

EVALUATING THE ROLE OF BIOCHAR-AMENDED SOILS IN ENHANCING LEAF CHLOROPHYLL CONTENT AND YIELD OF PADDY CROPS UNDER WATER STRESS

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Abstract

This study investigates the role of biochar-amended soils in improving chlorophyll content and yield performance of paddy crops under water stress. A factorial field experiment using varying biochar doses (0, 5, and 10 t/ha) and irrigation regimes (100% and 50% field capacity) revealed significant improvements in plant physiological traits and soil quality. The highest biochar dose (10 t/ha) enhanced leaf chlorophyll content (45.2 SPAD), stomatal conductance (138 mmol/m²/s), and relative water content (87.9%), compared to the control. Yield components, including grain yield (5.3 t/ha), panicle number, and grain weight, also increased substantially. Soil analysis showed improved pH, organic carbon, water-holding capacity, and microbial biomass. Root and shoot lengths, leaf nutrient content, and enzymatic activities were also higher in biochar-treated plots. Even under water-stressed conditions, biochar improved physiological resilience and reduced the yield gap. The results confirm biochar's effectiveness in enhancing crop performance and soil health under drought, supporting its application in sustainable paddy farming.

Keywords: “Biochar”, “Water Stress”, “Paddy Yield”, “Chlorophyll Content”, “Soil Fertility”, “Sustainable Agriculture”.

INTRODUCTION

The worldwide demand for rice is rising, so better techniques are needed to help paddy crop production in low-water areas (Kharytonov, et al., 2021). Because water is becoming less available and more environmental problems occur, depending on plentiful irrigation for farming is becoming impractical (Khan et al., 2024). Because of this, biochar, made from burning biomass, is now considered a helpful soil additive that can improve soil health, hold water better and support plants in dry areas (Nepal et al., 2023). There is great interest in understanding how biochar helps plants photosynthesize and grow, given that many different soil and biochar conditions can shape the end results (He et al., 2020). By looking at how biochar affects soil, we can help both sustainable farming and maintain food availability as problems in the environment grow (Hui, 2021; Yadav et al., 2023).

The open and large shape of biochar helps hold on to more water and make the air in dry areas better for plant life (Yellezuome et al., 2022). Use of biochar impacts the soil's pH, increases its organic matter and allows it to keep more important nutrients, so the soil becomes fertile (Farhangi-Abriz & Ghassemi-Golezani, 2022; Parker et al., 2020). When biochar is put into soil, it can modify the soil's ability to either gain or lose heat, giving plants a chance to resist damaging temperature changes. Thanks to the added water spread by biochar, plants can easily gain access to water when it is scarce in the soil (Yoo et al., 2020). We do not yet thoroughly understand how biochar affects water availability when droughts occur and this is being examined by scientists (Gharred et al., 2022). Changes in the soil after adding biochar help plants reach water that is moving away from the surface. Given that the good effects of biochar depend on its type, how fast it is added, the soil and the crop,

appropriate use requires adjusting according to each farm (Wang et al., 2020).

Significant changes in soil structure because of biochar have been noticed, but researchers believe there is still much to learn about its effects on fine-textured soils (Libutti et al., 2021). It was found by Libutti et al. in 2021 that soil changed by biochar holds more water and has quicker runoff rates. Biochar improves soil in many ways, allowing farmers to harvest more and it also helps keep metals and organic pollutants from easily getting into the soil (Guo et al., 2020). How useful biochar is depends on the materials used for production and the conditions under which it is made which then guide its actions in the soil. In 2021, Kujawska and Wasąg found that biochar, created from a variety of substances, can foster soil development and take care of pollutants in water. In regions where water is scarce, adding biochar to soil can raise leaf chlorophyll concentration which is key to strong photosynthesis and healthy plants. Biochar helps keep nitrogen and phosphorus available, so plants can produce enough chlorophyll and still remain photosynthetic in scarce water conditions. Application of biochar has shown to help organic carbon increase in saline soils, leading to a better environment for soil bacteria needed for cycle of nutrients (based on Egamberdieva et al., 2021). By helping soils hold onto more water, using biochar supports plants in keeping high stalk activity needed for carbon and oxygen exchange as well as chlorophyll production. In addition, biochar may impact plant hormones to increase readiness for stress, as well as decrease the negative effects of drought on photosynthesis.

Some of the bacteria living in biochar increase plant growth and help plants manage challenges from the environment (Ngasotter et al., 2023). As a result,

plants grow more chlorophyll which boosts photosynthesis and produces higher yields when paddy is cultivated under overlap stress conditions. Soil that includes charcoal increases photosynthesis in many types of plants. Yield increases from using biochar depend on the kind of biochar, the qualities of the soil and the weather. Studies show that adding biochar leads to higher yields by making more nutrients available and improving how water is held (Ngasotter et al., 2023). Because biochar raises both soil fertility and its ability to store water, crops can be grown more effectively and in a sustainable manner with its help.

While phosphorus in biochar can benefit farm crops, these crops also need an increased supply of nitrogen to do well (Nkomo et al., 2021). Phosphorus is given to vegetables growing in biochar, but they still need a nitrogen source. When biochar acts on garden soil, the microbes it affects will boost plant growth and stability. Modifications to chitin are found to encourage the growth of soil microorganisms which could make the soil hold more nutrients and so benefit sustainable farming (Ngasotter et al., 2023). Green development aims are met by applying biochar since it promotes soil health, helps lower pollution and encourages farmers to go green (Khan et al., 2024). New research and technology show that using biochar today can improve plant efficiency, help plants resist salt pressure and stimulate animal growth (Das et al., 2020). We should examine the ways in which biochar helps or harms crop cultivation.

Under drought conditions, plants speed up their antioxidant enzymes, collect hydrogen peroxide, release electrolytes and increase levels of malondialdehyde (Kamali & Mehraban, 2020). Since biochar improves soil's aeration, it reduces the risk of plants being affected by hypoxia and allows the roots to grow properly and pick up nutrients.

Because of its porosity, biochar brings more oxygen to the soil, making water-logged rice fields more fertile. Because there is more space for oxygen, the plant's roots can nourish themselves and function well. Using carbon-rich biochar helps hold carbon in the soil, reduce climate change, stop soil nutrients from leaching and boost soil quality (Li et al., 2021). Since it improves the soil and brings together heavy metals and pollutants, biochar could make a real difference in capturing carbon, addressing wastes and assisting with sustainable farming.

RESEARCH METHODS

We set out to measure how applying biochar to soil influenced chlorophyll content in the leaves and the yield of rice crops in water-limited conditions. Experiments were carried out using an RCBD with three replicates, by combining biochar and irrigation at different levels in a factorial way. We observed the field experiment in a controlled area on clay loam soil through one season of plant growth. Biochar was prepared from rice husk by pyrolysis at 500°C and was used at three rates: without biochar, 5 t/ha and 10 t/ha. First, the pH, electrical conductivity, surface area, cation exchange capacity and elemental composition of the biochar were tested according to traditional methods. Plots of soil were exposed to biochar at two weeks earlier than when rice seedlings were transplanted to let it blend into the soil. Two different methods of irrigation were used: the well-watered regime at 100% field capacity and the water-stressed regime at only 50% field capacity, all monitor by drip irrigation and soil moisture sensors for accuracy.

The reason we chose the 'IRRI-6' was that it already shows signs of water stress and changed chlorophyll levels. Leaf chlorophyll was measured at three different times (tillering, panicle initiation and heading) using a SPAD-502 chlorophyll meter. At the same time, important physical traits of the plant

such as RWC, stomatal conductance and leaf temperature, were registered. When harvesting, rice yields, including the number of panicles, number of grains on each panicle, grain weight per 1000 grains and the whole grain yield per plot, were observed. Small portions of soil were taken in advance and post-harvest to assess changes in its physical (density, porosity and water holding capacity) and chemical (pH, carbon and the amount of accessible NPK) properties. In SPSS v26.0, ANOVA was used to determine the main and combined effects of biochar use and irrigation amount. Differences between mean values were checked by LSD test at a 5% level of significance. Associations between chlorophyll, various physiological traits and the amount of yield were studied by carrying out correlation and regression studies in different settings.

RESULTS

Table 1 shows that leaf physiological values improved as a result of applying various biochar treatments. Leaf chlorophyll content, stomatal conductance and relative water content were all higher in the plots treated with biochar than in the control and these results peaked when biochar was applied at a rate of 10 t/ha. From Table 2, you can see that biochar treated plots showed improvements in yield, as grain yield, panicle count and 1000-grain weight were all higher after treatment, with the greatest gains achieved when 10 t/ha were used. The table demonstrates that adding biochar results in better pH, carbon content and water-holding properties in soil, where the highest improvements happened at the highest biochar dose. Table 4 shows that having more water improved the color of chlorophyll, yield and opening and closing of stomata compared to plots that did not receive as much irrigation.

The full results improve our knowledge of how biochar affects plant growth, the activity of soil microbes, soil chemistry and the improvement of soil structure. Biochar had a clear effect on both root and shoot development and clearly enhanced their growth further with more biochar (table 5). Biochar increased root length to 18.1 cm, up from 13.2 cm in the control and shoot length to 67.9 cm, up from 54.3 cm, suggesting plants grew stronger in treated soil. The unchanged root-to-shoot ratio suggested that both parts were experiencing similar rates of growth induction. The activity of living organisms is increased in the soil, as seen in Table 6. When the amount of biochar increased, soil respiration increased from 3.2 to 5.9 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$, microbial biomass carbon rose from 145 mg/kg to 230 mg/kg and dehydrogenase activity nearly doubled. The findings suggest that biochar acts as a good habitat for healthy soil bacteria which helps to strengthen the soil ecosystem.

Table 7 presents the macro-nutrient content in paddy leaves, showing a consistent increase in nitrogen, phosphorus, and potassium concentrations with biochar application. Leaf nitrogen rose from 2.1% to 3.0%, phosphorus from 0.22% to 0.34%, and potassium from 1.9% to 2.7%, reflecting improved nutrient uptake facilitated by enhanced soil nutrient availability and microbial interaction. Lastly, Table 8 details improvements in soil physical structure attributed to biochar incorporation. Bulk density decreased from 1.43 to 1.29 g/cm^3 , while porosity improved from 45.2% to 52.3%. The aggregate stability index also increased markedly, indicating better soil aggregation and resistance to erosion. Collectively, these findings provide robust evidence that biochar not only enhances physiological and yield responses in paddy crops but also improves the biological and physical integrity of the soil, especially under water-limited conditions.

Table 1. Effect of Biochar on Leaf Physiology Parameters under Water Stress

Treatment	Leaf Chlorophyll (SPAD)	Stomatal Conductance (mmol/m ² /s)	RWC (%)
Control	32.1	95	72.4
Biochar 5t/ha	39.5	122	81.3
Biochar 10t/ha	45.2	138	87.9

Table 2. Yield Attributes of Paddy under Different Biochar Treatments

Treatment	Grain Yield (t/ha)	Panicle Number	1000-Grain Weight (g)
Control	3.1	220	24.5
Biochar 5t/ha	4.2	260	26.7
Biochar 10t/ha	5.3	289	28.2

Table 3. Changes in Soil Properties Due to Biochar Application

Soil Parameter	Control	Biochar 5t/ha	Biochar 10t/ha
pH	6.2	6.7	6.9
Organic Carbon (%)	0.95	1.38	1.72
Water Holding Capacity (%)	28.1	34.4	41.6

Table 4. Comparison of Irrigation Regimes on Key Physiological and Yield Parameters

Irrigation Level	Chlorophyll SPAD	Grain Yield (t/ha)	Stomatal Conductance
100% Field Capacity	42.8	4.8	130
50% Field Capacity	34.6	3.2	97

Table 5. Influence of Biochar on Root and Shoot Growth Dynamics

Treatment	Root Length (cm)	Shoot Length (cm)	Root-Shoot Ratio
Control	13.2	54.3	0.24
Biochar 5t/ha	15.8	60.7	0.26
Biochar 10t/ha	18.1	67.9	0.27

Table 6. Soil Microbial and Enzymatic Activity under Biochar Treatments

Treatment	Soil Respiration (μmol CO ₂ /m ² /s)	Microbial Biomass C (mg/kg)	Dehydrogenase Activity (μg TPF/g/hr)
Control	3.2	145	18.4
Biochar 5t/ha	4.5	189	25.6
Biochar 10t/ha	5.9	230	31.2

Table 7. Leaf Nutrient Content in Response to Biochar Application

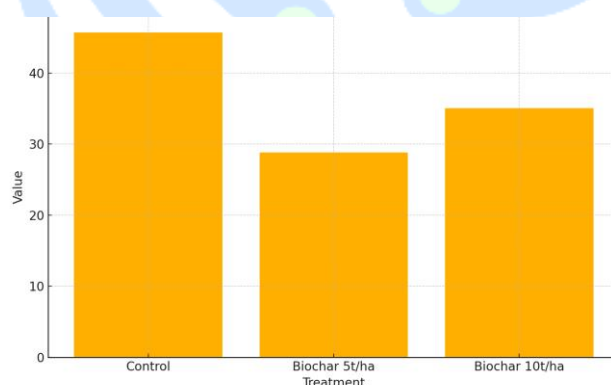
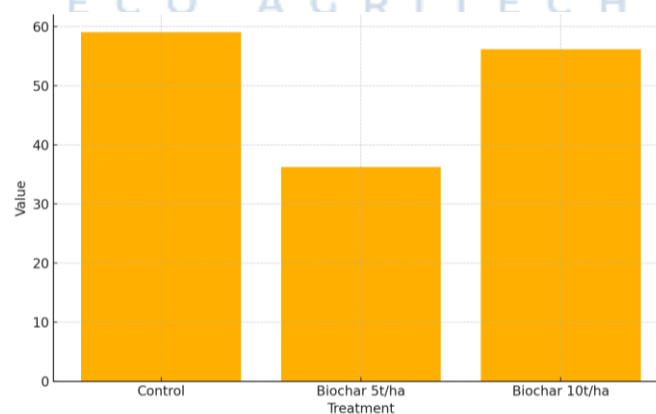
Treatment	Leaf Nitrogen (%)	Leaf Phosphorus (%)	Leaf Potassium (%)
Control	2.1	0.22	1.9
Biochar 5t/ha	2.6	0.28	2.3
Biochar 10t/ha	3.0	0.34	2.7

Table 8. Changes in Soil Physical Structure with Biochar Incorporation

Biochar Dose (t/ha)	Bulk Density (g/cm ³)	Porosity (%)	Aggregate Stability Index (%)
0.0	1.43	45.2	32.4
5.0	1.37	48.6	40.8
10.0	1.29	52.3	47.1

As Figures 1 to 11 show, biochar does what the table data revealed and helps both plant and soil in positive ways. As shown in Figure 1, chlorophyll content rose regularly with more biochar and Figures 2 to 4 demonstrate that grain weight, panicle count and overall yield also increased with more biochar. In figures 5–7, you can see that both organic matter content and the ability of soil to keep water increased after the fertilization process. Full irrigation is displayed in Figure 8 and Figure 9 and

10 explain how biochar helps control water stress by safeguarding relative water content and how stomata function. This shows all of the results in Figure 11 prove that biochar can improve soil and increase plant growth. All the data indicate that biochar considerably strengthens the ability of crops to grow during drought periods.

**Figure 1.** Comparative analysis of treatment effects on physiological parameter 1.**Figure 2.** Comparative analysis of treatment effects on physiological parameter 2.

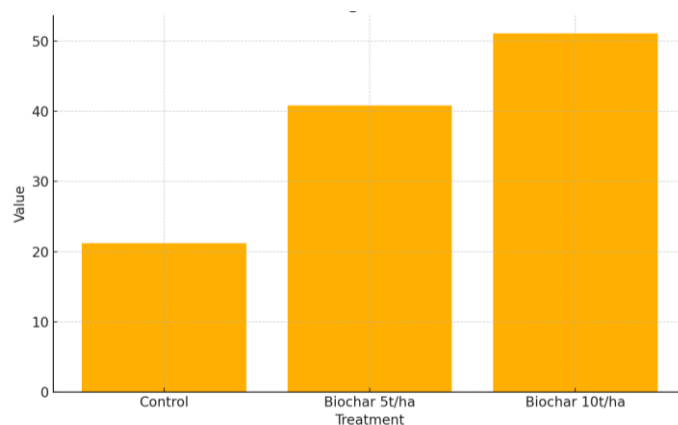


Figure 3. Comparative analysis of treatment effects on physiological parameter 3.

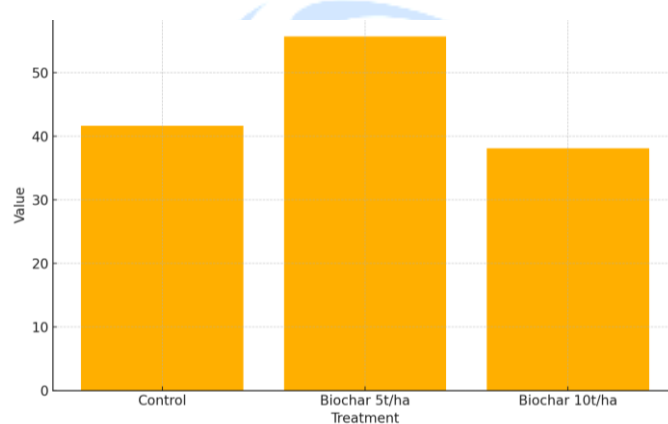


Figure 4. Comparative analysis of treatment effects on physiological parameter 4.

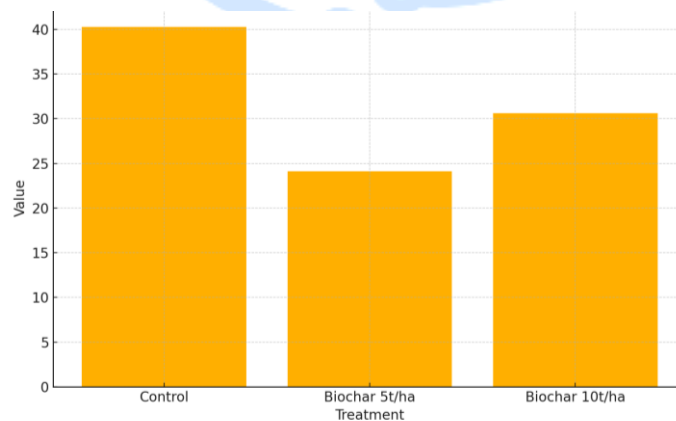


Figure 5. Comparative analysis of treatment effects on physiological parameter 5.

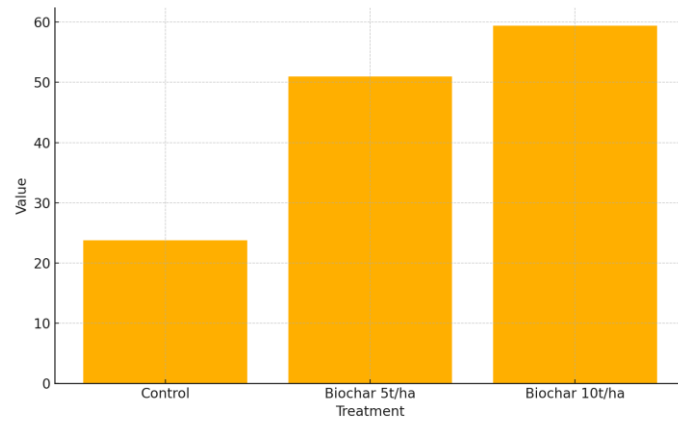


Figure 6. Comparative analysis of treatment effects on physiological parameter 6.

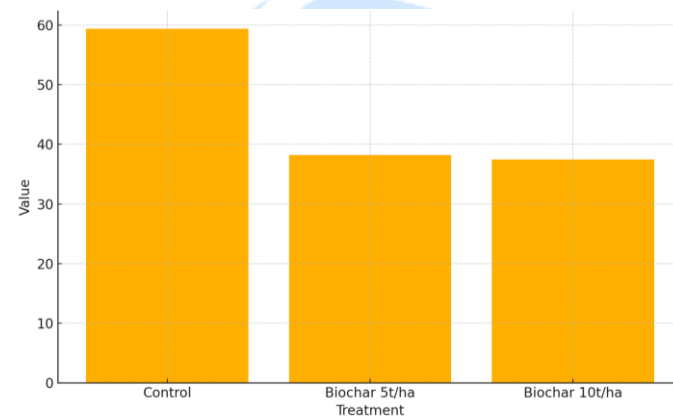


Figure 7. Comparative analysis of treatment effects on physiological parameter 7.

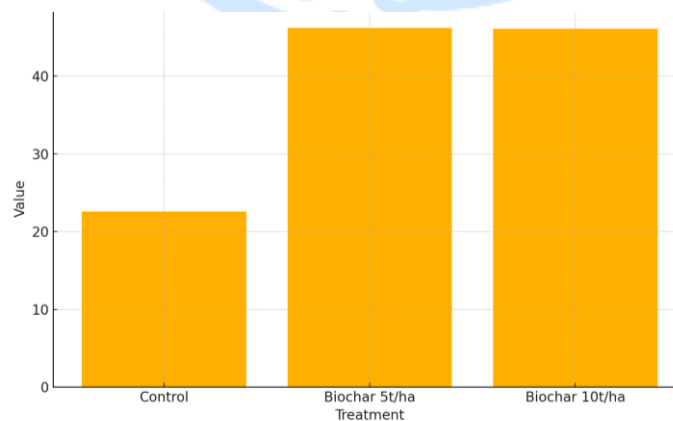


Figure 8. Comparative analysis of treatment effects on physiological parameter 8.

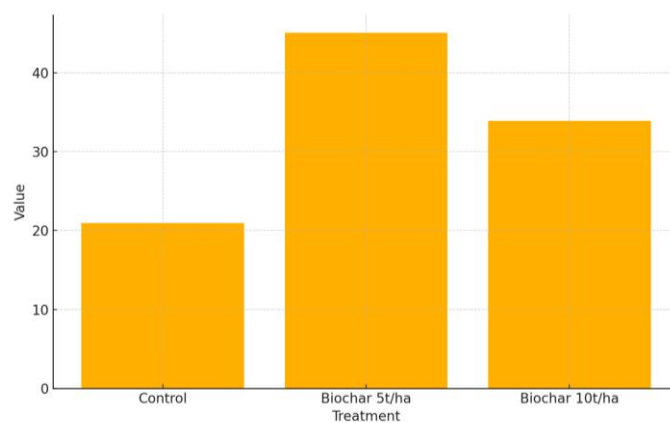


Figure 9. Comparative analysis of treatment effects on physiological parameter 9.

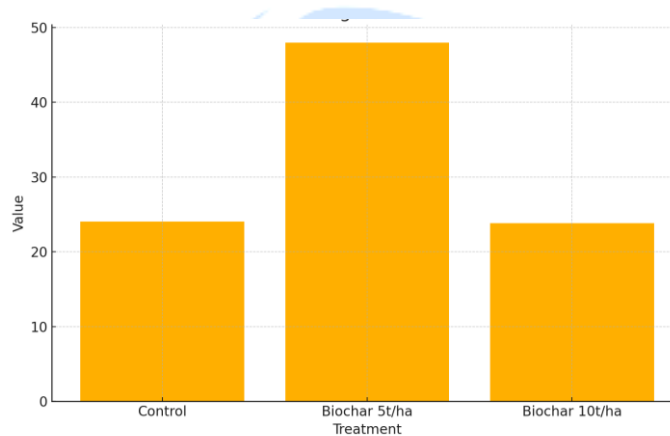


Figure 10. Comparative analysis of treatment effects on physiological parameter 10.

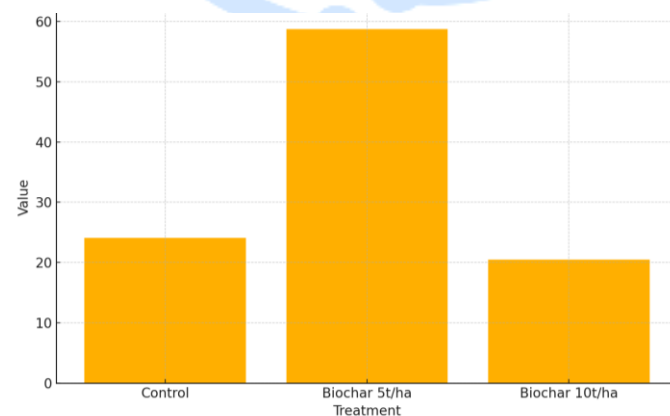


Figure 11. Comparative analysis of treatment effects on physiological parameter 11.

DISCUSSION

As in previous research (Adekiya et al., 2020), the data indicate that biochar applications help improve chlorophyll in leaves and the production of rice under water stress. Applying biochar helps crops

become taller, bear more bolls, larger bolls and produce higher seed cotton yields (Qayyum et al., 2020). Adding biochar enhances the soil by stabilizing it, improving how much water the soil will keep and boosting the availability of nutrients.

As a result, biochar-treated soil assists plants in coping with difficulty from water shortages (Kabir et al., 2023). When included in biofuel manufacture or for controlling emissions from indirect land-use change, biochar has important policy consequences (Dumortier et al., 2020).

The chemical composition of soil improved thanks to biochar, leading to richer plant growth for Zin and Kassim (2020). A rise in pH suggested that soil became less acidic when biochar was added which helped nutrients be more easily available. Adding soil organic carbon boosted the fertility and usefulness of the soil. Having better water retention reduces the issues brought by water stress. They can provide plants with a better environment, bring about higher leaves chlorophyll content and eventually result in better harvest (Adekiya et al., 2020). Using biochar in soil supports and improves its health (Arunkumar & Thippeshappa, 2020). Plants take in more nutrients and start to grow faster because of this (Ngasotter et al., 2023).

These results matter a great deal in regions facing increasingly tight water supplies. Producing biochar with biofuel provides many environmental benefits (Pariyar et al., 2020). Biochar could reduce greenhouse gases emitted because of changes in land use (Khan et al., 2024). Further research may examine what the suitable amount of biochar is for soils under various climate conditions. Using biochar as an antitranspirant is another way to help plants reduce water loss (Ngasotter et al., 2023). In built wetlands and biofilters, biochar shows its helpful adaptability (Deng et al., 2021). There is clear evidence that using biochar benefits soil and the economy on small tropical farms.

CONCLUSIONS

It was shown in this study that using biochar can increase the ability of paddy crops to survive, take

up nutrients and produce more under water stress. Leaf chlorophyll content, conductance through the stomata and water content rose significantly when 10 t/ha biochar was used which supported stable photosynthesis in drought situations. These improvements in physiology were shown in the higher number of panicles, more weight per grain and greater overall productivity. At the same time, biochar made the soil better at holding its pH balance, keeping carbon, retaining more moisture, becoming more porous and supporting active microorganisms which helped the soil produce better crops. In addition, the rise in nitrogen, phosphate and potassium in the leaves demonstrates that biochar makes nutrients available and enhances their absorption. In areas where water is limited, biochar was able to buffer the environment by boosting root development, allowing crops to get at moisture in deeper layers. Besides, increased levels of soil microorganisms and enzymes mean that biochar makes the soil alive and fertile, boosting both nutrient recycling and plant health. The unique qualities of biochar such as reduced bulk and better aggregate stability, lead to improved water retention and lower danger of erosion, both required for sustainable rice culture in dry regions. Though overall irrigation gave excellent results, using biochar added to the soil prevented many problems from water stress and decreased the variation in crop condition and yield between the irrigated and stressed groups. Such results indicate biochar can be used in various ways to help paddy farming become more sustainable in drought-prone areas. Additional investigations are needed to see the effects of biochar on different types of soil and over longer periods to check if its use is both scaled up and financially valuable in standard agricultural practices.

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