agronomy

Article

Short-Term Effect of In Situ Biochar Briquettes on Nitrogen Loss in Hybrid Rice Grown in an Agroforestry System for Three Years

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Abstract: *Kayu putih* (*Melaleuca cajuputi*) waste has the potential via in situ biochar briquettes to overcome the low availability of nitrogen in soil. This study evaluated the short-term effects of in situ biochar briquettes on nitrogen loss reduction and determined an optimum scenario for hybrid rice grown in an agroforestry system among *kayu putih* stands. This three-year experiment (2019–2021) was conducted using a randomised complete block design factorial with three blocks as replications. The treatments included biochar briquettes made from *kayu putih* waste (0-, 2-, 4-, and 6-grain plant^{-1} or 0, 5, 10, and 15 tonnes ha^{-1}) and urea fertiliser (0, 100, 200, and 300 kg ha^{-1}). The results demonstrated that the eco–environmental scenario was the most efficient strategy that improved the soil quality, the physiological characteristics, and the yield of the hybrid rice with the optimum application of the biochar briquettes at 5.54-grain plant^{-1} and the urea fertiliser at 230.08 kg ha^{-1}. This alternative approach illustrated a reduction in both the usage of urea fertiliser and the loss of nitrogen by 23.31% and 26.28%, respectively, while increasing the yield of the hybrid rice by 24.73%, as compared to a single application of 300 kg urea ha^{-1} without biochar briquettes.

Keywords: agroforestry; biochar briquettes; hybrid rice; *kayu putih*; nitrogen loss; optimum scenario

Citation: Suryanto, P.; Faridah, E.; Nurjanto, H.H.; Putra, E.T.S.; Kastono, D.; Handayani, S.; Boy, R.; Widyawan, M.H.; Alam, T. Short-Term Effect of In Situ Biochar Briquettes on Nitrogen Loss in Hybrid Rice Grown in an Agroforestry System for Three Years. *Agronomy* **2022**, *12*, 564. https://doi.org/10.3390/agronomy12030564

Academic Editor: Sara Di Lonardo

Received: 28 December 2021
Accepted: 18 February 2022
Published: 24 February 2022

1. Introduction

Rice is the primary food commodity cultivated by the majority of farmers in Indonesia. The Food and Agricultural Organisation (FAO) [1] has stated that rice is the principal source of income for farmers with less than one hectare of paddy land. Statistics Indonesia [2] reported that in 2019, rice production diminished by 4.60 million tons or 7.76% compared to 2018. The primary factor in this decline was the conversion of 96,512 hectares of agricultural land to non-agricultural land per year. Agricultural land is expected to recede from 8.10 million hectares to 5.10 million hectares by 2045 [3].

The implementation of hybrid rice varieties and land intensification between *kayu putih* (*Melaleuca cajuputi*) stands could augment rice production in agroforestry systems [4–7]. With a higher grain yield ranging between 6.1% and 11.9%, hybrid varieties are preferred by rice farmers compared to inbred rice [8,9]. An agroforestry system can be defined as a land-use system that integrates annual crops with perennial crops in conjunction with technological innovations [10,11]. The potential land area of *kayu putih* forests in Indonesia is 248,756 hectares [12]. The advantage of growing rice amongst the *kayu putih* stands is that there is no competition between the species for natural sunlight as the leaves and branches of the *kayu putih* are pruned twice annually. In addition, the root-zone differential mitigates any competition for nutrients and water [4–6].

In Indonesia, *kayu putih* forests are mostly found in alkaline soils with high clay content [12]. These ground conditions result in reduced availability of macronutrients, particularly regarding the nitrogen (N) content in the soil [13,14]. Nitrogen is one of the main elements that is required by plants in relatively large amounts. Its principal role is as the main element in the formation of chlorophyll in the leaves for photosynthesis [15]. Several studies have reported that its deficiency in rice has caused decreased cytokinin release, inhibited the photosynthetic rate as well as the root growth, resulting in stunted crops and decreased productivity [15–17]. There is also less N available in the soil due to several processes, namely volatilization (NH_3), leaching (NO_3^-–N), and denitrification into N_2O and N_2. Because hybrid rice requires high levels of N to produce a better yield, the low efficiency prediction of N fertilisation at only 45% and the high N loss in the soil result in contrasting depleted harvests [18–22].

The use of biochar has been suggested as an alternative solution to overcome the reduced N availability in *kayu putih* forests while increasing annual crop production in rainfed areas [13,23–25]. The biomass pyrolysis process with minimal or no oxygen conditions produces three main products: biochar, liquid, and syngas. The results of these three pyrolysis products are helpful for energy generation, soil quality improvement, waste management, and mitigating climate change or water pollution [26]. In agriculture, biochar reduces N loss from various processes (e.g., volatilisation, leaching, and denitrification) and increases nitrogen-use efficiency (NUE) and crop productivity [27–30]. Biochar has large pores on the surface (micro and macro effects), increasing porosity by 351.14% and reducing soil bulk density by 933.33% on clay textures. In addition, the application of biochar can increase the microbial content in the soil so that crop yields increase [31–33].

In situ *kayu putih* waste converted into biochar has proven to be useful as a soil-improvement agent [13,14]. *Kayu putih* waste originating from the distillation of leaves and branches has become a prevailing issue in nearly all the oil refineries in Indonesia due to its abundancy and availability [13]. The biochar potential of *kayu putih* waste is indicated by its pH (H_2O) as well as its C, H, N, and O contents, which have been measured at 8.05 g kg^{-1}, 738.8 g kg^{-1}, 23.2 g kg^{-1}, 1.7 g kg^{-1}, and 22.58 g kg^{-1}, respectively [13]. Cahayaningrum [34] and Sianturi [35] found that biochar made from *kayu putih* waste did not show a significant difference in the yield of hybrid maize in agroforestry systems with *kayu putih* stands during both the dry and wet seasons, as compared to rice-husk biochar, demonstrating that *kayu putih* waste biochar can replace the widely used rice-husk biochar.

Research conducted by Faridah et al. [14] revealed that the application of *kayu putih* waste biochar at 11.14 tonnes ha^{-1} to rice crops in an agroforestry system with *kayu putih* reduced the use of urea fertiliser by 15.75%, decreased the N loss by 63.41%, and increased the rice yield by 44.76%. The decrease in the N loss and the increase in the rice yield was also achieved by reducing the release rate of N nutrients to maximise nutrient absorption by plants [36]. Biochar briquettes made from *kayu putih* waste applied to soybeans under similar conditions increased the NUE by 19.07% and the soybean yield by 13.02% while reducing the N loss by 38.25% [37].

The objective of this study was to evaluate the short-term effect of in situ biochar briquettes on nitrogen loss and to determine the optimum scenarios for hybrid rice agroforestry systems with *kayu putih*. The results of this study provide information for farmers, researchers, corporations, and governing bodies to overcome the problem of *kayu putih* waste and to utilize its benefits in agroforestry systems with *kayu putih* to help reduce nitrogen loss and increase hybrid rice yield.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted over a period of three years (2019–2021) during the wet season (November–March) at the Menggoran Forest Resort (Playen Forest Section, Yogyakarta Forest Management, Indonesia). The experimental location was ±43 km to the southeast of Yogyakarta City (Figure 1). The experimental location had an altitude of ±150 m above sea level with an average total rainfall, air temperature, relative humidity, and wind speed of 1810.13 mm year^{-1}, 26.65 °C, 82.17%, and 3.67 m s^{-1}, respectively.

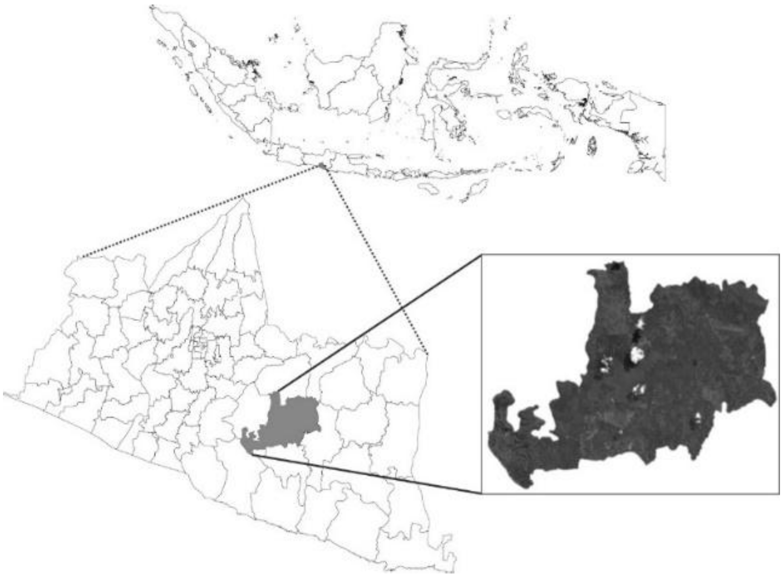


Figure 1. Geographical locations of the experimental site (latitude 7°52′59.5992″ S to 7°59′41.1288″ S and longitude 110°26′21.462″ E to 110° 35′7.4868″ E).

The soil type at the experimental site was Lithic Haplusterts [4,5]. Lithic Haplusterts belong to the order Vertisol and are characterized by contact with rocks at a depth of less than 50 cm from the soil surface, slickenside, with a vertic property (the seasonal cracking pattern pertains to non-irrigated soils). The soil moisture regime was categorised under the ustic moisture regime [38].

Soil texture was dominated by clay fraction (62.53%) with very low permeability (0.001 h^{-1}). The water-holding capacity (WHC) and the total porosity (TP) were measured at 40.36% and 38.64%, respectively. The values for CEC, soil pH (H_2O), and soil organic carbon (SOC) were 60.22 cmol(+) kg^{-1} (very high), 8.4 (alkaline), 1.80 (low), respectively. Total nitrogen (TN), phosphorus availability (P), and potassium (K) availability were measured at 0.09% (very low), 14 ppm (medium), and 0.24 cmol(+) kg^{-1} (low), respectively. The availabilities of calcium (Ca), magnesium (Mg), and sodium (Na) were measured at 24.52 cmol(+) kg^{-1} (very high), 2.23 cmol(+) kg^{-1} (high), and 0.85 cmol(+) kg^{-1} (high), respectively. Djaenudin et al. [39] stated that the study site was in the category of a marginally suitable class (S3) for upland rice cultivation.

2.2. Experimental Design

The experiment was designed by utilising the randomised complete block design factorial with three blocks as replications. The treatments included different levels of biochar briquettes made from *kayu putih* waste that consisted of 0-, 2-, 4-, and 6-grain plant^{-1} at 0, 5, 10, or 15 tonnes ha^{-1}, respectively. The nitrogen fertiliser supplied by urea consisted of 0, 100, 200, or 300 kg ha^{-1}, respectively, during the three-year period between 2019 and 2021.

2.3. Biochar Briquettes Preparation

The biochar briquettes were produced using the in situ waste of distilled *kayu putih* leaves and branches. The biochar was manufactured using the traditional kiln method [40] during the first stage of its preparation. Manufacturing of biochar used a stainless kiln (capacity 40 L) at temperatures of ± 250–350 °C with a long burning time of 3.5 h. The second stage involved mixing, moulding, and drying. The mixing process comprised the incorporation of the biochar with 2% adhesive (Figure 2A). The adhesive material used was molasses. The moulding process used a machine manufactured by Royal Genset Ltd., Jakarta Utara, Indonesia (15–18 hp and 200–300 kg h^{-1} capacity). The drying process utilised natural sunlight, yielding a moisture content of 14%. Each briquette weighed 10 g [37]. The laboratory analysis results of the biochar briquettes are provided in Table 1.

(**A**) (**B**)

Figure 2. (**A**) Biochar briquettes sourced from *kayu putih* waste. (**B**) Hybrid rice between *kayu putih* stands.

Table 1. The nutrient content and molar ratio of biochar briquettes.

Chemistry Characteristics [1]						Molar Ratio [1]			
pH	**C**	**H**	**O**	**N**	**S**	**H/C**	**O/C**	**(O + N)/C**	**(O + N + S)/C**
(1:10 H_2O)	(%)								
8.05	73.9	2.32	22.6	0.80	0.37	0.37	0.23	0.24	0.24

[1] pH: Potential of hydrogen; C: Carbon; H: Hydrogen; O: Oxygen; N: Nitrogen; and S: Sulphur.

2.4. Field Layout and Treatments Application

The experiment incorporated the Mapan-05 hybrid rice variety from Primasid Andalan Utama Ltd., Jakarta Utara, Indonesia. The experimental plots were strategically placed between the *kayu putih* stands of 24 m^2 (6 m × 4 m). The harvest area for hybrid rice was 20 m^2 and did not include the border crops. Soil tillage was completed prior to sowing with moderate ploughing. The hybrid rice seeds were planted directly with a spacing of 25 cm × 25 cm with one seed per planting hole. The biochar briquettes were applied one week after planting (WAP), and urea fertiliser was applied when the hybrid rice reached one and eight WAP. The urea fertiliser used in this experimental contained 45.89% of NO_3^-–N. Phosphorus and potassium fertilisations were applied at 100 and 150 kg ha^{-1}, one WAP, respectively. The application of biochar briquettes and inorganic fertilizers was made manually. Irrigation was not carried out during the study as the experimental plots were situated in a rainfed area (Figure 2B).

2.5. Data Collection

The observation parameters included for this study were water-holding capacity (WHC) [41], total porosity (TP) [42], soil organic carbon after harvesting (SOC) [43], total nitrogen in the soil after harvesting (TN) [44], total fungi in the soil after harvesting (TF) [45], total bacteria in the soil after harvesting (TB) [45], nitrate reductase activity (NRA) [46], total chlorophyll (TC) [47], leaf photosynthetic rate (LPR) [48], nitrogen loss (NL) [49], nitrogen-use efficiency (NUE) [50], and yield of hybrid rice (YHR) [51].

The WHC, TP, SOC, TN, TF, and TB observations were conducted during rice harvesting. The NRA, TC, and LPR were measured when the hybrid rice entered the maximum vegetative phase. The NL parameter was calculated by Equation (1) [49]:

$$\mathrm{N_{loss}} = \mathrm{N_{initial}} + \mathrm{N_{fertiliser}} - \mathrm{N_{plant}} - \mathrm{N_{residual}} \tag{1}$$

where $\mathrm{N_{loss}}$ is N losses (kg $\mathrm{ha^{-1}}$); $\mathrm{N_{initial}}$ is the initial of total N content in the soil up to 30 cm depth before planting (kg $\mathrm{ha^{-1}}$); $\mathrm{N_{fertiliser}}$ is the amount of N fertiliser applied (pure N (N applied × 45.89%)) and weight of biochar briquettes applied × 0.80% (kg $\mathrm{ha^{-1}}$); $\mathrm{N_{plant}}$ is the N uptake of the rice at harvesting (kg $\mathrm{ha^{-1}}$); and $\mathrm{N_{residual}}$ is the total N content in the soil up to 30 cm depth after harvesting (kg $\mathrm{ha^{-1}}$). The NUE parameter was calculated by Equation (2) [50]:

$$\mathrm{NUE} = \frac{\mathrm{Y}}{(\mathrm{N_{initial}} + \mathrm{N_{fertiliser}})} \tag{2}$$

where Y is the yield of the hybrid rice (kg $\mathrm{ha^{-1}}$); $\mathrm{N_{initial}}$ is the initial of the total N content in the soil; and $\mathrm{N_{fertiliser}}$ is the N fertiliser applied (pure N (N applied × 45.89%)) and weight of biochar briquettes applied × 0.80%.

The yield observation was conducted by harvesting the hybrid rice in the experimental plot, excluding the borders; then it was dried to 14% moisture content and weighed with a digital scale [51].

2.6. Statistical Approach

Each data parameter was required to be normally distributed with homogeneity variance assumptions. The normal distribution had a Q–Q plot and homogeneous variance with a residual vs. value graph [52]. Analysis of variance (ANOVA) ($p < 0.05$) was used to determine the interaction between treatment factors (biochar briquettes, urea fertilizer, and the experimental time period). Comparisons of response variables among experimental years was conducted using ANOVA ($p < 0.05$) and was followed by the least square means (LS-Means) test and the Tukey–Kramer test ($p < 0.05$) [52].

The response surface methodology (RSM) equation used in this experiment applied the uncoded independent variables. The response models for the two variables were fitted according to Equation (3) [53,54]:

$$y_i = \beta_0 + \sum_{i=1}^{2} \beta_i x_i^2 + \sum_{i=1}^{2} \sum_{j=1+1}^{2} \beta_{ij} x_i x_j \tag{3}$$

where y_i is the predicted response; β_i is the linear terms; β_{ii} is the squared terms; β_{ij} is the interaction terms; and x_i and x_j are the coded independent variables.

The full quadratic polynomial equation used the uncoded independent variables, according to Equation (4) [53,54]:

$$y\text{: } \beta_0 + \beta_{1\times1} + \beta_{2\times2} + \beta_{11}{x_1}^2 + \beta_{12}x_1x_2 + \beta_{22}{x_2}^2 \tag{4}$$

where x_1, x_2, … , and x_n are the linear terms in each of the variables; x^1 and x^2 are the squared terms in each of the variables; x_1x_2 is the first-order interaction term for each paired combination; β_1 and β_2 are the response-model coefficients; and β_0 is the intercept coefficient.

The fitted RSM model was evaluated by the value of R squared ($\mathrm{R^2}$), root mean square error (RMSE), and the lack-of-fit test. The lack-of-fit test had to be less than 5% [54]. The relationship between variables was analysed by partial least square structural equations modelling (PLS–SEM) and stepwise regression [6,7]. The optimum levels of biochar briquettes and urea fertiliser were incorporated using three scenarios (economic, environmental, and eco–environmental). The economic and environmental scenarios were based on the hybrid rice yield and the nitrogen-loss parameters while eco–environmental scenarios used NUE parameters [13,53]. Estimations of the three scenarios were applied to the ridge regression [55]. The analysis of ANOVA, RSM, ridge regression, and stepwise-regression analyses were performed using PROC GLM, PROC GLIMMIX, PROC RSREG, and PROC REG, respectively, in SAS 9.4 software [56]. PLS–SEM was performed using the SmartPLS 3 software [57].

3. Results

3.1. Interaction between Biochar Briquettes, Nitrogen Fertiliser, and the Experimental Time Period

The Q–Q plot and residual vs. value graph showed that the model had normally distributed data and homogeneous variance. The results of the ANOVA analysis on the variability of the soil properties demonstrated that only B × U on the TN parameter interacted while B × Y, U × Y, and B × U × Y showed no interactions. The biochar briquettes showed significant variance in WHC, TP, SOC, TN, TF, and TB. The application of urea fertiliser displayed a significant deviation in TN level. The total time period also showed considerable differences in the variability of the soil properties, including the WHC, TP, SOC, TN, TF, and TB. The variability results of the soil properties by ANOVA are shown in Table 2.

Table 2. Means square of ANOVA in soil properties.

Factors [2]	**Soil Properties** [1]					
	WHC	**TP**	**SOC**	**TN**	**TF**	**TB**
B	321.58 **	963.55 **	6.98 **	0.01 **	5.87×10^{8} **	8.06×10^{6} **
U	0.001 ^{ns}	42.08 ^{ns}	0.03 ^{ns}	0.67 **	4.06×10^{4} ^{ns}	2.99×10^{4} ^{ns}
Y	555.55 **	87.03 **	0.19 **	0.0008 **	1.23×10^{9} **	4.21×10^{6} **
B × U	0.01 ^{ns}	54.09 ^{ns}	0.03 ^{ns}	0.0008 **	2.76×10^{4} ^{ns}	8.99×10^{2} ^{ns}
B × Y	62.25 ^{ns}	97.37 ^{ns}	0.08 ^{ns}	0.000002 ^{ns}	1.45×10^{8} ^{ns}	7.24×10^{5} ^{ns}
U × Y	0.0001 ^{ns}	45.80 ^{ns}	0.0004 ^{ns}	0.001 ^{ns}	2.04×10^{5} ^{ns}	6.71×10^{2} ^{ns}
B × U × Y	0.0001 ^{ns}	46.15 ^{ns}	0.0004 ^{ns}	0.000003 ^{ns}	1.68×10^{4} ^{ns}	1.86×10^{2} ^{ns}

[1] ^{ns} indicates not significant at $p < 0.05$. ** significant at $p < 0.01$. WHC: Water-holding capacity (%); TP: Total porosity (%); SOC: Soil organic carbon in the soil after harvesting (%); TN: Total nitrogen in the soil after harvesting; TF: Total fungi in the soil after harvesting (colony g soil dry weight^{-1}); and TB: Total bacteria in the soil after harvesting (colony g soil dry weight^{-1}). [2] B: Biochar briquettes; U: Urea fertiliser; and Y: Year's period.

The results of the ANOVA analysis on the physiological characteristics and hybrid rice yield variables showed an interaction between B × U in NRA, TC, LPR, NL, NUE, and YHR. In contrast, there were no interactions between B × Y, U × Y, and B × U × Y in physiological characteristics or the hybrid rice yield variables. The treatments with biochar briquettes showed noteworthy variance in NRA, TC, LPR, NL, NUE, and YHR. The urea fertiliser applications also demonstrated considerable variance in NRA, TC, LPR, NL, NUE, and YHR. The experimental time period displayed significant differences in NRA, TC, LPR, NL, NUE, and YHR. The ANOVA results of the physiological characteristics and the hybrid rice yield variables are presented in Table 3.

Table 3. Means square of the ANOVA for physiological characteristics and yield of hybrid rice.

Factors	**Physiological Characteristics and Yield of Hybrid Rice** [1]					
	NRA	**TC**	**LPR**	**NL**	**NUE**	**YHR**
B	0.93 **	0.014 **	5742.37 **	243.77 **	7.73 **	5.24 **
U	4.33 **	0.14 **	37,816.55 **	2087.78 **	46.56 **	37.47 **
Y	0.55 **	0.12 **	14,914.79 **	344.58 **	27.31 **	9.66 **
B × U	0.11 **	0.0007 **	194.36 **	45.89 **	0.24 **	0.35 **
B × Y	0.02 ^{ns}	0.0003 ^{ns}	67.41 ^{ns}	4.93 ^{ns}	0.17 ^{ns}	0.12 ^{ns}

Table 3. *Cont.*

Factors	Physiological Characteristics and Yield of Hybrid Rice [1]					
	NRA	TC	LPR	NL	NUE	YHR
U × Y	0.02 ^{ns}	0.002 ^{ns}	95.43 ^{ns}	72.04 ^{ns}	0.34 ^{ns}	1.02 ^{ns}
B × U × Y	0.01 ^{ns}	0.0002 ^{ns}	57.94 ^{ns}	1.22 ^{ns}	0.21 ^{ns}	0.02 ^{ns}

[1] ^{ns} not significant at ($p < 0.05$). ** significant at ($p < 0.01$). NRA: Nitrate reductase activity (μmol NO_2^- g^{-1} h^{-1}); TC: Total chlorophyll (g g $leaf^{-1}$); LPR: Leaf photosynthesis rate (CO_2 m^{-2} s^{-1}); NL: Nitrogen loss (kg ha^{-1}); NUE: Nitrogen-use efficiency (kg grain kg $N_{fertiliser}^{-1}$); and YHR: Yield of hybrid rice (tonnes ha^{-1}). [2] B: Biochar briquettes; U: Urea fertiliser; and Y: Year's period.

3.2. Comparison of Response Variables between Experimental Years

The LS-Means values showed a significant variance between the experiments conducted in 2019, 2020, and 2021 (Table 4). It was illustrated by the differences in all the response variable values tested in this experiment, namely, the WHC, TP, SOC, TN, TF, TB, NRA, TC, LPR, NL, NUE, and YHR. There was a considerable elevation in all response variables except for the NL variable which lessened in value. The average increase in WHC, TP, SOC, TN, TF, TB, NRA, TC, LPR, NL, NUE, and YHR during 2019–2021 were 19.60%, 6.37%, 9.11%, 3.22%, 896.59%, 52.65%, 8.46%, 20.69%, 12.02%, −26.02%, 56.11%, and 32.12%, respectively.

Table 4. Least square means (LS-Means) of hybrid rice.

Response Variables [2]	Years [1]		
	2019	2020	2021
WHC	40.60 c	46.72 b	48.56 a
TP	39.87 c	43.41 b	42.96 a
SOC	1.59 c	1.71 b	1.74 a
TN	0.28 c	0.29 b	0.29 c
TF	1.27×10^3 c	1.12×10^4 b	1.27×10^4 a
TB	1.31×10^3 b	1.85×10^3 a	2.00×10^3 a
NRA	3.09 c	3.21 b	3.35 a
TC	0.58 c	0.65 b	0.70 a
LPR	359.33 c	381.22 b	402.51 a
NL	21.63 a	15.89 b	16.00 b
NUE	3.23 c	4.45 b	5.04 a
YHR	3.42 c	4.01 b	4.52 a

[1] Numbers followed by the same letter and rows showed no significant difference in the Tukey–Kramer Test ($p < 0.05$). [2] WHC: Water-holding capacity (%); TP: Total porosity (%); SOC: Soil organic carbon in the soil after harvesting (%); TN: Total nitrogen in the soil after harvesting; TF: Total fungi in the soil after harvesting (colony g soil dry $weight^{-1}$); TB: Total bacteria in the soil after harvesting (colony g soil dry $weight^{-1}$); NRA: Nitrate reductase activity (μmol NO_2^- g^{-1} h^{-1}); TC: Total chlorophyll (g g $leaf^{-1}$); LPR: Leaf photosynthesis rate (CO_2 m^{-2} s^{-1}); NL: Nitrogen loss (kg ha^{-1}); NUE: Nitrogen-use efficiency (kg grain kg $N_{fertiliser}^{-1}$); and YHR: Yield of hybrid rice (tonnes ha^{-1}).

3.3. Fitted Models and Estimated Outcome of Response Variables

The RSM results for the full quadratic regression of the independent variables is presented in Table 5. The lack-of-fit test was utilised to evaluate the fitted performance of the RSM model. The lack-of-fit test displayed no significant differences in any response variables analysed in this experiment. The RSM model with a significance of less than 5% indicated that the model was feasible to use. The fitted models for the experimental variables are presented in Table 5.

Table 5. Regression coefficients and fitted model.

Variables [2]	**Response of Independent Variables** [1]						**R^2**	**RMSE**	**Lack of Fit**
	β_0	$\beta_1 x_1$	$\beta_2 x_2$	$\beta_{11} {x_1}^2$	$\beta_{12} x_1 x_2$	$\beta_{22} {x_2}^2$			
WHC	40.11 **	3.60 **	0.0003 ^{ns}	–0.41 ^{ns}	–0.00003 ^{ns}	–0.0000004 ^{ns}	0.935	0.904	0.136
TP	33.29 **	4.31 **	–0.02 ^{ns}	–0.28 ^{ns}	–0.002 ^{ns}	–0.00007 ^{ns}	0.830	2.776	0.467
SOC	1.08 **	0.25 **	–0.0007 ^{ns}	–0.008 ^{ns}	–0.00005 ^{ns}	–0.000002 ^{ns}	0.982	0.071	0.101
TN	0.07 **	0.007 **	0.001 **	–0.00002 ^{ns}	0.00002 **	–0.0000004 ^{ns}	0.992	0.015	0.572
TF	1337.38 **	4646.69 *	0.84 ^{ns}	–496.90 ^{ns}	0.01 ^{ns}	–0.002 ^{ns}	0.972	79.614	0.885
TB	928.73 **	444.59 **	0.01 ^{ns}	–39.53 **	0.03 ^{ns}	–0.00006 ^{ns}	0.986	66.211	0.890
NRA	2.36 **	0.12 *	0.006 **	–0.004 ^{ns}	–0.0001 **	–0.000007 *	0.904	0.146	0.301
TC	0.50 **	0.01 *	0.001 **	–0.00004 ^{ns}	–0.00002 **	–0.000001 **	0.943	0.019	0.990
LPR	311.17 **	7.09 *	0.49 **	–0.22 ^{ns}	0.001 **	–0.0006 **	0.927	11.479	0.945
NL	11.62 **	–1.82 **	0.06 **	0.10 ^{ns}	–0.001 **	0.00005 ^{ns}	0.959	1.969	0.547
NUE	4.68 **	0.22 *	0.02 **	0.009 ^{ns}	0.0004 **	–0.00003 **	0.899	0.503	0.801
YHR	2.01 **	0.12 *	0.01 **	0.002 ^{ns}	0.0003 **	0.00002 **	0.969	0.231	0.990

[1] X_1: Biochar briquettes (grain plant^{-1}) and X_2: Urea fertiliser (kg ha^{-1}). * and ^{ns} significant and not significant, respectively, at (p < 0.05). ** significant at (p < 0.01). x_1 and x_2 indicate biochar briquettes (grain plant^{-1}) and urea fertiliser (kg ha^{-1}), respectively. [2] WHC: Water-holding capacity (%); TP: Total porosity (%); SOC: Soil organic carbon in the soil after harvesting (%); TN: Total nitrogen in the soil after harvesting; TF: Total fungi in the soil after harvesting (colony g soil dry weight^{-1}); TB: Total bacteria in the soil after harvesting (colony g soil dry weight^{-1}); NRA: Nitrate reductase activity (µmol NO_2^- g^{-1} h^{-1}); TC: Total chlorophyll (g g leaf^{-1}); LPR: Leaf photosynthesis rate (CO_2 m^{-2} s^{-1}); NL: Nitrogen loss (kg ha^{-1}); NUE: Nitrogen-use efficiency (kg grain kg $N_{fertiliser}{}^{-1}$); and YHR: Yield of hybrid rice (tonnes ha^{-1}).

The application of the biochar briquettes remarkably improved the WHC, in contrast withto the urea fertiliser, as presented in Table 5. The applications of biochar briquettes and urea fertiliser illustrated linear patterns. The applications of 6-grain plant^{-1} biochar briquettes and 300 kg ha^{-1} showed the highest WHC value at 47.52% (Table 6). The optimum application of the biochar briquettes at 4.47-grain plant^{-1} and the urea fertiliser at 136.23 kg ha^{-1} exhibited the maximal level of WHC, which was recorded at 48.18% (Figure 3A). The biochar-briquette treatment also ameliorated the TP value, as compared to the TP value when treated with urea fertiliser (Table 5). The applications of biochar briquettes and urea fertiliser showed a linear pattern. The applications of 6-grain plant^{-1} and 300 kg ha^{-1} urea fertiliser showed the highest TP value at 46.98% (Table 6). A maximum TP value of 47.34% was achieved with the optimum application of biochar briquettes and urea fertiliser at 5.52-grain plant^{-1} and 68.38 kg ha^{-1}, respectively (Figure 3B).

Similarly, the biochar-briquette treatment also elevated the SOC accumulation, as compared to the urea fertiliser (Table 5). The biochar briquettes and the urea fertiliser both showed a linear pattern for the SOC. The biochar briquettes at 6-grain plant^{-1} and the urea fertiliser at 300 kg ha^{-1} resulted in the highest SOC at 2.23% (Table 6). Furthermore, the optimum application of the biochar briquettes and the urea fertiliser at 3.04-grain plant^{-1} and 299.99 kg ha^{-1} resulted in the highest SOC value at 2.25% (Figure 3C). The application of the biochar briquettes and the urea fertiliser also significantly increased the TN level (Table 5). The applications of the biochar briquettes and the urea fertiliser illustrated a similar linear pattern. The application of a 6-grain plant^{-1} of biochar briquettes and 300 kg ha^{-1} of the urea fertiliser yielded the highest TN amount at 0.50% (Table 6). The maximum TN value of 0.48% was achieved by applying the optimum application of the biochar briquettes and the urea fertiliser at 3.57-grain plant^{-1} and 297.19 kg ha^{-1}, respectively (Figure 3D).

Both the biochar briquettes and the urea fertiliser exhibited a linear pattern for TF growth (Table 5). A treatment of 6-grain plant^{-1} of the biochar briquette and 300 kg ha^{-1} of the urea fertiliser resulted in TF growth of 1.18×10^4 colony g soil dry weight^{-1} (Table 6). The optimum application of the biochar briquettes at 4.69-grain plant^{-1} and the urea fertiliser at 274.02 kg ha^{-1} resulted in an increase in TF of 1.23×10^4 colony g soil dry weight^{-1} (Figure 3E). The treatments with the biochar briquettes showed a significant increase in TB growth, as compared to the urea fertiliser treatment, and both exhibited (Table 5) a linear pattern. The biochar briquettes and the urea fertiliser at 6-grain plant^{-1} and 300 kg ha^{-1}, respectively, produced the highest TB growth of 2.24×10^3 colony g soil dry weight^{-1} (Table 6). In addition, the optimum application of the biochar briquettes and the urea fertiliser at 5.55-grain plant^{-1} and 229.00 kg ha^{-1}, respectively, enhanced the TB growth by 2.22 × 10^3 colony g soil dry weight^{-1}(Figure 3F).

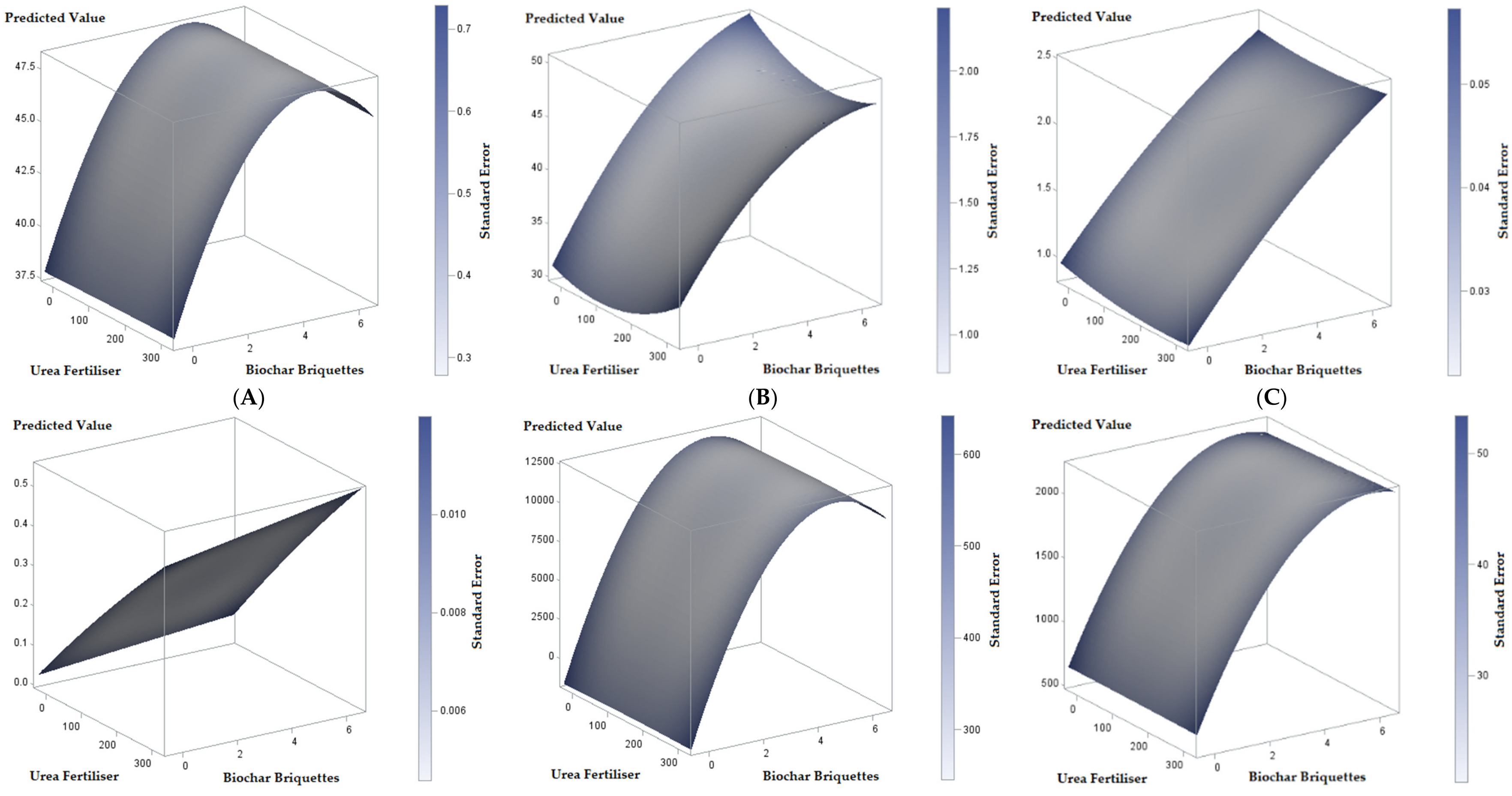
Table 6. Least square means (LS-Means) of independent variables under experimental factors.

Runs	Dependent Variables [1]		Estimates Response of Independent Variables [2]											
	X_1	X_2	WHC	TP	SOC	TN	TF	TB	NRA	TC	LPR	NL	NUE	YHR
1	0	0	39.81	36.54	1.08	0.08	1.07×10^3	9.13×10^2	2.21	0.51	312.95	9.29	5.27	2.26
2	2	0	46.61	41.65	1.59	0.08	9.45×10^3	1.73×10^3	2.53	0.53	326.26	8.02	5.20	2.29
3	4	0	47.18	44.85	1.91	0.10	1.11×10^4	$1.99 \times 10_3$	2.84	0.56	337.32	5.79	5.78	2.53
4	6	0	47.53	48.05	2.23	0.10	1.12×10^4	2.20×10^3	3.02	0.58	342.27	5.62	5.95	2.65
5	0	100	39.83	24.69	1.05	0.19	1.07×10^3	8.96×10^2	3.13	0.60	348.59	21.62	5.32	2.82
6	2	100	46.60	41.65	1.49	0.20	9.74×10^3	1.74×10^3	3.16	0.61	364.70	18.37	6.29	3.29
7	4	100	47.20	43.78	1.91	0.22	1.11×10^4	2.01×10^3	3.17	0.63	375.79	10.46	7.00	3.66
8	6	100	47.56	49.12	2.33	0.25	1.12×10^4	2.22×10^3	3.25	0.67	395.77	9.47	8.61	4.42
9	0	200	39.86	35.88	0.90	0.32	1.08×10^3	9.03×10^2	3.23	0.66	388.58	24.65	7.29	4.14
10	2	200	46.60	40.58	1.49	0.36	9.73×10^3	1.75×10^3	3.28	0.68	399.39	19.78	8.07	4.57
11	4	200	47.19	44.85	1.80	0.38	1.11×10^4	2.03×10^3	3.48	0.70	406.92	17.87	8.52	4.86
12	6	200	47.55	48.05	2.33	0.40	1.17×10^4	2.23×10^3	3.62	0.71	419.33	16.56	9.41	5.31
13	0	300	39.82	35.88	1.00	0.45	1.07×10^3	9.07×10^2	3.37	0.70	400.82	33.60	7.20	4.62
14	2	300	46.68	40.58	1.59	0.47	9.68×10^4	1.75×10^3	3.55	0.71	407.73	30.39	7.70	4.89
15	4	300	47.16	44.85	1.91	0.48	1.11×10^4	2.04×10^3	3.86	0.72	437.12	28.81	8.95	5.70
16	6	300	47.52	46.98	2.23	0.50	1.18×10^4	2.24×10^3	3.79	0.72	432.78	25.13	9.03	5.69

[1] X_1: Biochar briquettes (grain plant^{-1}) and X_2: Urea fertiliser (kg ha^{-1}). [2] WHC: Water-holding capacity (%); TP: Total porosity (%); SOC: Soil organic carbon in the soil after harvesting (%); TN: Total nitrogen in the soil after harvesting; TF: Total fungi in the soil after harvesting (colony g soil dry weight^{-1}); TB: Total bacteria in the soil after harvesting (colony g soil dry weight^{-1}); NRA: Nitrate reductase activity (µmol NO_2^- g^{-1} h^{-1}); TC: Total chlorophyll (g g leaf^{-1}); LPR: Leaf photosynthesis rate (CO_2 m^{-2} s^{-1}); NL: Nitrogen loss (kg ha^{-1}); NUE: Nitrogen-use efficiency (kg grain kg $N_{fertiliser}{}^{-1}$); and YHR: Yield of hybrid rice (tonnes ha^{-1}).

The biochar briquettes and the urea fertiliser showed a noteworthy increase in NRA (Table 5). However, the biochar briquettes exhibited a linear pattern, whereas the urea fertiliser showed a quadratic pattern. The application of a 4-grain plant^{-1} of the biochar briquettes and 300 kg ha^{-1} of the urea fertiliser produced the highest NRA at 3.86 mol NO_2^- g^{-1} h^{-1} (Table 6). The maximum NRA value of 3.70 NO_2^- g^{-1} h^{-1} was recorded with the optimum application of the biochar briquettes at 4.76-grain plant^{-1} and the urea fertiliser at 271.33 kg ha^{-1} (Figure 4A). The biochar briquettes and the urea fertiliser also resulted in increased TC levels (Table 5). The biochar briquettes showed a linear pattern while the urea fertiliser showed a quadratic pattern. The applications of the biochar briquettes and the urea fertiliser at 4-grain plant^{-1} and 300 kg ha^{-1}, respectively, produced the highest TC at 0.72 g g leaf^{-1} (Table 6). The optimum application of the biochar briquettes and the urea fertiliser were at 4.74-grain plant^{-1} and 272.38 kg ha^{-1}, respectively, yielding the maximal TC value of 0.72 g leaf^{-1} (Figure 4B).

The treatments of biochar briquettes and urea fertiliser showed a coequally significant differential in the LPR analysis (Table 5). The regression patterns had a linear pattern for the biochar-briquette treatment, whereas a quadratic pattern was found for the urea fertiliser treatment. A biochar-briquette application of 4-grain plant^{-1} and urea fertiliser of 300 kg ha^{-1} produced the highest LPR at 437.12 CO_2 m^{-2} s^{-1} (Table 6). The optimum application of biochar briquettes of 4.75-grain plant^{-1} and urea fertiliser of 271.92 kg ha^{-1} accelerated to the maximum LPR value of 427.47 CO_2 m^{-2} s^{-1} (Figure 4C). Equivalently, the applications of biochar briquettes and urea fertiliser displayed a noteworthy difference (Table 5) in linear patterns for the NL value. The value of NL was highest at 33.60 kg ha^{-1} with a 0-grain plant^{-1} of the biochar briquettes and 300 kg ha^{-1} of the urea fertiliser (Table 6). The maximum NL value of 30.03 kg ha^{-1} was recorded by applying the optimum application of the biochar briquettes at 1.96-grain plant^{-1} and the urea fertiliser at 290.72 kg ha^{-1} (Figure 4D).



(**A**) (**B**) (**C**)

(**D**) (**E**) (**F**)

Figure 3. The response of soil properties to in situ biochar briquettes (grain plant^{-1}) and urea fertiliser (kg ha^{-1}). (**A**) Water-holding capacity (%), (**B**) Total porosity (%), (**C**) Soil organic carbon in the soil after harvesting (%), (**D**) Total nitrogen in the soil after harvesting, (**E**) Total fungi in the soil after harvesting (colony g soil dry weight^{-1}), and (**F**) Total bacteria in the soil after harvesting (colony g soil dry weight^{-1}).

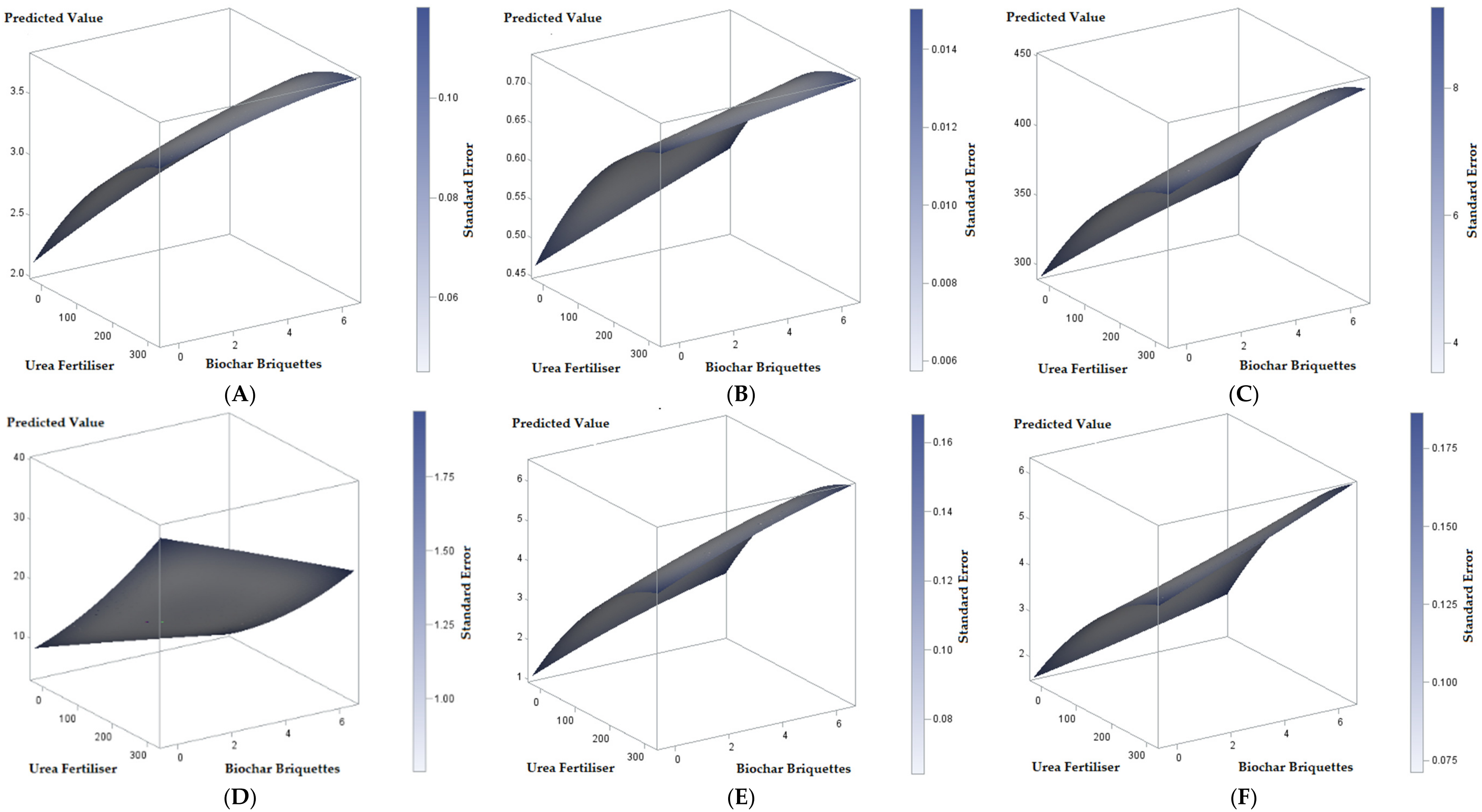


Figure 4. The response of physiological characteristics and yield of hybrid rice to in situ biochar briquettes (grain plant^{-1}) and urea fertiliser (kg ha^{-1}). (**A**) Nitrate reductase activity (µmol NO_2^- g^{-1} h^{-1}), (**B**) Total chlorophyll (g g leaf^{-1}), (**C**) Leaf photosynthesis rate (CO_2 m^{-2} s^{-1}), (**D**) Nitrogen loss (kg ha^{-1}), (**E**) Nitrogen-use efficiency (kg grain kg $N_{fertiliser}{}^{-1}$), and (**F**) Yield of hybrid rice (tonnes ha^{-1}).

A similar result of a significant differential was noted in NUE under the treatment of biochar briquettes and urea fertiliser (Table 5). However, the biochar briquettes showed a linear pattern while the urea fertiliser exhibited a quadratic pattern. The biochar briquettes at 6-grain plant^{-1} and the urea fertiliser at 200 kg ha^{-1} resulted in the highest NUE value of 9.41 kg grain kg $N_{fertiliser}{}^{-1}$. The optimum application of the biochar briquettes at 4.71-grain plant^{-1} and the urea fertiliser at 273.16 kg ha^{-1} resulted in a maximal NUE value of 5.90 kg grain kg $N_{fertiliser}{}^{-1}$ (Figure 4E). The applications of biochar briquettes and urea fertiliser illustrated (Table 5) a linear pattern and a quadratic pattern, respectively, with an ameliorated YHR. The treatments using a 4-grain plant^{-1} of the biochar briquettes and 300 kg ha^{-1} urea fertiliser produced the highest YHR at 5.70 tonnes ha^{-1} (Table 6). The maximum YHR of 5.49 tonnes ha^{-1} was achieved by applying the optimum application of the biochar briquettes at 4.74-grain plant^{-1} and the urea fertiliser at 272.35 kg ha^{-1} (Figure 4F).

3.4. Relationship between Soil Properties, Physiological Characteristics, and Hybrid Rice Yield

The interactions between the response variables, namely, the soil physics, chemistry, biology, and physiological characteristics as well as the rice yield, were determined using SEM and stepwise regression. The SEM analysis concluded that, in general, the response variables that affected the YHR were soil properties (physics and chemistry) and physiological traits of soil (Figure 5). The parameters that affected the hybrid rice yield were determined in detail using the stepwise regression method. The stepwise regression results showed that the parameters that significantly affected the YHR were TN, TF, NRA, LPR, NL, and NUE. The regression equation was $Y = -0.65^{ns} + 3.62\ TN^{**} - 114{,}500\ TF^{*} - 0.33\ NRA^{*} + 0.01\ LPR^{**} - 0.03\ NL^{**} + 0.51\ NUE^{**}$ ($R^2 = 0.998^{**}$).

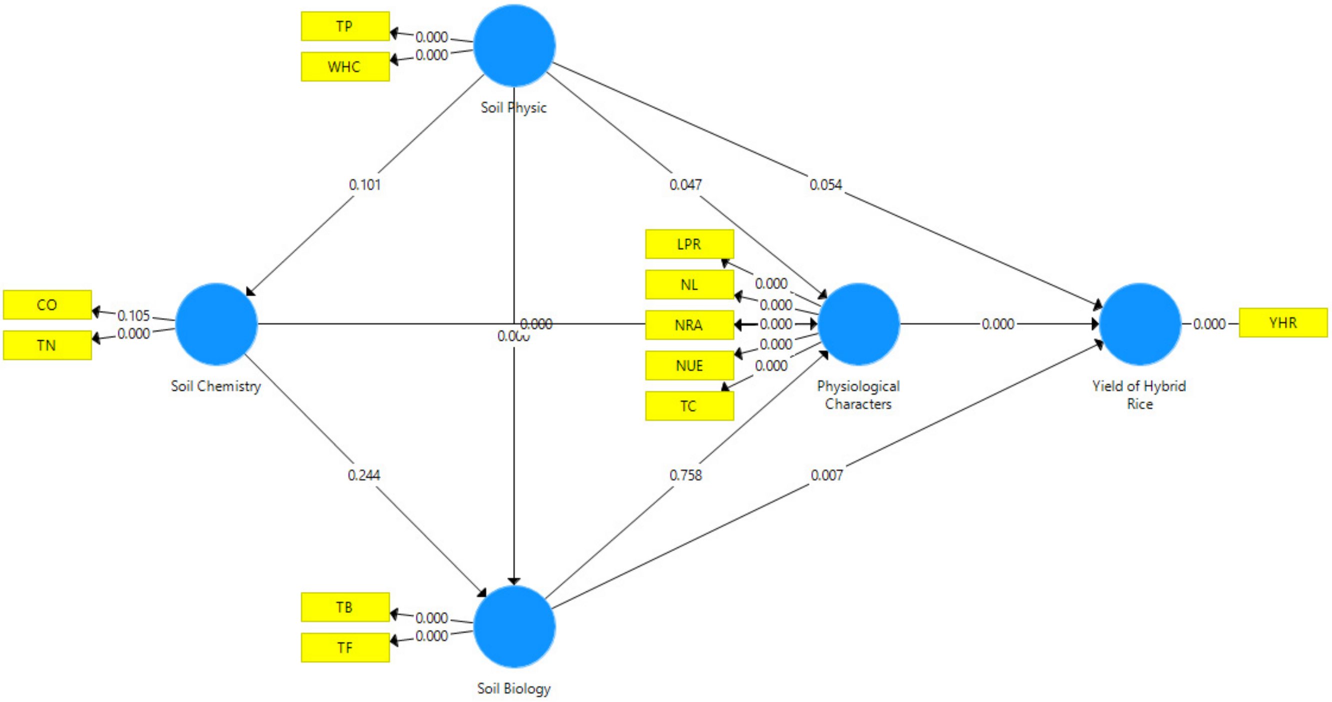


Figure 5. Relationship between soil properties (physic, chemistry, biology), physiological traits, and yield of hybrid rice.

3.5. Determining the Optimum Scenarios

Determination of the optimum application under both biochar briquettes and urea fertiliser treatments for hybrid rice variables was conducted by establishing three scenarios, namely, economic, environmental, and eco–environmental (Table 7). The economic scenario included the optimum levels of the biochar briquettes at 4.73-grain plant^{-1} and the urea fertiliser at 272.40-grain plant^{-1} with a hybrid rice yield of 7.22 tonnes ha^{-1} (Table 7). The hybrid rice yield reduced the eco–environmental and environmental scenarios to 10.12% and 34.98%, respectively, as compared to the economic scenario.

Table 7. Optimized value of in situ biochar briquettes and nitrogen fertiliser for response variables.

Variables and Treatments [1]		**Scenarios**		
		Economic	**Environmental**	**Eco–Environmental**
Response Variables	WHC	47.98	47.11	47.48
	TP	34.20	37.30	37.65
	SOC	1.68	1.54	1.89
	TN	0.37	0.25	0.34
	TF	1.23×10^4	1.07×10^4	1.19×10^4
	TB	2.19×10^3	1.90×10^3	2.22×10^3
	NRA	3.82	3.42	3.78
	TC	0.72	0.66	0.71
	LPR	430.05	394.51	425.96
	NL	24.01	17.91	19.75
	NUE	9.66	8.05	9.71
	YHR	7.29	4.69	6.49
Independent Variables [2]	X_1	4.73	2.89	5.54
	X_2	272.40	163.98	230.08

[1] WHC: Water-holding capacity (%); TP: Total porosity (%); SOC: Soil organic carbon in the soil after harvesting (%); TN: Total nitrogen in the soil after harvesting; TF: Total fungi in the soil after harvesting (colony g soil dry weight^{-1}); TB: Total bacteria in the soil after harvesting (colony g soil dry weight^{-1}); NRA: Nitrate reductase activity (µmol NO_2^- g^{-1} h^{-1}); TC: Total chlorophyll (g g leaf^{-1}); LPR: Leaf photosynthesis rate (CO_2 m^{-2} s^{-1}); NL: Nitrogen loss (kg ha^{-1}); NUE: Nitrogen-use efficiency (kg grain kg $N_{fertiliser}{}^{-1}$); and YHR: Yield of hybrid rice (tonnes ha^{-1}). [2] X_1: Biochar briquettes (grain plant^{-1}) and X_2: Urea fertiliser (kg ha^{-1}).

Conversely, the environmental scenario consisted of optimal levels of biochar briquettes and urea fertiliser at 2.89-grain plant^{-1} and 163.98 kg ha^{-1}, respectively, resulting in a minimum NL value of 17.90 kg ha^{-1} (Table 7). In both the economic and eco–environmental scenarios, the increased NL levels were recorded at 34.10% and 10.33%, respectively, as compared to the environmental scenario.

The eco–environmental scenario included an optimal level of the biochar briquettes at 5.54-grain plant^{-1} and the urea fertiliser at 230.08 kg ha^{-1} with a NUE accumulation of 9.71 kg grain kg $N_{fertiliser}{}^{-1}$ (Table 7). The reduced NUE levels in the economic and environmental scenarios were measured at 0.51% and 17.06%, respectively, as compared to the eco–environmental scenario.

The most favourable eco–environmental scenario produced the highest hybrid rice yield while still sustaining the environment. The eco–environmental scenario was proficient in reducing the usage of urea fertiliser by 23.31% while increasing WHC, TP, SOC, TN, TF, TB, NRA, TC, LPR, NL, NUE, and YHR by 19.24%, 4.93%, 88.66%, 23.74%, 1015.26%, 144.41%, 12.19%, 0.73%, 6.27%, −41.21%, 34.86%, and 40.41%, respectively, as compared to a single urea application of 300 kg ha^{-1} without the biochar briquettes.

4. Discussion

Biochar briquettes have been used to slow the release of nutrients while reducing their loss, especially for nitrogen and its derivates [36,37]. Zhao et al. [58] reported that the leaching process resulted in NH_4^+–N and NO_3^-–N losses recorded at 28.10% and 187.00%, respectively. It has been shown to significantly reduce N loss through ammonia volatilisation [36]. When urea fertiliser was applied topically, it caused a total loss of 35% of nitrogen, whereas when co-treated with briquettes, only 4% of total N was lost in the process [59].

Our research conducted between 2019 and 2021 analysed a significant increase in all response variables, except for the NL variable, which declined considerably. The increases were due to the accumulation of biochar-briquette residue in the soil. This was evidenced by the increasing values for most variables, namely, WHC, TP, SOC, TN, TF, and TB during each year of our research (2019–2021) at rates of 5.36%, 21.37%, and 47.37%, respectively. As mentioned in Table 1, biochar made from *kayu putih* waste had a high C, H, O, N, and S content to improve this research's soil properties. Biochar affects the nutrient absorption by plants by changing the dynamics of the nutrient release from the soil system to the plants [60–62].

In previous studies, the incorporation of biochar briquettes into soil not only improved the physical properties and qualities of the soil, but it also enhanced the clay's texture by increasing the water retention and the porosity, aggregating stability, and reducing the bulk density [32,63,64]. In addition, biochar also ameliorates the chemical and biological properties of the soil. Increased biochar application has been positively correlated to an increase in C, N, and microbial content in soil [65–68]. Urea fertilisation only showed a significant increase in TN while WHC, TP, SOC, TF, and TB did not exhibit a considerable differential in our research. Diniz et al. [69] showed that N fertilisation at 20, 40, and 80 kg ha^{-1} could not increase soil microbes in Oxisol soils.

NRA is a molybdoenzyme that converts nitrate to nitrite [15]. The increase in NRA in hybrid rice was positively correlated with the increased application of biochar briquettes and urea fertilisation into the soil. However, while biochar slows the release of N in the soil, this has been shown to have implications for the availability of N in the soil, which results in an increase in the NRA content [70]. Research conducted by Loussaert et al. [71] showed that an increase in NH_4^+–N and NO_3^-–N sourced from N fertilisers was correlated with an increase in the NRA contents of the plants.

Chlorophyll is an essential pigment and one of the main factors contributing to the photosynthesis process. The primary function of chlorophyll is to absorb sunlight at various wavelengths [72]. The addition of biochar briquettes and urea fertilisation into the soil increased the TC in the hybrid rice. In previous research, biochar played a significant role in increasing the chlorophyll content of groundnuts during phase 3 tetrafoliolate (V3), beginning bloom (R1), and beginning pod (R3) [73]. Biochar conspicuously affected the chlorophyll content, thereby increasing not only the PS II activity but also facilitating the electron transport as well as ameliorating the photosynthesis rate in [74]. Comparatively, urea fertilisation also contributed to elevating the TC level in the hybrid rice in our study. A study conducted by Lai et al. [75] reported that the application of biochar at 9.00 tonnes ha^{-1} and N fertilisation at 120 kg ha^{-1} notably raised the chlorophyll content in rice.

Photosynthesis is an important component of and one of the major determinants in increasing crop production [76]. The increase in the LPR of the hybrid rice was in line with the increase in the application of the biochar briquettes and the urea fertiliser. Biochar stimulates the root growth, which improves the water supply to the plants and consequently boosts the photosynthesis rate [77]. Zhang et al. [78] reported that an increase in N application was in line with an increased CO_2 concentration between cells, stomatal conductance, transpiration, and photosynthesis in soybean crops. Another study conducted by Nurmalasari et al. [79] showed that the application of *kayu putih* biochar and urea fertilisation by 13.29 tonnes ha^{-1} and 245.35 kg ha^{-1}, respectively, increased the LPR by 18.09%.

Nitrogen loss is a major concern that influences its availability in the plants. Biochar briquettes have been shown to play a role in decreasing NL in hybrid rice by reducing NO_3^-−N and NH_4^+−N leaching in the soil and enabling the adsorption of these ions onto the biochar surface [80]. In addition, 15.00% of the total organic matter applied reduced the N loss by 27.00% in [81]. Other studies have revealed that adding 2% and 4% biochar to the clay texture reduced the loss of N by 29.19% and NO_3^-–N by 28.65%. However, the application of N fertiliser significantly increases the NL in vegetable commodities [57]. Alam et al. [13] reported that using a mixture of biochar and compost made from *kayu putih* waste proved to be an effective alternative to reduce the nitrogen loss while increasing the soybean yield in crops planted between *kayu putih* stands.

NUE is a measure of the economic and the environmental efficiency for agro-ecosystem sustainability [82]. Sarfraz et al. [83] showed that a 50% increase in efficiency when using N fertiliser as well as an increase in NUE of 65% could be achieved by adding 1% w w^{-1} biochar to the soil. The addition of urea fertiliser affects the dynamics of the NUE value. The application of low N fertilisers by farmers has generally resulted in low NUE levels [84].

The YHR increased with expanded applications of both biochar briquettes and urea fertilisation in our study. This was in line with the research conducted by Nurmalasari et al. [79], who showed that *kayu putih* waste biochar could improve maize yield by 61.78% while the efficient use of nitrogen from urea rose by 18.22%. In addition, the biochar briquettes made from *kayu putih* waste at 3.70-grains^{-1} or 9.25 tonnes ha^{-1} combined with the ammonium–sulphate fertiliser at 76.31 kg ha^{-1} increased soybean yield by 13.02%, while reducing losses by 38.25% compared to the application of a single N fertiliser application at 100 kg ha^{-1} [37]. Another study concerning rice showed that the application of N fertiliser at 240 kg ha^{-1} that was applied at 30% in the seedling phase, 20% at 10 days after planting (DAP), and 50% at 36 DAP resulted in an improvement in rice harvest of 10.20 tonnes ha^{-1}, or an increase of 46.87% compared to without N fertiliser [85].

The eco–environmental scenario is the most suitable strategy because it can sustain a balance between the production and the land. This is in line with research conducted by Koocheki et al. [53], who obtained an optimum application of water irrigation, nitrogen fertiliser, and plant density in canola. In addition, Alam et al. [13] also used an eco–environmental scenario to determine the optimum application of biochar, compost, and ammonium sulphate in soybeans in an agroforestry system with *kayu putih*.

5. Conclusions

The experimental results demonstrated significant improvements in all response variables during the time period of 2019–2021, except for the NL variable, which declined considerably. The average increase in the values for WHC, TP, SOC, TN, TF, TB, NRA, TC, LPR, NL, NUE, and YHR from 2019 to 2021 were 19.60%, 6.37%, 9.11%, 3.22%, 896.59%, 52.65%, 8.46%, 20.69%, 12.02%, 26.02%, 56.11%, and 32.12%, respectively. The parameters that affected the hybrid rice yield were TN, TF, NRA, LPR, NL, and NUE. The eco–environmental scenario was proven to be the most efficient strategy for improving the soil quality, physiological characteristics, and YHR with the optimum application of biochar briquettes at 5.54-grain plant^{-1} and the urea fertiliser at 230.08 kg ha^{-1}. This alternative approach not only reduced the usage of urea fertiliser by 23.31% but also increased the WHC, TP, SOC, TN, TF, TB, NRA, TC, LPR, NL, NUE, and YHR by 17.34%, 7.06%, 8.10%, 2.42%, 838.02%, 46.48%, 6.12%, 16.58%, 9.05%, −26.28%, 47.07%, and 24.73%, respectively, as compared to a single application of 300 kg urea ha^{-1} without biochar briquettes.

Author Contributions: Conceptualization, P.S. and T.A.; methodology, E.T.S.P., S.H., M.H.W. and T.A.; software, M.H.W. and T.A.; validation, P.S., E.T.S.P., D.K., S.H. and T.A.; formal analysis, T.A.; investigation, P.S., D.K., S.H. and T.A.; resources, P.S. and T.A.; data curation, S.H., D.K. and T.A.; writing—original draft preparation, P.S. and T.A.; writing—review and editing, P.S., E.F., H.H.N., E.T.S.P., D.K., S.H., R.B., M.H.W. and T.A.; visualization, T.A.; supervision, P.S., D.K., S.H. and T.A.; project administration, T.A.; funding acquisition, P.S., E.F., H.H.N., R.B. and T.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable for studies not involving humans or animals.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank the field technicians of Teguh for their technical assistance and the laboratory technicians at the Soil Laboratory, Microbiology Laboratory, and Crop Production and Management Laboratory, Faculty of Agriculture of the Universitas Gadjah Mada, Indonesia.

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

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