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Rice Growth Performance, Nutrient Use Efficiency and Changes in Soil Properties Influenced by Biochar under Alternate Wetting and Drying Irrigation

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Abstract: Water-saving irrigation occasionally causes an inconsequential yield loss in rice; thereby, biochar incorporation in this context has great scope due to its properties, including the release of nutrients and improving soil physicochemical properties. An experiment was conducted to investigate the effect of biochar combined with fertilizer on physiological response, water and nutrient efficiency of rice and changes in biochemical properties of soil under AWD (alternate wetting and drying) irrigation system. Two types of irrigation practice, such as AWD and CF (continuous flooding), and four types of fertilizer combination, namely T1: 25% Rice husk biochar (RHB) + 75% of recommended fertilizer dose (RFD); T2: 25% oil palm empty fruit bunch biochar (EFBB) + 75% of RFD; T3: 100% RFD; and T0: 0% biochar and fertilizer, were assigned to assess their impacts. The AWD irrigation produced a sharply reduced grain yield (210.58 g pot^{-1}) compared to CF irrigation (218.04 g pot^{-1}), whereas the biochar combination treatments T1 and T2 produced greater yields (260.27 and 252.12 g pot^{-1}, respectively), which were up to 12.5% higher than RFD. Within AWD, irrigation water usage by T1 and T2 (98.50 and 102.37 g L^{-1}, respectively) was profoundly reduced by up to 28.8%, with improved water use efficiency (WUE). The main effect of biochar treatment T1 and T2 also increased photosynthesis rate during vegetative and maturing stage (up to 17.6 and 24.4%, respectively), in addition to boosting agronomic efficiency of nitrogen (N), phosphorous (P) and potassium (K) compared to RFD (T3). Nevertheless, T1 and T2 significantly enhanced the total carbon and nitrogen; dehydrogenase and urease enzyme activities also increased in both irrigation regimes. The results reveal that the integrated application of RHB and EFBB with fertilizer in the AWD regime significantly reduces irrigation water usage and improves nutrient use efficiency, WUE and soil biochemical properties with a minimum yield penalty for rice.

Keywords: rice; water use efficiency; biochar; photosynthesis; nutrient uptake and soil enzymes

Citation: Haque, A.N.A.; Uddin, M.K.; Sulaiman, M.F.; Amin, A.M.; Hossain, M.; Solaiman, Z.M.; Mosharrof, M. Rice Growth Performance, Nutrient Use Efficiency and Changes in Soil Properties Influenced by Biochar under Alternate Wetting and Drying Irrigation. *Sustainability* **2022**, *14*, 7977. https://doi.org/10.3390/su14137977

Academic Editor: Sean Clark

Received: 10 December 2021
Accepted: 10 January 2022
Published: 30 June 2022

1. Introduction

Over four billion people depend on rice as their main food, and the requirement is projected to rise through 2025 as the world's population grows [1]. In 2017, over 748 million tons of rice were produced worldwide, involving more than 160 million hectares of land [2]. Irrigation of rice consumes one-third of the world's developed freshwater [3] and accounts for half of Asia's total freshwater supply [4]. As the global population grows, the freshwater requirement for irrigation will rise unless water management strategies that minimize water usage are developed and applied [5].

There are two kinds of rice produced in Malaysia: wetland paddy in Peninsular Malaysia and upland paddy in Sabah and Sarawak. Lowland irrigated paddy fields in Peninsular Malaysia account for around 88% of total rice-producing land [6]. In Malaysia, the agriculture sector uses approximately 68% of total water usage, whereas the irrigation efficiency varies from <40 to 50% in the context of small to large irrigation schemes [7]. Malaysia still depends on lowland irrigated paddy for rice production; although the yield of lowland rice is greater, it needs a large amount of water [8]. To overcome this excessive water demand, many water-saving regimes have been practised, such as an aerobic rice system, direct seeding and non-flooded mulching culture, etc. In this context, alternate wetting and drying (AWD) irrigation has a great potential to overcome the core problem of increasing rice yield while coping with less irrigation input [9].

The AWD is considered to be one of the most efficient irrigation systems. It restrains irrigation until a few days after ponded water disappears, through which up to 43% of irrigation water can be saved without significant yield loss [9,10]. Rice roots may access water in the subsoil, which remains moist even when ponded water is absent; this fact is considered for AWD irrigation. Irrigating the field when the water reaches a depth of 15 cm and maintaining the field wet for 10 days after transplanting, or 20 days after direct seeding, as well as one week before and after flowering, is advised in the AWD [9]. The efficacy of AWD might vary and be significantly influenced by soil type and hydrological factors, resulting in yield loss of rice [11]. In AWD irrigation, the soil undergoes significant modifications when it switches from flooded to non-flooded regimes; these alternate changes cause a rather substantial alteration in the soil physio-chemical environment [12]. In comparison to flooded irrigation, AWD produces greater oxidizing conditions in the soil, which increases the microbial breakdown of plant waste and organic compounds in the soil [13]. Additionally, heterotrophic respiration of soil microbes takes place during the dry stage of AWD, causing enhanced mineralization of soil organic carbon [14], and the enhanced activity of denitrifying bacteria accelerates the release of oxides of N by the denitrification process [15]. Furthermore, due to the water-limiting condition during the dry cycles AWD, plants absorb a reduced quantity of nutrients than conventional flooded rice, resulting in reduced water productivity [16]. However, nutrient absorption of rice under AWD varies from that in continuous flooding (CF) due to the physiological response of rice to water stress and nutrition available in the AWD technique [17]. These phenomena may overlook the water-saving effectiveness of AWD irrigation. To address these challenges of AWD, the application of organic amendments such as biochar into the soil has the potential to improve soil properties. The incorporation of organic amendments to overcome these limitations of AWD irrigation for sustainable rice production is the main challenge of this study.

Biochar is produced from organic waste pyrolyzed at high temperatures under a depleted oxygen atmosphere, characterized by black-colored, carbonaceous, highly porous and most stable organic compounds [18]. Biochar can be a replacement that not only impacts soil carbon (C) sequestration but also alters its physicochemical and biological characteristics [19]. Due to the presence of humic substances and nutrients, biochar incorporation increases the pH, cation exchange capacity, organic C, total N and available P status of the soil [20]. Biochar application to soil may enhance soil nutrient retention for N, P and K, as well as increase the balance of soil organic matter [21]. Soil enzymes are a key indicator of soil quality in crop production systems and are involved in biochemical processes of nutrient cycling [22]; moreover, biochar-amended soil showed advantages in improving soil quality and retaining nutrients, increasing plant growth [23]. Due to these beneficial characteristics, the addition of biochar increased the rice yield, as reported in several studies [24,25]. Fresh rice husks obtained as a byproduct of the procedure are used as fuel in big rice processing mills in Malaysia and produced an estimated 592,477 tons of rice husk and 32,000 tons of rice husk biochar (RHB) in 2011 [26]. Malaysia is the world's second top oil palm producer, and many byproducts are produced from the processing industry [27]. Oil palm empty fruit bunches (EFB) accounted for a significant quantity of waste compared to other oil palm waste, and turning EFB into biochar may be an alternate waste management method [28].

Due to the ameliorating capacity of biochar, the application of biochar with AWD water-saving irrigation practice to improve the soil properties for increased rice yield with better environmental quality is the new contribution of this research. Therefore, this study hypothesized that integrated use of rice husk biochar (RHB) and oil palm empty fruit bunch biochar (EFBB) with chemical fertilizer enhanced the physiological response, yield and also the nutrient availability and soil chemical properties under AWD irrigation. Considering this issue, this experiment was conducted to investigate the effect of integrated use of RHB and EFBB with fertilizer on rice growth responses and water use efficiency under AWD irrigation; moreover, we intended to determine the combined impact of RHB and EFBB with fertilizer on nutrient use efficiency and biochemical properties of soil.

2. Materials and Methods

2.1. Experimental Location and Pot Setup

A pot experiment was conducted from September to December 2020 at the glasshouse of the Agriculture faculty, Universiti Putra Malaysia, located in Serdang, Selangor, Malaysia (3°00′ N, 101°71′; 56.8 m). The monthly weather data during this experimental period is given in Appendix A (Table A1). The experiment was carried out in a randomized complete block design (RCBD) with four replications. There were two factors used in this experiment. Two irrigation regimes, i.e., alternate wetting and drying (AWD) and continuous flooding (CF), were assigned as the first factor, and four levels of integrated use of biochar with fertilizer treatments were considered as T1: 25% NPK from rice husk biochar + 75% NPK from chemical fertilizer; T2: 25% NPK from oil palm empty fruit bunch biochar + 75% NPK from chemical fertilizer; T3: 100% NPK from chemical fertilizer; and T0: no biochar and chemical fertilizer application. Here, N, P and K represent nitrogen, phosphorus and potassium, respectively, and the nutrient reduction in the integrated biochar treatments was calculated based on the N content of the biochar.

In this experiment, altogether, 32 pots of 45 cm in diameter and 52 cm in height were used, and the pots were filled with 50 kg of air-dried soil collected from 0–15 cm depth of paddy field from the TanjungKarang, Kuala Selangor, Malaysia (3°28.2730′ N and 101°8.7050′ E). Furthermore, in the AWD irrigation-treated pots (16 pots), a perforated PVC pipe (4 cm in diameter and 30 cm in height) was placed in the soil up to 20 cm deep while staying 10 cm above the soil surface. The remaining pots under continuous flooding irrigation (16 pots) retained the standard. The base of each pot was sealed to prevent water loss, and biochars were applied in the respective pot and mixed thoroughly and irrigated for decomposition about 10 days before the transplantation of seedlings.

A rice variety MR297, which was developed by the Malaysian Agricultural Research and Development Institute (MARDI), was used in this experiment. According to the recommendation of MARDI, N (121 kg ha^{-1}), P (29 kg ha^{-1}) and K (100 kg ha^{-1}) were supplied from urea, triple superphosphate (TSP) and muriate of potash (MOP), respectively. Considering this recommendation, 100% N, P and K-treated pots were 3.1 g, 0.7 g and 2.5 g, respectively.

Four seedlings (21 days old) were transplanted per pot by keeping a 15 cm planting distance; for the next 15 days, a further 3–5 cm of ponding water level was retained for seedling establishment. Moreover, in the individual AWD-treated pots, a perforated PVC pipe was inserted up to 20 cm below the soil surface to monitor the water levels in the soil. In AWD pots, the soil was allowed to dry until water levels reached 15 cm from the surface, and after that, the pots were flooded to 5 cm above the soil surface. This periodical drying cycle continued for the whole growth period, except in the flowering stage, while in the continuously flooded irrigation pot, water levels were kept above 3–5 cm from the soil surface during the whole growth period of the rice. Other intercultural operations, such as weeding and spraying pesticides, were conducted when necessary. Rice was harvested 98 days after transplanting, when it had reached full maturity.

2.2. Chemical Characterization of Soil and Biochar

An auger was used to collect the post-harvest soil samples (0–15 cm depth) from each pot. After collecting soil samples, they were air-dried, pulverized and sieved through a 2 mm screen to analyze soil chemical properties. Fresh soil samples were used to determine the enzyme activities.

A glass electrode digital pH meter was used to test the soil pH in a soil solution (soil:water = 1:2.5). A dry combustion technique was used to determine the total carbon (TC), nitrogen (TN) and sulphur (TS) content of the soil by a CNS elemental analyzer (LECO Corporation, Saint Joseph, MO, USA). Bray and Kurtz's method was used to extract the available Pin the soil, which used 0.03 N and 0.1 N HCl as its extracting solution, and an inductively coupled plasma spectrometry (ICP-OES) was used to determine the P concentration in that solution. The ammonium acetate (NH_4OAc) leaching method, described by Schollenberger (1945), was used to determine the cation exchange capacity of soil. Ammonium acetate (NH_4OAc) was used to replace the exchangeable cation of soil by ammonium (NH_4^+) ions, followed by replacing the ammonium by 1 M potassium chloride (KCl); the replaced NH_4^+ was measured to obtain the CEC value of the soil. The exchangeable cations (K^+, Ca^{2+} and Mg^{2+}) in the soil replaced by ammonium acetate (NH_4OAc) were determined using an atomic absorption spectrophotometer (PerkinElmer Analyst 400). The initial soil properties are shown in Appendix A (Table A2).

There were two types of commercially produced biochar used in this study: rice husk biochar (produced from rice husk pyrolyzed at 300 °C) and oil palm empty fruit bunch biochar (produced from oil palm bunch pyrolyzed at 450 °C). A CNS analyzer (LECO Corporation) was used to analyze the total C, N and S content in the biochar. Total P, K and Ca in the biochar were analyzed by the dry-ashing method [29], followed by using an atomic absorption spectrophotometer (AAS, PerkinElmer Analyst 400). The pH of the biochar was measured from the 1:10 (w/w) ratio solution of biochar and water using a glass electrode digital pH meter. The chemical properties of RHB and EFBB are given in Appendix A (Table A3).

2.3. Data Collection

2.3.1. Physiological Parameters of Rice

A portable photosynthesis device (Li6400XT, LICOR Environmental, Lincoln, NE, USA) was used to assess the photosynthesis rate, stomatal conductance and transpiration rate of rice. All the parameters were measured at random between 9.00 a.m. and 11 a.m., with the temperature and humidity ranging from 25 to 32 °C and 60 to 90%, respectively. Measurements were taken from the abaxial surface of the flag leaves during the vegetative and maturing (25 and 86 days after transplanting, respectively) growth stages of rice. The measurements were completed within one hour to reduce the error caused by the diurnal cycle of photosynthesis.

2.3.2. Yield-Contributing Parameters and Yield of Rice

Different yield-contributing characters, such as tiller number per hill, panicle length and number of grains per panicle, were recorded at harvest. Grain and straw were sorted and weighed after harvesting from each pot. The biological yield of a pot is the sum of total grain and straw production.

2.3.3. Quantity of Irrigation Water Volume and Water Productivity

The total volume of water (L) consumed by the plants in a pot was calculated by subtracting the volume of water required for pot preparation before transplanting seedlings from the total volume of water applied until crop harvesting. A volumetric jar was used to measure the amount of water applied during each irrigation.

Water use efficiency (WUE) of rice was calculated by dividing the biological yield by the total volume of water applied:

$$\text{WUE (g L}^{-1}\text{) = Biological yield (g)/Total irrigated water (L)}$$

2.3.4. Determination of Enzymatic Activities of Soil

The dehydrogenase activity of soil was determined by reducing 2,3,5-triphenyl tetrazolium chloride using the method by Casida et al. [30]. An amount of 5 g of soil was treated with 0.05 g of calcium carbonate ($CaCO_3$) and 1 mL of 3% 2,3,5-triphenyl tetrazolium chloride aqueous solution (TTC), and the mixture was incubated at 37 °C for 24 h. TTC converted to 2,3,5-triphenyl formazan (TPF) due to dehydrogenase enzyme activity. This converted TPF was extracted with acetone and filtered by Whatman No. 42, and the absorbance was determined with a spectrophotometer at 485 nm.

The urease activity was assayed by the procedure described by McGarity and Myers [31]. Fresh soil (1g) was taken in a 100 mL volumetric flask, followed by adding 1 mL of toluene and leaving it standing for 15 min. Following that, 10 mL of buffer solution (pH 7) and 5 mL of urea solution (10%) were added to the flask; the flask was then shaken and incubated for 3 h at 37 °C. Next, the contents of the flask were mixed thoroughly and filtered by Whatman No. 42. The released ammonia due to the urease activity was measured by the indophenol blue method, and a spectrophotometer was used to detect absorption at 630 nm.

The acid phosphatase activity of soil was determined by following the method of Tabatabai and Bremner [32]. One gram of fresh soil was taken in a 50 mL volumetric flask and added to 0.2 mL of toluene followed by 4 mL of modified universal buffer (MUB, pH 6.5) and 1 mL of 0.05 M *p*-nitrophenyl solution. After mixing the contents for a few seconds, the mixture was incubated at 37 °C for 1 h. At the end of incubation, 1 mL of 0.5 M $CaCl_2$and 4 mL of NaOH (sodium hydroxide) were combined with the mixture. After that, the flask was swirled for a few seconds and filtered with Whatman No. 42, and the intensity of the color was measured by a spectrophotometer at 430 nm.

2.3.5. Determination of Nutrient Concentration and Uptake by Rice

After harvesting the plants at maturity, grain and straw were collected, separated and dried in the oven at 70° C for 72 h to get a stable weight. Further, the dried samples were finely milled for total N, P and K in samples. Total N content in grain and straw samples was measured by dry combustion using a CNS analyzer (LECO Corporation). The dry-ashing technique was used to determine total P and K concentration in the grain and straw samples, followed by an atomic absorption spectrophotometer analysis (AAS, PerkinElmer Analyst 400). Moreover, the nutrient uptake by the plant was calculated by the following equation:

$$\text{Nutrient uptake } = \frac{\text{Grain/straw yield } \times \text{Nutrient concentration in grain/straw}}{100}$$

2.3.6. Estimation of Nutrient Use Efficiency

Different nutrient use efficiency parameters were measured by the following equations:

$$\text{Agronomic nutrient use efficiency } \left(\text{g g}^{-1}\right) = \frac{\text{Gf} - \text{Gu}}{\text{Na}}$$

Here,

Gf = Grain yield in the fertilized pot, Gu = Grain yield in the unfertilized pot, Na = Amount of applied nutrient.

2.3.7. Percent Relative Data

For each element, the relative data of the value were presented as percentages relative to control. Relative data $(\%) = \frac{\text{Treatment value}-\text{control value}}{\text{control value}} \times 100$.

2.4. Statistical Analysis

The statistical software R (version 3.6.1, R Foundation for Statistical Computing, Vienna, Austria) was used to analyze the experimental data. The two-way analysis of variance (ANOVA) was conducted to evaluate the statistical difference among the treatments. Tukey's test was used to compare the significant difference between the mean values at a 0.05 level of significance.

3. Results

3.1. Physiological Response of Rice Influenced by Integrated Application of Biochar and Fertilizer under Two Irrigation Regimes

Photosynthesis activity of rice was significantly affected ($p < 0.05$) by irrigation regimes and biochar treatments, and their interaction was insignificant during the vegetative stage and maturing stage (Table 1). In the main effect of irrigation, during the vegetative and maturing stage, CF irrigation showed a higher photosynthesis rate (19.91 and 18.48 µmol $m^{-2}s^{-1}$, respectively) over the AWD regime (18.08 and 16.18 µmol $m^{-2}s^{-1}$, respectively). On the other hand, for the main effect of biochar, T1 and T2 biochar treatments showed statistically similar and significantly higher photosynthesis rate (21.72 and 21.11 µmol $m^{-2}s^{-1}$, respectively), followed by T3 (18.47 µmol $m^{-2}s^{-1}$) and the lowest from T0 (14.67 µmol $m^{-2}s^{-1}$) during the vegetative stage, while similar trends were also observed in the maturing stage.

Table 1. Physiological response of rice influenced by integrated application of biochar and fertilizer under two irrigation regimes.

Irrigation	Photosynthesis Rate (µmol $m^{-2}s^{-1}$)		Stomatal Conductance (mmol $m^{-2}s^{-1}$)		Transpiration Rate (mmol $m^{-2}s^{-1}$)	
	Vegetative Stage	Maturing Stage	Vegetative Stage	Maturing Stage	Vegetative Stage	Maturing Stage
AWD	18.08 b	16.18 b	0.66 b	0.51 b	9.14 b	7.56 b
CF	19.91 a	18.48 a	0.85 a	0.73 a	11.76 a	9.92 a
Significance level	**	**	***	***	***	***
Biochar Treatment						
T1	21.72 a	20.90 a	0.94 a	0.76 a	11.52 a	9.88 a
T2	21.11 a	19.90 a	0.87 a	0.73 a	11.20 a	9.41 ab
T3	18.47 b	16.80 b	0.70 b	0.62 a	10.74 a	8.71 b
T0	14.67 c	11.73 c	0.50 c	0.37 b	8.34 b	6.96 c
Significance level	***	***	***	***	***	***

Means in a column with different letters reveal a significant difference ($p < 0.05$) between the main effect of irrigation system and biochar treatment. In contrast, no significant variation ($p < 0.05$) was found for the interaction effect by two-way ANOVA. Symbols ** and *** indicate significant variation among the treatments at p values < 0.01 and 0.001, respectively. AWD, alternate wetting and drying; CF, continuous flooding; RHB, rice husk biochar, EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose. T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar).

There was a significant effect ($p < 0.05$) of different irrigation regimes and biochar treatments on stomatal conductance of rice during the vegetative and maturing stages, though no effect was found in their interaction (Table 1). Considering the main effect of irrigation, the AWD regime reduced stomatal conductance compared to CF irrigation (0.66 and 0.85, respectively) at the vegetative stage, whereas identical findings were also observed in the maturing stage. Moreover, in the case of the biochar effect, statistically similar and higher stomatal conductance was obtained by T1 and T2 (0.94 and 0.87 mmol $m^{-2}s^{-1}$, respectively) over T3 and T0 (0.78 and 0.63 mmol $m^{-2}s^{-1}$, respectively) during the vegetative stage. However, at the maturing stage, T1, T2 and T3 produced similar results (0.76, 0.73and 0.62 mmol $m^{-2}s^{-1}$, respectively) compared to T0 (0.37 mmol $m^{-2}s^{-1}$).

The transpiration rate of rice was significantly ($p < 0.05$) influenced by different irrigation regimes and biochar treatments, but their interaction occurred during the two growth stages (Table 1). Like photosynthesis and stomatal conductance, the AWD regime decreased the transpiration rates during the vegetative and maturing stages (9.14 and 7.56 mmol $m^{-2}s^{-1}$, respectively) compared to the CF irrigation (11.76 and 9.92 mmol $m^{-2}s^{-1}$, respectively). Furthermore, T1, T2 and T3 produced identical transpiration rates for the biochar effect (11.52, 11.20 and 10.74 mmol $m^{-2}s^{-1}$, respectively) but significantly greater than T0 (8.34 mmol $m^{-2}s^{-1}$) at the vegetative stage of rice. At the maturing stage, similar transpiration rates were found for T1 and T2 (9.88 and 9.41 mmol $m^{-2}s^{-1}$, respectively), followed by T3 (8.71 mmol $m^{-2}s^{-1}$) and the lowest observed in T0 (6.96 mmol $m^{-2}s^{-1}$).

3.2. Effect of Integrated Biochar and Fertilizer Application under Two Irrigation Regimes on Yield-Contributing Characters and Yield of Rice

Yield-contributing characters, such as the number of tillers hill^{-1} and grain numbers panicle^{-1}, were significantly ($p < 0.05$) impacted by several irrigation and biochar treatments, while their interaction was insignificant (Table 2). From the main effect of irrigation, the AWD regime produced a reduced number of tillers hill^{-1} and grain numbers panicle^{-1} (22.81 and 196.08, respectively) compared to CF irrigation (23.63 and 200.52, respectively). Nevertheless, considering the main effect of biochar, higher and similar number of tillers hill^{-1} and grain numbers panicle^{-1} were produced by T1 (27.88 and 208.39, respectively) and T2 (28.15 and 208.31, respectively). These numbers were profoundly greater than T2 (24.97 and 201.00, respectively), and the lowest values were obtained by T0 (11.88 and 175.49, respectively).

Table 2. Yield-contributing characters and yield influenced by the significant main effect of irrigation regimes and integrated use of biochar and fertilizer.

Irrigation	Number of Tillers Hill^{-1}	Grain Numbers Panicle^{-1}	Grain Yield (g Pot^{-1})	Straw Yield (g Pot^{-1})
AWD	22.81 b	196.08 b	210.58 b	270.25 b
CF	23.63 a	200.52 a	218.04 a	278.97 a
Significance level	*	**	*	*
Biochar Treatment				
T1	27.88 a	208.39 a	260.27 a	327.34 a
T2	28.15 a	208.31 a	252.12 a	319.36 a
T3	24.97 b	201.00 b	231.27 b	304.83 b
T0	11.88 c	175.49 c	113.58 c	146.91 c
Significance level	***	***	***	***

Means in a column with different letters reveal a significant difference ($p < 0.05$) between the main effect of the irrigation system and biochar treatment. In contrast, no significant variation ($p < 0.05$) was found for the interaction effect by two-way ANOVA. Symbols *, ** and *** indicate significant variation among the treatments at p values < 0.05, 0.01 and 0.001, respectively. AWD, alternate wetting and drying; CF, continuous flooding; T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar; EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

The grain and straw yields of rice were significantly ($p < 0.05$) impacted by the effect of the different irrigation regimes and biochar treatments, but their interaction was insignificant (Table 2). The main effect of irrigation demonstrated that the CF irrigation enhanced rice grain and straw yields (218.04 and 278.97 g Pot^{-1}, respectively) over the AWD regime (210.58 and 270.25 g Pot^{-1}, respectively). For the main effect of biochar, greater grain yield was produced by T1 (260.27 g Pot^{-1}), which was statically similar to T2 (252.12 g Pot^{-1}), followed by T3 (231.27 g Pot^{-1}) and the minimum grain yield obtained by T0 (113.58 g Pot^{-1}). Consecutively, a similar trend of treatment variation by different biochar treatments was also observed in the straw yield production, and the values varied from 146.91 to 327.34 g Pot^{-1}.

3.3. Irrigation Water Volume and Water Use Efficiency of Rice Influenced by Various Biochar Treatments under AWD and CF Irrigation

The irrigation water volume (IWV) and water use efficiency (WUE) of rice were significantly ($p < 0.05$) influenced by the interaction effect of irrigation regimes and biochar treatments (Figure 1). The greater IWV usage occurred through consumption in biochar treatments such as T1, T2 and T3 with CF irrigation (130.40, 135.12 and 138.25 L, respectively). In contrast, comparatively lower significant but similar IWV usage was observed in AWD with T1 and T2 (98.50 and 102.38 L, respectively) and the lower results obtained by T0 with AWD and CF irrigation (68.92 and 90.22 L, respectively). Simultaneously, in the same biochar treatment case, CF-treated Pots showed significantly greater irrigation water consumption than AWD irrigation.

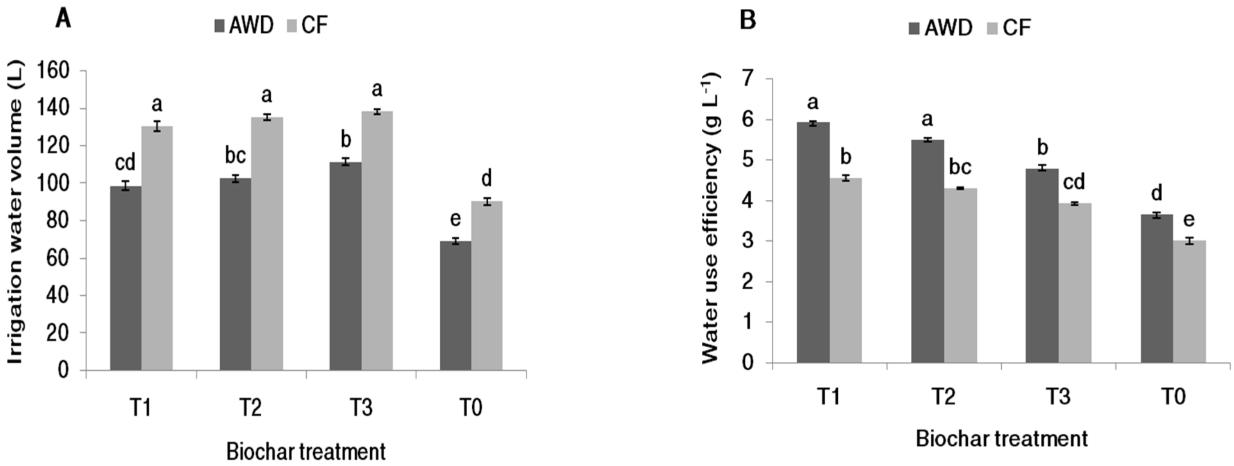

Figure 1. Irrigation water volume (**A**) and water use efficiency (**B**) of rice influenced by various biochar treatments under AWD and CF irrigation. Means with different letters reveal a significant difference ($p < 0.05$) between the treatments. Significant interaction effect between irrigation and biochar was observed by two-way ANOVA. Vertical bars indicate standard error of means (±SE, $n = 8$). T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar, EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

A significantly improved WUE was exhibited by T1 and T2 (5.91 and 5.49 g L^{-1}, respectively) compared to T3 (4.77 g L^{-1}) and T0 (3.64 g L^{-1}) of biochar treatments under the AWD regime. With the CF irrigation, the lowest WUE was observed in T0 (3.01 g L^{-1}) compared to the rest of the biochar treatments; furthermore, T1 and T2 exhibited identical and significantly higher results (4.56 and 4.30 g L^{-1}, respectively), followed by T3 (3.93 g L^{-1}). Meanwhile, T3 with AWD regime showed identical results compared to T1 and T2 treatments of CF irrigation. Significantly increased WUE was observed in AWD irrigation with the same biochar treatment over the CF regime.

3.4. Nutrient Uptake of Rice Influenced by Integrated Application of Biocharand Fertilizer under Two Irrigation Regimes

Nitrogen (N) and phosphorus (P) uptake by rice was significantly ($p < 0.05$) influenced by different irrigation and biochar treatments, while their interaction did not show any significant effect (Table 3). Moreover, Potassium (K) uptake was only significantly ($p < 0.05$) impacted by biochar treatments. In the case of the main effect of irrigation, a markedly reduced uptake of N and P (4.86 and 1.43 g Pot^{-1}, respectively) was observed under the AWD regime compared to CF irrigation (5.26 and 1.63 g Pot^{-1}, respectively). From the biochar effect, the higher N uptake was observed in T1 (6.57 g Pot^{-1}) and T2 (6.19 g Pot^{-1}) treatments, followed by T3 (5.19 g Pot^{-1}) and the lowest uptake by T0 (2.28 g Pot^{-1}). Moreover, maximum P uptake was obtained by T1 treatments, which was significantly different from other treatments by showing the following trend: T1 > T2 > T3 > T0 with values 2.10, 1.85, 1.59 and 0.58 g Pot^{-1}, respectively. Meanwhile, much as the N uptake, significantly enhanced K uptake was found in T1 and T2 (5.87 and 6.01 g Pot^{-1}, respectively) over T3 (4.98 g Pot^{-1}) and T0 (1.89 g Pot^{-1}).

Table 3. Nutrient uptake of rice influenced by integrated application of biochar and fertilizer under two irrigation regimes.

Irrigation	Nitrogen Uptake (g Pot^{-1})	Phosphorus Uptake (g Pot^{-1})	Potassium Uptake (g Pot^{-1})
AWD	4.86 b	1.43 b	4.65 a
CF	5.26 a	1.63 a	4.71 a
Significance level	**	***	ns
Biochar Treatment			
T1	6.57 a	2.10 a	5.87 a
T2	6.19 a	1.85 b	6.01 a
T3	5.19 b	1.59 c	4.98 b
T0	2.28 c	0.58 d	1.89 c
Significance level	***	***	***

Means in a column with different letters reveal a significant difference ($p < 0.05$) between the main effect of the irrigation system and biochar treatment. In contrast, two-way ANOVA found no significant variation ($p < 0.05$) for the interaction effect. Symbols **, *** and ns indicate significant variation among the treatments at p values < 0.01, 0.001 and non-significant, respectively. AWD, alternate wetting and drying; CF, continuous flooding; T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar, EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

3.5. Nutrient Use Efficiency of Rice Influenced by Integrated Application of Biochar and Fertilizer under Two Irrigation Regimes

Agronomic use efficiency of N, P and K nutrients was sinfluenced significantly ($p < 0.05$) by different biochar treatments, while the irrigation regimes and their interaction with biochar were insignificant (Table 4). For the main effect of biochar treatment, T1 and T2 exhibited similar but significantly greater agronomic N use efficiency of rice (47.32 and 44.69 g g^{-1}, respectively) in comparison to T3 (37.97 g g^{-1}). Concurrently, a similar tendency of results was also observed in P and K use efficiency. The values varied from 168.14 to 209.55 g g^{-1}and 47.08 to 58.68 g g^{-1} for the agronomic use efficiencyof P and K, respectively.

Table 4. Nutrient use efficiency of rice influenced by integrated application of biochar and fertilizer under two irrigation regimes.

	Agronomic Use Efficiency (g g^{-1})		
Biochar Treatment			
T1	47.32 a	209.55 a	58.68 a
T2	44.69 a	197.94 a	55.42 a
T3	37.97 b	168.14 b	47.08 b
Significance level	***	***	***

Means in a column with different letters reveal a significant difference ($p < 0.05$) between the main effect of biochar treatment. In contrast, there was no significant variation ($p < 0.05$) found for the irrigation system and interaction effect by two-way ANOVA. Symbol *** indicates significant variation between the treatments at p values < 0.001. T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar; EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

3.6. Effect of Integrated Biochar and Fertilizer Application under Two Irrigation Regimes on Soil Dehydrogenase and Urease Enzyme Activities

Soil dehydrogenase activity was significantly ($p < 0.05$) influenced by the interaction of irrigation practice and biochar treatments (Table 5). The maximum dehydrogenase activities found in T2 with CF (84.97 µg TPF g^{-1} dry soil 24 h^{-1}) followed by T1 under the same irrigation regime (79.25 µg TPF g^{-1} dry soil 24 h^{-1}) were significantly higher than T1 and T2 under AWD (67.24 and 73.43 µg TPF g^{-1} dry soil 24 h^{-1}, respectively). The minimum dehydrogenase activity was found in T0 (24.67 and 30.21 µg TPFg^{-1} dry soil 24 h^{-1}, respectively) under AWD and CF irrigation. For the same biochar treatment, CF irrigation regime significantly ($p < 0.05$) increased the dehydrogenase enzyme activities of the soil.

Table 5. Effect of integrated biochar and fertilizer application under two irrigation regimes on soil dehydrogenase and urease enzyme activities.

Irrigation	Biochar Treatment	Dehydrogenase (µg TPF g^{-1} Dry Soil 24 h^{-1})	Urease (µg $NH_4^+ - N$ g^{-1} Dry Soil 3 h^{-1})
AWD	T1	67.24 d	277.41 b
	T2	73.43 c	281.96 b
	T3	44.56 f	240.77 c
	T0	24.67 h	128.76 d
CF	T1	79.25 b	297.82 a
	T2	84.97 a	302.44 a
	T3	56.17 e	226.30 c
	T0	30.21 g	106.52 e
Significance level		*	***

Means in a column with different letters reveal a significant difference ($p < 0.05$). A significant ($p < 0.05$) interaction between irrigation regime and biochar treatments was found by two-way ANOVA. Symbols * and *** indicate significant variation among the treatments at p values < 0.05 and 0.001, respectively. AWD, alternate wetting and drying; CF, continuous flooding; T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar; EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

Significantly greater but similar urease activity was observed in T1 and T2 biochar treatments (277.41 and 281.96 µg $NH_4^+ - N$ g^{-1} dry soil 3 h^{-1}) followed by T3 and T0 (240.77 and 128.76 µg $NH_4^+ - N$ g^{-1} dry soil 3 h^{-1}) under AWD irrigation (Table 5). In the CF irrigation regime, higher urease activity was observed in T2 (302.44 µg $NH_4^+ - N$ g^{-1} dry soil 3 h^{-1}), which was statistically similar to T1 (297.82 µg $NH_4^+ - N$ g^{-1} dry soil 3 h^{-1}), and the lowest activity was obtained by T0 (128.76 µg $NH_4^+ - N$ g^{-1} dry soil 3 h^{-1}). In the case of the same biochar treatment, urease activity of soil was significantly ($p < 0.05$) improved by the CF irrigation compared to the AWD regime.

3.7. Acid Phosphatase Activity of Soil Impacted by Main Effect of Biochar Treatment

Acid phosphatase activity in the soil is boosted by biochar application (Figure 2). A significantly enhanced but identical acid phosphatase activity was obtained by T1 and T2 (186.64 and 181.04 µg *p*-NPP g^{-1} dry soil h^{-1}, respectively) over T3 (149.14 µg *p*-NPP g^{-1} dry soil h^{-1}, respectively), and the minimum activity was found in T0 (125.73 µg *p*-NPP g^{-1} dry soil h^{-1}, respectively).

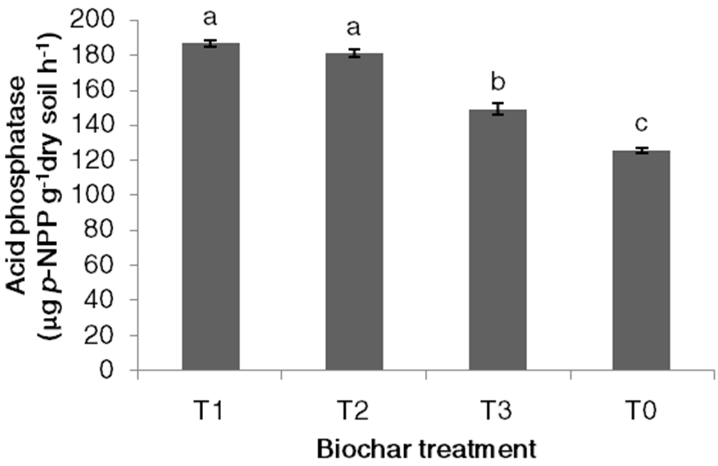

Figure 2. Acid phosphatase activity of soil. Means with different letters reveal a significant difference ($p < 0.05$) between the treatments. Two-way ANOVA observed a significant main effect of biochar treatment. In contrast, the main effect of irrigation and its interaction was non-significant. Vertical bars indicate standard error of means ($n = 8$). T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar; EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

3.8. Effect of Integrated Biochar and Fertilizer Application underTwo Irrigation Regimes on Total C and N of Post-Harvest Soil

Total carbon (TC) and total nitrogen (TN) content of the soil after harvest were influenced significantly ($p < 0.05$) by the interaction of irrigation practices and biochar treatments (Table 6). Biochar treatments such as T2 significantly accelerated the TC content (68.65 g kg^{-1}) compared to T1 (61.98 g kg^{-1}) under the AWD irrigation, whereas reduced but identical values were observed in T3 and T0 (45.33 and 47.63 g kg^{-1}, respectively). Simultaneously, a similar pattern of variation in the TC also resulted under the CF irrigation. Considering the same biochar treatment, CF with T3 and T0 treatment significantly enhanced the soil TC (54.90 and 56.15 g kg^{-1}, respectively) over the AWD regime. Under the AWD irrigation, biochar treatment T2 showed the highest total soil nitrogen (3.55 g kg^{-1}), followed by T1 and T3 (3.03 and 2.03 g kg^{-1}, respectively) and lowest from T0 (1.03 g kg^{-1}). While within CF, T1 and T2 exhibited similar results for N (3.23 and 3.65 g kg^{-1}, respectively) over T3 (2.68 g kg^{-1}) and T0 (1.73 g kg^{-1}). For the same biochar treatments, T3 and T0 with CF resulted in greater values over AWD irrigation, while statistically similar values of TN were obtained by T1 and T2 between two irrigation practices.

Table 6. Effect of integrated biochar and fertilizer application under two irrigation regimes on total C and N of post-harvest soil.

Irrigation	Biochar Treatment	Total C (g kg^{-1})	Total N (g kg^{-1})
AWD	T1	61.98 b	3.03 bc
	T2	68.65 a	3.55 a
	T3	45.33 d	2.03 d
	T0	47.63 d	1.03 e
CF	T1	62.55 ab	3.23 ab
	T2	69.18 a	3.65 a
	T3	54.90 c	2.68 c
	T0	56.15 c	1.73 d
Significance level		**	*

Means in a column with different letters reveal a significant difference (p <0.05). A significant ($p < 0.05$) interaction between irrigation regime and biochar treatments was found by two-way ANOVA. Symbols * and ** indicate significant variation among the treatments at p values < 0.05 and 0.01, respectively. AWD, alternate wetting and drying; CF, continuous flooding; T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar; EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

3.9. Main Effect of Irrigation Regime and Integrated Application of Biochar on Chemical Properties of Post-Harvest Soil

Due to the different irrigation regimes and biochar treatments, the pH value of post-harvest soil was significantly ($p < 0.05$) impacted, but its interaction was unaffected (Table 7). The main effect of irrigation showed that CF irrigation significantly increased the soil pH value over AWD (5.90 and 5.78, respectively). Moreover, from the main effect of biochar, treatment such as T2 exhibited maximum pH (6.51), followed by T1 (6.25), which was significantly greater than T3 (5.33) and T0 (5.27). Several integrated biochar treatments only impacted the cation exchange capacity (CEC), but no significant effect was found for the effect of irrigation and its interaction with biochar. The biochar treatment, including T1 and T2, showed identical and higher values of CEC (18.40 and 18.38 $cmolc_{(+)}$ kg^{-1}, respectively) compared to T3 and T0, which also produced the same results (16.50 $cmolc_{(+)}$ kg^{-1}).

Table 7. Main effect of irrigation regime and integrated application of biochar on chemical properties of post-harvest soil.

Irrigation	pH	CEC ($cmolc_{(+)}$ kg^{-1})	Available P (mg kg^{-1})	Exchangeable K ($cmolc_{(+)}$ kg^{-1})
AWD	5.78 b	17.46	10.92 b	2.08 b
CF	5.90 a	17.42	11.90 a	2.37 a
Significance level	**	ns	***	***
Biochar Treatment				
T1	6.25 b	18.40 a	14.61 a	2.49 b
T2	6.51 a	18.38 a	13.68 b	3.60 a
T3	5.33 c	16.50 b	10.80 c	1.90 c
T0	5.27 c	16.50 b	6.55 d	0.90 d
Significance level	***	***	***	***

Means in a column with different letters reveal a significant difference ($p < 0.05$) between the main effect of the irrigation system and biochar treatment. In contrast, no significant variation ($p < 0.05$) was found for the interaction effect assessed by two-way ANOVA. Symbols **, *** and ns indicate significant variation among the treatments at p values < 0.01, 0.001 and non-significant, respectively. AWD, alternate wetting and drying; CF, continuous flooding; T1: 25% RHB + 75% RFD; T2: 25% EFBB + 75% RFD; T3: 100% RFD; and T0: control (no fertilizer or biochar). RHB, rice husk biochar; EFBB, oil palm empty fruit bunch biochar; RFD, recommended fertilizer dose.

Available N, P and K content of the soil was significantly ($p < 0.05$) influenced by various irrigation regimes and biochar treatments, while their interaction did not show any significant effect (Table 7). The irrigation regime CF showed greater values of available P and exchangeable K (11.90 mg $kg^{-1}$and 2.37 $cmolc_{(+)}$ kg^{-1}, respectively) over AWD regime (10.92 mg kg^{-1} and 2.08 $cmolc_{(+)}$ kg^{-1}, respectively). On the other hand, the main effect of biochar showed that maximum available P was found in T1 (14.61 mg kg^{-1}), followed by T2 (13.68 mg kg^{-1}) and T3 (10.80 mg kg^{-1}) and minimum from T0 (6.55 mg kg^{-1}). Meanwhile, biochar treatment T2 produced highest exchangeable K (3.60 $cmolc_{(+)}$ kg^{-1}), which was significantly greater than T1 (2.49 $cmolc_{(+)}$ kg^{-1}) and T3 (1.90 $cmolc_{(+)}$ kg^{-1}); the lowest result was found in T0 (0.90 $cmolc_{(+)}$ kg^{-1}).

3.10. Relation between Grain Yield, Water Productivity, Physiological Parameters and Biochemical Properties of Soil

Pearson's correlation analysis evaluated the association between grain yield, water productivity, physiological parameters and soil biochemical properties (Table 8). A positive and significant correlation was found in grain yield with photosynthesis rate (r = 0.66 *), dehydrogenase, urease and acid phosphatase activities of soil (r = 0.70 ***, 0.74 *** and 0.75 ***, respectively). Nevertheless, soil enzymes, such as dehydrogenase, urease and acid phosphatase activities, exhibited positive and significant relation with soil carbon (r = 0.89 ***, 0.76 *** and 0.78 ***, respectively) and nitrogen content (r = 0.88 ***, 0.77 ** and 0.78, respectively).

Table 8. Correlation coefficients between grain yield, photosynthesis rate and biochemical properties of soil.

	GY	**P*n***	**DHA**	**URE**	**Ac*P***	**pH**	**CEC**	**STC**	**STN**	**AP**
GY										
P*n*	0.66 *									
DHA	0.70 ***	0.60 **								
URE	0.74 ***	0.36 **	0.89 ***							
Ac*P*	0.75 ***	0.43 *	0.82 ***	0.82 ***						
pH	0.68 ***	0.40 ns	0.92 ***	0.89 ***	0.87 ***					
CEC	0.65 ***	0.34 ns	0.80 ***	0.81 ***	0.89 ***	0.89 ***				
STC	0.61 **	0.44 *	0.89 ***	0.76 ***	0.78 ***	0.93 ***	0.76 ***			
STN	0.56 **	0.50 *	0.88 ***	0.77 ***	0.78 ***	0.91 ***	0.79 ***	0.91 ***		
AP	0.71 ***	0.52 *	0.88 ***	0.88 ***	0.92 ***	0.87 ***	0.85 ***	0.76 ***	0.75 ***	
Ex. K	0.40 *	0.33 ns	0.82 ***	0.71 ***	0.61 **	0.84 ***	0.67 ***	0.85 ***	0.85 ***	0.56 ***

Notes: GY, grain yield; P*n*, Photosynthesis rate; DHA, dehydrogenase; URE, urease; Ac*P*, acid phosphatase, CEC, cation exchange capacity of soil; STC, soil total carbon; STN, soil total nitrogen, AP, available phosphorus in soil and Ex. K, exchangeable Potassium in the soil. The symbols *, ** and *** denote p-value < 0.05, 0.01 and 0.001, respectively; ns, non-significant.

4. Discussion

4.1. Enzymatic Activities and Chemical Properties of Post-Harvest Soil

Soil enzymes are key indicator of soil quality in crop production systems and direct biochemical processes for nutrient cycling C, N and P; organic and inorganic fertilizers significantly impact soil quality [22]. In this study, integrated use of RHB and EFBB with fertilizer (T1 and T2) increased the dehydrogenase (DHA) enzyme activities up to 50.9 and 64.8%, respectively, over the recommended fertilizer dose (RFD: T3) under AWD irrigation, and in the CF it was 41.1 and 51.2%. Furthermore, urease activities under AWD and CF irrigation were boosted up to 17.11% and 33.65%, respectively, due to biochar inclusion. Meanwhile, acid phosphatase activities increased by RHB and EFBB increased up to 25.1% and 21.4%, respectively. Several previous studies reported that biochar inclusion increased the enzyme activities of soil. Futa et al. [33] revealed that incorporating wheat straw biochar accelerated the soil's DHA, urease and acid phosphatase activities. Biochar incorporation accelerated the soil enzyme activities by supplying nutrients to the soil and increasing the soil organic carbon content and microbial activities [34]. Biochars such as RHB and EFBB used in this study are enriched with carbon and contain several plant nutrients, which might influence the enhanced DHA, urease and acid phosphatase activities of paddy soil. Nevertheless, decreased activity of DHA and urease under AWD over CF might be due to soil drying intermittently, thereby reducing microbial activities. The reduced moisture levels decrease soil enzymatic activities, as reported by Denardin et al. [35] and Zhao et al. [36].

Integrated application of RHB and EFBB increased the soil pH by 0.92 and 1.18 units compared to RFD. The higher pH value of EFBB may help to raise the soil pH [25]. Application of wood biochar and bamboo biochar significantly increase the pH of acidic soil [37]. The ability of biochar to improve soil acidity was also reported in many studies [38,39]. Biochar shows a different mechanism to control soil pH due to its unique surface chemistry and various functional organic groups and compounds [40]. Likewise, biochar boosted the CEC of soil up to 11.3%; this increase may be due to the biochars' complex surface chemistry, such as greater cation exchange sites and the presence of acid functional groups [41].

A remarkable enhancement of total carbon in RHB and EFBB-treated soil in this study might be attributed to their high carbon content. Biochar possesses special properties that promote long-term carbon reserve in soil [42]. The integrated biochar application enhanced soil carbon under AWD, as also reported by Yang et al. [43] and Haque et al. [25]. Furthermore, a significant increase in total N, available P and exchangeable K content of the soil was found due to the RHB and EFBB addition with fertilizer. Biochar inclusion boosts soil fertility in two ways: first, by adding nutrients to the soil, and second, by adsorbing nutrients from other sources [44]. A recent study by Chen et al. [45] observed that adding rice husk and straw biochar increased the total N, available P and exchangeable K up to 86.8%, 171.7% and 14.4 times, respectively. Another study reported a substantial fluctuation in soil's N, P and K content, affected by straw and woodchip biochar in the subtropical paddy [46].

4.2. Nutrient Use Efficiency

Biochar is a Potent organic amendment, and it can efficiently improve the nutrient use efficiency of rice [47]. In this study, agronomic efficiency (AE) of N, P and K was enhanced by RHB and EFBB. Nutrient use efficiency of rice depends on various factors, such as soil nutrient availability, the amount of fertilizer applied, plant nutrient uptake and crop yield response. [48]. In this context, improved uptake of nutrients (N, P and K) was observed due to the integrated application of biochars (RHB and EFBB, respectively) and fertilizers under both irrigation regimes, which resulted in iproved rice yields. Several studies reported that improved nutrient uptake of rice was observed due to biochar application [10,38]. This could be due to the boosted colonization of arbuscular mycorrhizal fungi (AMF) in the rhizosphere by biochar application [49]. The association of AMF with plants profoundly enhances the N and P uptake, as recently reported by Kalia et al. [50]. Moreover, biochars used in this study also enhanced the nutrient availability, CEC and pH of the soil through which biochar creates a suitable rhizospheric environment that helps in better nutrient absorption by rice [24]. A previous study reported that RHB combined with urea increased the AE of N up to 140 [47]. Lee et al. [51] reported that combined biochar application with NPK fertilizer enhanced the N, P and K use efficiency. An improved P use efficiency by biochar was also revealed by Arif et al. [52]. Overall, the integrated application of biochar with chemical fertilizer improved nutrient uptake and its use efficiency with different crops.

4.3. Physiological Parameters

Integrated application of RHB and EFBB with chemical fertilizer (T1 and T2, respectively) boosted the photosynthesis up to 17.6% and 24.4% compared to RFD at the vegetative and maturing stages, respectively. Nitrogen is widely recognized for its importance in promoting photosynthesis and growth in rice. Ali et al. [53] reported that biochar affects soil nitrogen and is predicted to improve leaf nitrogen and photosynthesis; once biochar inclusion improves nitrogen absorption, it also tends to boost leaf nitrogen content, which stimulates photosynthesis [54]. Application of 40 t ha^{-1} cassava biochar accelerates the photosynthetic rate, and this rise in the leaf photosynthetic rate was attributable to enhanced nitrogen uptake [53]. Furthermore, the addition of maize straw biochar at the rate of 10 t ha^{-1} also enhanced the photosynthesis in peanut leaf [55]. Nevertheless, a profound decrease in photosynthesis rate in the AWD compared to the CF may be caused by a moisture deficit condition in the AWD irrigation. Carbon isotope discrimination in the rice leaf revealed that rice faces a moisture deficit condition to some extent under AWD, which can be recovered by applying biochars, such as RHB and EFBB [25].

The increasing stomatal conductance and transpiration rate by integrated use of RHB and EFBB biochar over unamended soil may be due to biochar's high water holding capacity. Enhanced transpiration and stomatal conductance may be linked to improved soil water retention capacity, which might be attributed to the porous structure of biochar [56]. A meta-analysis observed that biochar markedly accelerated stomatal conductance and transpiration rate by 19.6% and 26.9%, respectively [57]. During the drying cycles in the safe AWD, the water level is maintained at 15 cm from the surface; as a result, the rice roots are not fully exposed to water and slight moisture stress is faced by the plants [25]. Due to this condition, the AWD regime reduces stomatal conductance and transpiration rate in rice, which could act in abscisic acid-induced stomatal movement under water deficit conditions [58]. Overall, biochar application alleviates soil acidity, enhances CEC and nutrient availability; these improved soil properties ultimately increase the photosynthesis, stomatal conductance and transpiration of rice.

4.4. Yield and Water Use Efficiency

The impact of rice cultivation practices on its grain production is one of the most important aspects of choosing a cultivation method. Previous research comparing the effects of AWD on grain yield to other irrigation approaches has found a wide range of results, from yield reductions to yield enhancements [25,59]. In this study, the main effect of irrigation was observed where 3.4% of grain yield was reduced by AWD irrigation compared to CF. Meanwhile, from the main effect, integrated application of RHB and EFBB with fertilizer (T1 and T2) increased the grain yield by 12.5% and 9.0%, respectively, compared to RFD (T3). This increase in rice yield may be triggered by several factors, including improved physiological activity [53], nutrient uptake and improved soil properties [25]. Improved physiological activities, such as photosynthesis, stomatal conductance and transpiration, increase rice yield [60]. Furthermore, the enhanced rice production owing to the incorporation of biochar was caused by a suitable rhizospheric condition, which aids in greater nutrient absorption by improving the physicochemical properties of soil [25]. The most crucial advantage of using AWD irrigation is that it reduces water usage and increases use efficiency and compared to irrigated rice, AWD can reduce about 35% of water usage [61]. In contrast, yield loss under AWD is frequently observed compared to flooded irrigated rice [3], but overall, AWD enhances water productivity relative to total water input, since the yield loss is less than the volume of water saved [10]. Furthermore, integrated application of RHB and EFBB with fertilizer (T1 and T2) under the AWD regime reduced irrigation water usage by 28.8% and 25.9%, respectively, compared to unamended RFD (T3) treatment of CF irrigation; meanwhile, T3 with AWD reduced only 19.5% of irrigation water. Simultaneously, RHB and EFBB declined water consumption by 11.5 and 8.0% over RFD under AWD irrigation. The water use efficiency of rice mainly depends on rice yield and the amount of irrigation water used. In this context, the integrated application of RHB and EFBB with AWD boosted water use efficiency up to 50.6 and 39.8% compared to RFD with the CF regime. This suggests that the inclusion of these two biochars might help retain soil moisture by decreasing soil water loss during water-saving irrigation. The biochar originating from crop residue is enriched with silicon. This silica interacts with water molecules, shows properties similar to those of silica hydrogel and reduces the loss of water by retaining water [62]; furthermore, porous internal structure and high surface area of biochar also stores water [63]. Based on the application rate of bamboo and rice straw biochar, the soil moisture was enhanced in clay loam soil, up to 9% and 15%, respectively, for rice production [64]. Kameyama et al. [65] observed an increase in available water capacity with an increasing rate of biochar in clay soil; moreover, a significant increment of gravimetric water in paddy soil was included in different biochars, as also demonstrated by Haque et al. [40].

5. Conclusions

A sharply reduced grain yield with improved WUE was obtained by AWD irrigation. The integrated use of rice husk biochar (RHB) and oil palm empty fruit bunch biochar (EFBB) with chemical fertilizer improved gas exchange parameters, especially photosynthesis. The carbon-enriched biochars also boosted the soil enzyme activities, which enhanced nutrient availability for plants, resulting in improved nutrient use efficiency. Thereby, this minor yield penalty in AWD irrigation could be recovered by applying biochar, which ultimately makes AWD preferable over CF irrigation. On the other hand, the combination of biochar and fertilizer with CF irrigation also improved the rice grain and biochemical properties of soil, but it is not recommended, since it uses a lot of irrigation water with lower WUE. This study suggested that the integrated application of biochar and fertilizer under AWD might be a better alternative paddy soil management practice because it could enhance rice growth and soil properties, which leads to improved soil fertility and productivity. However, this study was conducted in a glasshouse under controlled conditions, and the findings are material, dosage and soil-specific; further economic viability of biochar application for large-scale rice production should be examined in detail, and economic analysis should be carried out to provide farmers with recommendations.

Author Contributions: Conceptualization, M.K.U. and M.F.S.; methodology, A.N.A.H. and M.F.S.; formal analysis, A.N.A.H., A.M.A. and M.M.; investigation, M.K.U.; data curation, Z.M.S.; writing—original draft preparation, A.N.A.H.; writing—review and editing, M.H., A.M.A. and Z.M.S.; supervision, M.K.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Agricultural Technology Program Phase-II Project, Bangladesh Agricultural Research Council (Vote No. 6282514-10201). Fundamental Research Grant Scheme (FRGS 1/2020/WAB04/ Vote no 5540389), Universiti Putra Malaysia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from thecorresponding authors. The data are not publicly available because they are part of a PhD study.

Acknowledgments: Authors are grateful to the National Agricultural Technology Program Phase-II Project, Bangladesh Agricultural Research Council for the financial support and Universiti Putra Malaysia, Selangor Darul Ehsan, Malaysia, for the research facilities.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Monthly average temperature and humidity during the experiment.

Month	Temperature (°C)		Relative Humidity (%)
	Maximum	Minimum	
September	32	23	81
October	32	24	79
November	31	24	80
December	30	22	82

Table A2. Chemical properties of initial soil.

Parameter	Value
pH (Soil:water = 1:2.5)	5.14
Cation exchange capacity (cmolc$_{(+)}$ kg^{-1})	16.46
Total Carbon (g kg^{-1})	53.60
Total Nitrogen (g kg^{-1})	4.00
Available P (mg kg^{-1})	12.34
Exchangeable K (cmolc$_{(+)}$ kg^{-1})	1.38
Exchangeable Ca (cmolc$_{(+)}$ kg^{-1})	12.01
Exchangeable Mg (cmolc$_{(+)}$ kg^{-1})	7.71
Total S (mg kg^{-1})	1400

Table A3. Chemical properties of biochars.

Parameters	Biochar Type	
	Rice Husk Biochar (RHB)	Oil Palm Empty Fruit Bunch Biochar (EFBB)
pH (Soil:water = 1:10)	7.12	8.50
Cation exchange capacity (cmolc$_{(+)}$ kg^{-1})	50.42	58.32
Total C (g kg^{-1})	248.60	521.10
Total N (g kg^{-1})	3.80	11.30
Total P (g kg^{-1})	3.10	1.90
Total K (g kg^{-1})	16.67	50.82
Total Ca (g kg^{-1})	1.65	7.09
Total Mg (g kg^{-1})	1.69	3.90
Total S (g kg^{-1})	1.50	1.50

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