. This result is in line with the findings of Jiang et al. (2025) that confirm higher yields of hydrochar are consistently observed across various feedstocks, with wood often yielding up to 65% hydrochar as compared with biochar.

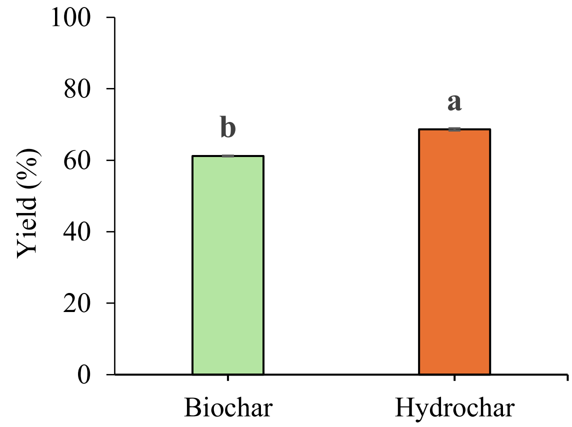

Figure 1. BC and HC yield obtained from pyrolysis and HTC of PL and ES

Bars with a different letter indicate significant differences ($p \leq 0.05$).

Physicochemical analysis

The difference in the operational conditions for the BC and HC production processes resulted to variations in their physicochemical properties. These differences in their end products' properties make them suitable for various applications such as soil amendments, wastewater treatment, and so on (Kumar et al., 2020). The results of physical properties such as bulk density, moisture content, and ash content (Table 1), were significantly different between BC and HC, with HC showing higher values, and this could be attributed the fact that the HTC process which occurs in a wet, low-temperature, and high-pressure environment that promotes polymerization reactions leading to the formation of dense particles with low pore spaces and as well as high oxygen-containing functional groups (e.g., carboxyl, hydroxyl) making it more hydrophilic and capable of retaining moisture (Kumar *et al.,* 2020).

In this current study, BC and HC showed similar alkaline pH values of 9.04 and 8.70, while their EC values were 8.67 and 2.08 (mS/cm), respectively. Other chemical properties determined from BC and HC showed a significant difference, with BC showing higher in terms of measured nutrients except for Ca, which is higher in HC, and this could be due to the incorporation of the eggshell with poultry litter prior to the production of HC, the high Ca content from the eggshell increases its content in the resulting HC. Additionally, higher carbon was observed in BC than HC, likely originating from the differences in operating temperature and residence during production. Increased in pyrolysis temperature breaks down organic matter, leading to higher concentration of mineral components as reported by (Sathyabama and Firdous, 2025). Similar results were reported by Katuwal *et al.* (2022 as most of the properties of biochar increases with increasing pyrolysis temperature. It was reported by (Piash *et al.,* 2025) that poultry litter biochar has higher some physiochemical properties than hydrochar.

Table 1. Mean showing the physicochemical properties of BC and HC used for the experiment

Parameters	BD g/cm^3	MC (%)	Ash (%)	pH	EC	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	C (%)	OM (%)	C/N (%)
Biochar	0.38^{b}	95.80 b	34.60 b	9.04 a	8.67 a	2.97 a	4.64 a	12.80 a	6.66 a	9.72 b	47.08 a	61.03 a	11.91 b
Hydrochar	0.47^{a}	99.14 a	71.91 a	8.70 b	2.08 b	1.16 b	1.87 b	9.53 b	4.48 b	13.23 a	24.22 b	31.40 b	15.65 a

*Different letters in the same column show significant difference at ($p \leq 0.05$) using Duncan multiple range test.

Effects of BC and HC on germination parameters

Results from this study demonstrate that both BC at lower and HC at higher concentration respectively, significantly influence the sprouting performance of rice seed to develop and into a plant. At the lowest and highest concentrations tested (0%-6%), BC at lower and HC at higher concentrations notably increased the final germination percentage (GP), mean germination time (MGT), germination rate index (GRI), and germination energy (GE) by 70.2%, 66.6%, 70.2%, and 70.2%, respectively, compared to control. These findings suggest that BC at lower and HC positively impact early-stage seedling growth. The average values for GP, MGT, GRI, and GE of rice seeds amended with BC and HC over the ten-day germination period are presented in (Table 2). Significant differences were observed across various treatment concentrations for all measured parameters, indicating that BC and HC influence rice seed germination in different ways. Lower and higher concentrations of BC and HC were effective in promoting germination.

Control treatment from BC and HC showed no significant differences, highlighting the role of BC and HC in either facilitating or inhibiting seed germination. The study aligns also of finding of Evamoni *et al.* (2023) on the assessment of germination performance and early seedling growth of Malaysian indica rice genotypes under drought conditions as the GP increases all other germination index performances (GI, GE and GR) increased significantly; however, the response of the genotypes was different at different drought levels. Germination and growth promotion improved, are often ascribed to increased physical characteristics and nutrient availability following carbon-rich materials addition (Fornes and Belda, 2018). The study did not observe any toxicity in 1% and 2% of BC or 4% and 6% of HC. This indicates the safety and beneficial application of these carbon-rich materials in enhancing the early stages of growth of rice. The improved germination of seed using BC at lower concentrations could be attributed to the availability of more nutrients, and improved moisture that facilitated microbial activity and reduces the activation of enzymes responsible for seedling emergence which minimizes phytotoxicity and provides a favourable environment to the growth of rice seedlings (Dembélé *et al.,* 2021). This may not however be true at the higher concentrations since carbon or nutrient imbalance may occur. This observed germination success across all treatments can likely be attributed to the energy reserves in the seed coatings, which are mobilized during germination (de Jager and Giani, 2021). Furthermore, the positive impact of BC on the germination parameters of *Oryza sativa* was most notable at lower concentrations of 1% and 2%. This aligns with findings by Solaiman *et al.* (2012) that observed higher germination rates for wheat (*Triticum spp.*) at lower BC concentrations (0.125% vs. 0.25%). Similarly, Chen *et al.* (2025) found that the parameter of seedling growth increased with the low concentration of biochar and decreased with the high concentration. Washing of the HC produced with water has been effective in removing volatile fatty acids and other organic compounds hence making it less toxic to plants (Wang *et al.,* 2025) This decrease in toxicity has resulted in greater fresh and dry shoot weights of higher concentrations of 4% and 6% of HC. From the standpoint of crop production, a low concentration of BC and a larger concentration of hydrochar may effectively enhance the biological performance of rice, particularly in well-managed conditions. The presence of moisture significantly influenced the improvement of germination percentage (GP) and mean germination time (MGT). Hydrochar as a treatment that has higher moisture than the biochar resulted in quicker germination (lower MGT) and higher GP; this aligns with findings by Hou *et al.* (2022), who reported that moisture availability directly affects seedling growth and germination in rice. GRI and GE were similarly improved in treatments with optimal moisture, as adequate water availability supports seedling vigour (Evamoni *et al.,* 2023).

These results confirm the significant role of hydrochar's moisture retention in enhancing both germination rates and seedling growth.

Table 2. Mean (S.E) showing the effect of BC and HC on germination percentage (GP), Mean germination time (MGT), germination rate index (GRI), and germination energy (GE)

	GP		MGT		GRI		GE	
TRT	**BC**	**HC**	**BC**	**HC**	**BC**	**HC**	**BC**	**HCs**
T1(0%)	57 ± 3.33[a]	57 ± 3.33[a]	6 ± 0.33[a]	6 ± 0.33[a]	0.57 ± 0.03[a]	0.57 ± 0.03[a]	57 ± 3.33[a]	57 ± 3.33[a]
T2(1%)	93 ± 3.33[a]	73 ± 3.33[b]	9 ± 0.33[a]	7 ± 0.33[b]	0.93 ± 0.03[a]	0.73 ± 0.03[b]	93 ± 3.33[a]	73 ± 3.33[b]
T3(2%)	97 ± 0.10[a]	77 ± 3.33[b]	10 ± 0.10[a]	8 ± 0.33[b]	0.97 ± 0.01[a]	0.77 ± 0.03[b]	97 ± 0.10[a]	77 ± 3.33[b]
T4(4%)	77 ± 3.33[b]	97 ± 0.10[a]	8 ± 0.33[b]	10 ± 0.10[a]	0.77 ± 0.03[b]	0.97 ± 0.01[a]	77 ± 3.33[b]	97 ± 0.10[a]
T5(6%)	80 ± 5.77[a]	93 ± 3.33[a]	8 ± 0.57[a]	9 ± 0.33[a]	0.80 ± 0.06[a]	0.93 ± 0.03[a]	80 ± 5.77[a]	93 ± 3.33[a]

*Different letters in the same row indicate significant difference at ($p \leq 0.05$) using Duncan multiple range test.

Effects of BC and HC on growth both materials parameters of *Oryza sativa*

Shoot length (cm)

The shoot length showed a significant difference across the different treatment concentrations with regards to the addition of amended carbon-rich materials (Figure 2). The results show that BC has resulted in higher shoot lengths at lower concentrations (1% and 2%) with about 44% increased under (2%) as compared with control (0%), while HC shows more impact at higher concentrations (4% and 6%) with increase of about 60% under (4%) in comparison with control (0%). This result indicates the effectiveness of the materials in enhancing shoot length development that depends on the concentration, with biochar outperforming at lower concentrations (1%-2%) and hydrochar at higher concentrations (4%-6%). The improved shoot length at lower biochar concentrations could be attributed to the creation of an optimal balance of physicochemical properties that promote growth whereas inhibit growth at higher concentrations. Fedeli *et al.* (2024) reported similar results: BC at lower concentrations (0.5%) promotes germination and seedling, including radicle length, without inducing any toxicity. Also, it was reported by Jabborova *et al.* (2021) that biochar improved shoot length at lower concentrations as compared to higher concentration. These findings yielded an important outlook on the optimal use of biochar and hydrochar for plant growth, suggesting that both materials have effective benefits at specific concentration levels. The result of this study confirms that lower concentrations of BC (1-2%) are suitable for improving soil structure and nutrient availability without causing nutrient imbalances form regarding practical application. HC at higher concentrations could be important for areas with water stress or poor nutrient availability, as it helps with moisture retention and provides slow-release nutrients. Therefore, BC and HC can be considered as effective soil amendments to improve seedling growth and stem elongation in agricultural settings, depending on the specific needs of the soil. High concentrations of BC (especially above 2%) may lead to nutrient imbalances or toxicity in plants, particularly due to high pH or excessive carbon content, which can affect seedling development. For HC, higher concentrations (4-6%) can significantly enhance moisture retention, but in excessive amounts, they could potentially lead to waterlogging or impaired gas exchange in the soil. These effects need to be carefully managed to avoid any negative impact on plant growth.

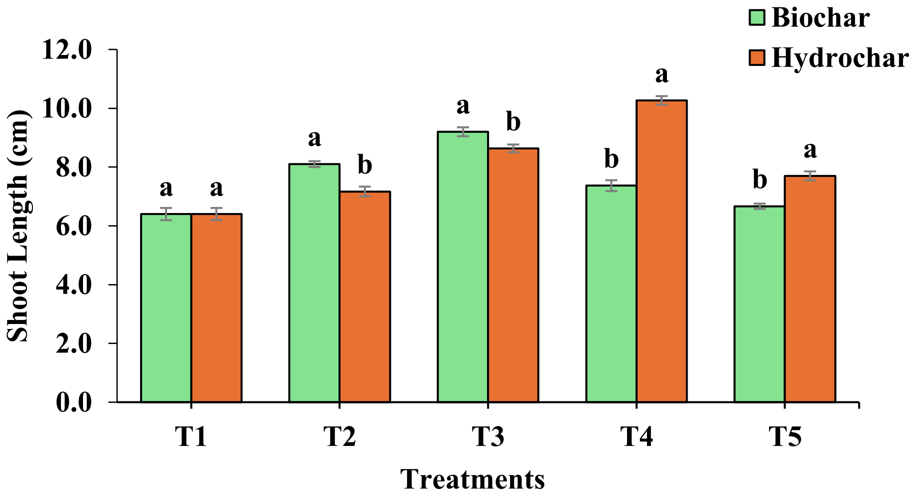

Figure 2. Effect of Biochar and hydrochar concentration on the length of shoot

Different letters on bars indicate significant differences ($p \leq 0.05$).

Fresh shoot and dry weight (g)

The weights of fresh and dry shoot of the rice seedlings at the end of the germination test experiment with BC and HC at different treatment concentrations are presented in (Figure 3). There was a significant difference observed in the fresh and dry shoot weight of the two materials at different concentrations. The results show higher fresh and dry weights from the BC at lower treatment concentrations (1% and 2%), whereas higher fresh and dry shoot weights were observed at higher HC concentrations (4% and 6%). There is about 90%, 68.42% and 95%, 84.21% increase in fresh and dry root weight at 2% and 4% from BC and HC respectively. This result signifies that the different concentrations of the two materials play a critical role in determining the effectiveness of BC and HC in promoting shoot growth and development. It was found that BC and HC are important Carbon-rich products that play a crucial role in improving rice seedlings growth by increasing the nutrients retention by enhancing the efficiency of roots so that nutrients are absorbed by the plants. This causes growth in the length of shoot, weight of fresh and dry shoots and roots to increase with significant improved overall seedling growth. BC and HC promoted the better growth of seedlings at low and high concentrations, especially the germination parameters, fresh and dry shoot and root weights.

These studies have implications for associating the use of BC and HC in agricultural applications. This finding aligns with the study of (Liu *et al.,* 2021) that biochar extract could stimulate rice seedling growth and root development consistently at a low dosage (<0.05% biochar equivalent) but not at a dosage of up to 0.1% in hydroponic conditions. High BC application (16%) as reported by (Gautam *et al.,* 2025) significant reductions in shoot, root, and seedling lengths were observed, with better growth at lower concentrations, specifically 4% for shoot length, 0% for root length, and 8% for seedling length.

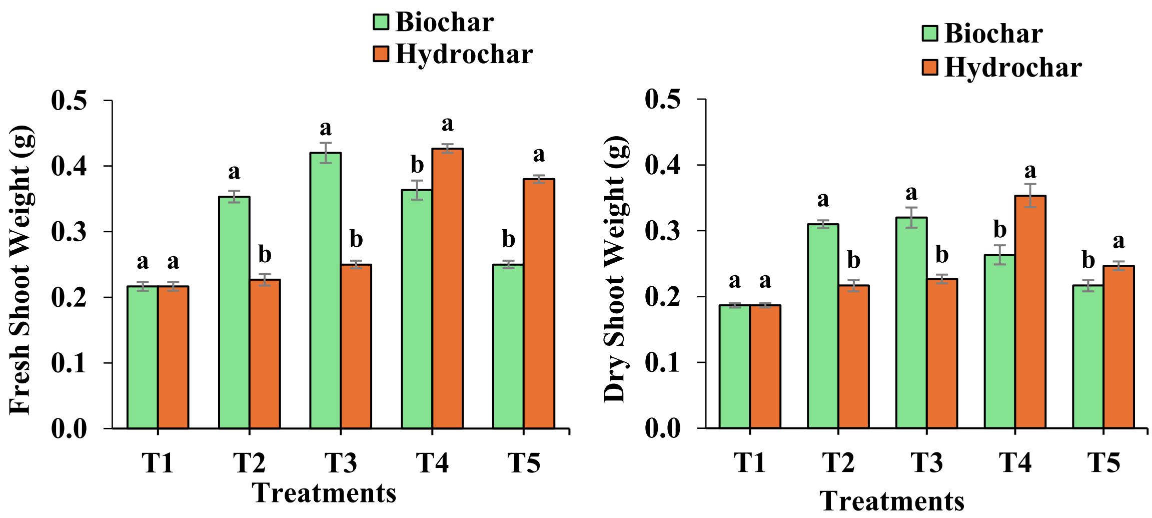

Figure 3. Influence of biochar and hydrochar on fresh and dry weight of rice seedlings shoot after 10 days of germination testing

Bars with a different letter indicate significant differences ($p \leq 0.05$).

Fresh and dry root weight (g)

The fresh and dry root weights of BC and HC on a rice seedling at the end of a ten (10)-day germination test experiment at different treatment concentrations are summarized in (Figure 4). The results show no significant difference between the two materials under the control level, whereas there was a significant difference observed across the various treatment concentrations. The results suggest that BC is more effective in promoting fresh and dry root growth at lower treatment concentrations (1% and 2%), while HC demonstrated a slight growth at higher concentrations (4% and 6%). There is about 122.7%, 175% and 68.2%, 106.3% increase in fresh and dry root weight at 2% and 4% from BC and HC respectively. The observed improvement in growth parameters at the higher HC concentrations (4% and 6%) compared to BC may be due to the higher presence of organic constituents in BC. This scenario is true at these higher HC concentrations, where more soluble compounds are available. HC addition at high application rates did not negatively affect the plant. The result from this finding is the same with previous studies by (de Jager and Giani, 2021). These findings indicate the concentration-dependent impacts of BC and HC on fresh and dry root growth, signifying that both material type and concentration should be carefully observed when optimizing these materials for promoting plant growth in agricultural or environmental applications. This result aligns with the study of (Celletti *et al.,* 2021) that hydrochar at higher extraction stimulate root growth and development and (Zhu *et al.,* 2018) that biochar increases root length at 0.75% and 1.5%, respectively.

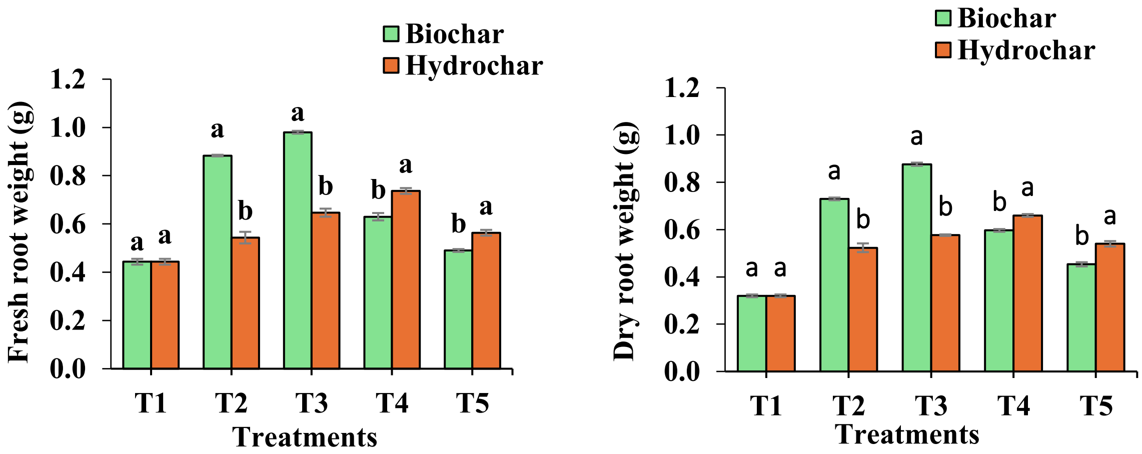

Figure 4. Effect of biochar and hydrochar on fresh and dry root weight of rice seedlings after 10 days of germination test

Different letter on bars indicates significant differences ($p \leq 0.05$).

Root/shoot ratio and plant biomass weight (g)

The different concentrations' effects of biochar (BC) and hydrochar (HC) on the root/shoot ratio of rice seedlings are presented in Figure 5. Although there was no significant difference recorded across the various treatments' concentrations, the overall trend showed that both BC and HC positively enhanced root and shoot development across all concentrations. However, when considering the root/shoot ratio, BC at T2 (1%) showed an approximate 60% increase compared to the control T1 (0%), signifying that lower BC concentrations might be more effective in enhancing balanced seedling growth. Looking at HC at T5 (6%) resulted in a 27.3% increase in the root/shoot ratio, from 1.72 to 2.19, compared to the control. These results signify that HC performs better at higher concentrations, which could be due to the increased water retention and higher oxygenated functional groups present in HC, promoting seedling vigor. While the root/shoot ratio did not show consistent significance across treatments, both BC and HC led to significant increases in plant biomass, with BC at lower concentrations (1%-2%) enhancing biomass weight, and HC at higher concentrations (4%-6%) showing similar improvements. These results indicate that biochar may be more efficacious at reduced concentrations, presumably due to its porous structure and extensive surface area, which supply vital nutrients and enhance soil aeration. In contrast, hydrochar, with its hydrophilic nature and higher moisture retention, may better support root development at higher concentrations. As Taweengern *et al.* (2025) reported, both BC and HC, when applied at lower and higher concentrations (112.5% and 220.0%), can contribute to improved plant growth. Our findings align with these results, suggesting that the distinct physical and chemical properties of BC and HC contribute to their concentration-dependent effects. Specifically, BC's hydrophobic surface and high nutrient retention make it more effective at lower concentrations, while HC's oxygenated functional groups and water retention capabilities make it more beneficial at higher concentrations.

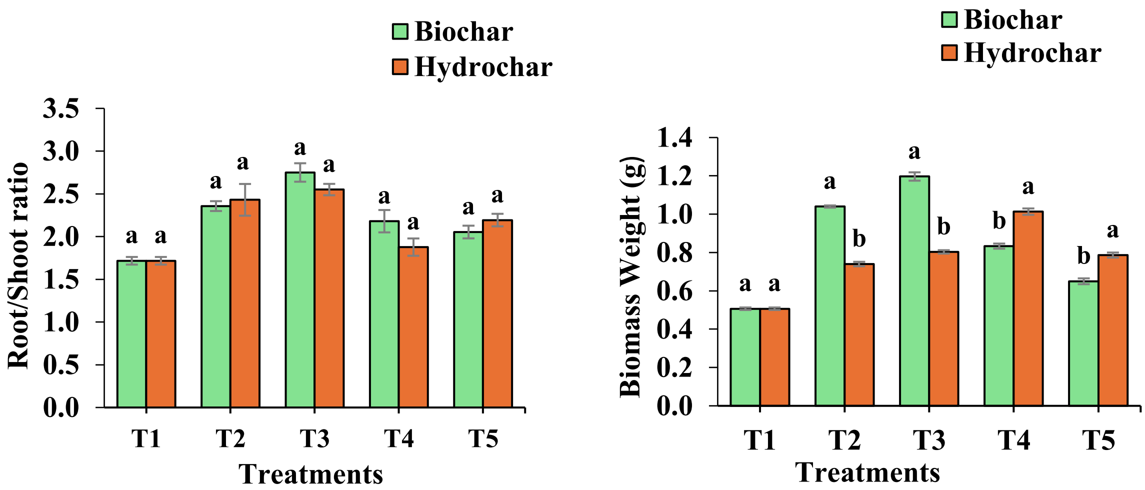

Figure 5. Influence of Biochar and hydrochar on root/shoot ratio and plant biomass weight of rice seedlings after 10 days of germination test

Different letters on bars indicate significant differences ($p \leq 0.05$).

Conclusions

The use of BC and HC improved some aspects of *Oryza sativa* germination rates and growth, particularly at various application concentrations of carbon-rich materials. The findings reveal that application of BC and HC significantly improves seed sprouting, which enhanced germination rates, shoot length, fresh and dry shoot weight, fresh and dry root weight, and overall plant biomass weight. It could also be observed that BC at lower and HC at higher concentrations enhance the release of nutrients respectively, during the early stages of germination. This process provides vital support for seedling development and promotes faster and more evenly sprouting. Therefore, the incorporation of BC and HC will be of great importance for rice establishment. However, more studies are needed to improve the techniques of BC and HC addition and release the basic mechanisms accountable for these important benefits in a different environmental condition. Nonetheless, additional research is required to assess the impact of BC and HC on rice seed germination in open field conditions, where diverse concentrations are commonly employed for crop cultivation.

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Conflict of Interest

We declared lack of conflict as per the content of this paper.

Funding Declaration

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Authors Contribution

Conceptualization: S.K. Methods: S.A.H., S.K., F.M.J. Data Analysis: S.A.H. Investigation: S.A.H Data curation: S.K. Original draft writing: S.A.H Review writing and editing: S.A.H., S.K. Supervision: S.K., F.M.J., N.S.N. Research administration: S.K. Acquisition of fund: S.K. The final reviewed manuscript version was approved by all co-authors before submission.

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