land

MDPI

Article

# Co-Composted Chicken Litter Biochar Increases Soil Nutrient Availability and Yield of *Oryza sativa* L.

**Maru Ali [1], Osumanu Haruna Ahmed [2,*], Mohamadu Boyie Jalloh [3,*], Walter Charles Primus [4], Adiza Alhassan Musah [5,6] and Ji Feng Ng [7]**

1. School of Agriculture, SIREC, CBAS, University of Ghana, Legon, Accra 23321, Ghana
2. Faculty of Agriculture, Sinaut Campus, Universiti Islam Sultan Sharif Ali, Km 33 Jln Tutong Kampong Sinaut, Tutong TB1741, Brunei
3. Crop Production Programme, Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, Sandakan Branch, Locked Bag No. 3, Sandakan 90509, Sabah, Malaysia
4. Department of Basic Science and Engineering, Faculty of Agricultural Science and Forestry, Universiti Putra Malaysia Bintulu Sarawak Campus, Bintulu 97008, Sarawak, Malaysia
5. Department of Business Management and Law, Faculty of Business Management and Professional Studies, Management and Science University, University Drive, Off Persiaran Olahraga Section 13, Shah Alam 40100, Selangor, Malaysia
6. Graduate School of Management, Post Graduate Centre, Management and Science University, University Drive, Off Persiaran Olahraga Section 13, Shah Alam 40100, Selangor, Malaysia
7. Department of Crop Science, Faculty of Agricultural Science and Forestry, Universiti Putra Malaysia Bintulu Sarawak Campus, Bintulu 97008, Sarawak, Malaysia

* Correspondence: ahmed.haruna@unissa.edu.bn (O.H.A.); mbjalloh@ums.edu.my (M.B.J.)

**Abstract:** Intensified cultivation of rice has accelerated weathering of most tropical acid soils leading to significant loss of base cations. In most developing countries, rice yield is low and this results in its production being costly because productivity versus labor is low. The objectives of this study were to (i) enhance soil chemical properties, nutrient uptake, and grain yield of rice grown on a mineral tropical acid soil using agro-wastes; (ii) determine the agro-waste (chicken manure, cow dung, forest litter, and *Leucaena*) that has the potential to significantly increase rice yield; and (iii) determine the residual effects of the organic soil amendments produced from the agro-wastes on soil and rice productivity. The treatments used in this three-cycle field study were (i) soil without amendments (S0); (ii) prevailing recommended rates for fertilizers (NPK-Mg); (iii) biochar–forest litter compost (OSA1); (iv) biochar–chicken litter compost (OSA2); (v) biochar–cow dung compost (OSA3); (vi) biochar–*Leucaena* compost (OSA4); and (vii) biochar–*Leucaena*–chicken litter compost (OSA5). Standard procedures were used to determine the plants' rice growth, grain yield, plant nutrient concentrations and uptake, and selected soil chemical properties. The use of organic soil amendments (OSA1 to OSA5) significantly improved the soil chemical properties, rice plant growth, nutrient uptake, and grain yield compared with the prevailing method of cultivating rice (NPK-Mg). The application of organic soil amendments reduced the use of inorganic N, P, K, MgO, and trace elements fertilizers up to 25%, 100%, 64%, 100%, and 100%, respectively. The organic soil amendments with *Leucaena* significantly increased rice grain yield of OSA5 at 11.17, 13.11, and 10.06 t $ha^{-1}$ in the first, second, and third cropping cycles, respectively. The residual effect of the organic soil amendments also improved rice plant growth, nutrient uptake, and rice grain yield although these were slightly reduced as compared to those of the two previous cropping cycles, the afore-stated treatments were superior to the prevailing method of cultivating rice (NPK-Mg). Transforming agro-wastes into organic soil amendments can improve tropical mineral acid soils and rice productivity.

**Keywords:** animal waste; crop productivity; organic amendments; plant wastes; residual effect; soil productivity



**Citation:** Ali, M.; Ahmed, O.H.; Jalloh, M.B.; Primus, W.C.; Musah, A.A.; Ng, J.F. Co-Composted Chicken Litter Biochar Increases Soil Nutrient Availability and Yield of *Oryza sativa* L.. *Land* **2023**, *12*, 233. https://doi.org/10.3390/land12010233

Academic Editor: Chang Liang

Received: 13 November 2022
Revised: 17 December 2022
Accepted: 28 December 2022
Published: 11 January 2023

## 1. Introduction

Southeast Asian soils are dominated by Oxisols and Ultisols [1]. Ultisols are among the highly weathered cultivated soils which are generally infertile because of the accumulation of high quantities of Fe and Al in these soils [2,3]. Ultisols in particular are low in silt but high in sand, resulting in low water holding capacity. This makes them less suitable for rice production [4]. Apart from being acidic because of their parent materials are mainly feldspars and micas, these soils are low in cation exchange capacity (CEC) and base saturation [5]. High Al:Ca ratios which resulted from subsoil acidity makes root extension to this zone difficult for most crops [6].

The aforementioned problems are further deteriorated because most farmers excessively use chemical fertilizers to improve soil productivity. For example, the current rice yield in Malaysia is considered low in a range of 3.5 to 4 t $ha^{-1}$ [7]. The low yield and increasing fertilizer costs cause the rice production to become an expensive venture in most developing countries [8]. Intensified cultivation of rice because of increasing human population has accelerated weathering of most tropical soils leading to significant loss of base cations [2,9]. These processes significantly reduce soil fertility; thus, restoration is done through the use of chemical fertilization to increase rice production [9]. However, the impacts of increasing use of chemical N, P, and K fertilizers is not just causing an increase in rice production costs, but it also leads to environmental pollution and poor grain quality [10,11].

Sustainable and cost-effective methods of producing rice using organic soil amendments are gaining recognition. The quality of organic soil amendments depends mainly on the type and source of wastes used [12]. This is because animal manure and plant residues such as cow dung, chicken litter, forest litter, and *Leucaena* have different nutrient contents. The assignment of a general or fixed percentage for nutrients in animal manures is not feasible due to the variations of such components according to animal type, age, ration, and feed consumption of the animals [13]. Plant residues are high in organic matter and can be used to restore soil organic matter in an intensive rice field. Some plant residues such as *Leucaena leucocephala* are nutritious and are used for fodder, controlling soil erosion, and mulching [14]. Meena et al. [15] demonstrated that total N and P contents of the leaves of *Leucaena leucocephala* were 4.2% and 0.23%, respectively. From the foregoing rationale, organic soil amendments which were produced from cow dung, poultry manure, forest litter, and *Leucaena* co-composted with chicken litter biochar were used to (i) improve soil chemical properties, rice plant growth, nutrient uptake, and grain yield on a tropical mineral acid soil; (ii) determine the type of agro-waste (chicken manure, cow dung, forest litter, and *LLeucaena*) that has the potential to significantly increase rice yield; and (iii) determine the residual effects of the organic soil amendments produced from the agro-wastes in this present study on soil and rice productivity.

## 2. Materials and Methods

### *2.1. Field Study Area*

This research was conducted at a rice plot at Universiti Putra Malaysia Bintulu Campus Sarawak, Malaysia, which has the geographical coordinates of latitude 3° 12′ 54.48″ N and longitude 113° 05′ 39.03″ E (Figure 1). The elevation of the rice plot is 31 m and the soil used for the field study is the Nyalau series (*Typic Paleudults*).

### *2.2. Experimental Plots Preparation*

The entire research area was 24 m long and 23 m wide (552 $m^2$). The design used for this research was a Randomized Complete Block Design with four blocks. The size of each plot was 2 m × 2 m (4 $m^2$). The distance between plots was 1 m and the distance between blocks was 2 m. The well fenced experimental site was initially cleared from plant debris. Afterwards, the edges of the plots were covered with silver shine to mitigate weed infestation and soil run-off. The plots were netted to prevent birds from getting into the plots to feed on rice grains.


**Figure 1.** Aerial view of the rice plot at Universiti Putra Malaysia Bintulu Sarawak Campus, Malaysia.

### 2.3. Experimental Plots Fertilization

The organic soil amendments used in this field study were based on the most promising treatments selected from our pot study (Table 1). The chemical properties of the organic soil amendments used in this present study are presented in Table 2. The application rate of the organic soil amendments was 5 t ha$^{-1}$ [16] and the quantity used was scaled down based on 100 hills plot$^{-1}$ (Table 3). In the first and second cropping cycles, 2 kg of each organic amendment was applied to the respective plots labeled T3 (OSA1), T4 (OSA2), T5 (OSA3), T6 (OSA4), and T7 (OSA5) (Table 1). The organic soil amendments were spread on the soil surface and subsequently mixed well with the aid of a shovel. Thereafter, the plots were watered. In the third cropping cycle, application of the organic soil amendments was skipped because this aspect of the present study was to assess the residual effect of the organic soil amendments used in the two previous cropping cycles. Chemical fertilizers were broadcast on the soil surface of each plot on 15, 35, 50, and 70 days after transplanting (Table 3). The fertilization regime adopted in this study was in accordance with the recommendation by MADA (Table 3). Nitrogen, P, K, and trace elements were reduced by 25%, 100%, 64%, and 100 %, respectively, in the first and second cropping cycles of the present study. However, in the third planting cycle, N was applied at 100 % of the recommended fertilization due to the lower N in the organic residues.

**Table 1.** Codes and description of the treatments used in the field study.

| Treatment | Code | Description |
|---|---|---|
| T1 | S0 | Soil without amendments |
| T2 | NPK-Mg | Full chemical fertilizers rate (N, P, K, and Mg) * |
| T3 | OSA1 | Chicken litter biochar–forest litter compost (1:1) ** |
| T4 | OSA2 | Chicken litter biochar–chicken litter compost (1:1) ** |
| T5 | OSA3 | Chicken litter biochar–cow dung compost (1:1) ** |
| T6 | OSA4 | Chicken litter biochar–*Leucaena* compost (1:1) ** |
| T7 | OSA5 | Chicken litter biochar–*Leucaena*–chicken litter compost (2:1:1) ** |

* MADA [7]; ** Maru [17].

### 2.4. Experimental Plots Irrigation

A day before transplanting, the 28 plots were irrigated up to 1.5 cm depth using tap water. Afterwards, the water level in the plots was maintained at 1.5 cm above the soil surface to mimic waterlogged conditions until the rice plants were established (14 days after transplanting). Thereafter, the water level was increased and maintained to approximately 2.5 cm to 4 cm throughout the study.

**Table 2.** Initial chemical properties of organic soil amendments.

| | OSA1 | OSA2 | OSA3 | OSA4 | OSA5 |
|---|---|---|---|---|---|
| pH in water | 7.37 ± 0.52 | 9.32 ± 0.72 | 8.47 ± 0.63 | 8.57 ± 0.28 | 8.68 ± 0.53 |
| pH in KCl | 6.87 ± 0.47 | 8.79 ± 1.04 | 8.10 ± 0.56 | 8.04 ± 0.57 | 8.26 ± 0.87 |
| | | | (%) | | |
| Organic matter | 67.00 ± 5.23 | 55.00 ± 3.15 | 37.66 ± 4.78 | 53.00 ± 2.45 | 57.33 ± 5.44 |
| ash content | 33.00 ± 3.21 | 45.00 ± 6.75 | 62.33 ± 4.16 | 47.00 ± 4.72 | 42.66 ± 5.39 |
| Total N | 0.20 ± 0.05 | 0.30 ± 0.01 | 0.13 ± 0.01 | 0.64 ± 0.02 | 0.29 ± 0.01 |
| Total P | 1.65 ± 0.29 | 3.04 ± 0.34 | 1.81 ± 0.13 | 1.98 ± 0.13 | 2.02 ± 0.31 |
| C/N ratio | 192.19 ± 26.24 | 106.27 ± 6.78 | 164.00 ± 9.41 | 48.26 ± 4.33 | 113.92 ± 9.93 |
| C/P ratio | 23.69 ± 1.68 | 10.56 ± 1.58 | 12.18 ± 4.87 | 15.66 ± 1.38 | 16.75 ± 1.92 |
| | | | (g $kg^{-1}$) | | |
| Total K | 426.53 ± 23.21 | 393.23 ± 27.47 | 372.80 ± 32.41 | 361.97 ± 13.54 | 389.13 ± 34.12 |
| Total Ca | 70.93 ± 3.43 | 72.36 ± 2.48 | 64.06 ± 3.11 | 63.87 ± 1.45 | 78.60 ± 4.82 |
| Total Na | 11.96 ± 0.67 | 16.88 ± 2.42 | 12.30 ± 0.7.4 | 8.73 ± 0.25 | 15.26 ± 1.78 |
| Total Mg | 14.46 ± 0.46 | 18.13 ± 2.84 | 14.56 ± 1.67 | 12.50 ± 0.83 | 15.53 ± 2.58 |
| Total Zn | 0.51 ± 0.034 | 0.85 ± 0.06 | 0.49 ± 0.02 | 0.59 ± 0.023 | 0.64 ± 0.08 |
| Total Cu | 0.06 ± 0.004 | 0.15 ± 0.008 | 0.08 ± 0.002 | 0.10 ± 0.004 | 0.15 ± 0.007 |
| Total Mn | 0.66 ± 0.03 | 0.84 ± 0.12 | 0.68 ± 0.07 | 0.54 ± 0.014 | 0.65 ± 0.11 |
| Total Fe | 1.85 ± 0.21 | 0.92 ± 0.08 | 1.38 ± 0.18 | 4.02 ± 0.10 | 3.10 ± 0.48 |

**Table 3.** Application rates of organic soil amendments and fertilizers used in the field study.

| Plant Growth Stages | | Early Tillering | Active Growth | Stalk Formation | Grain Filling |
|---|---|---|---|---|---|
| Days after Transplanting | | 15 to 20 | 35 to 40 | 50 to 55 | 70 to 75 |
| Code | Amount of Organic Soil Amendment | Amount of Chemical Fertilizers | | | |
| | g $Plot^{-1}$ | | | | |
| S0 | 0 | 0 | 0 | 0 | 0 |
| NPK-Mg | 0 | Mix NPK [1] | 40 urea | Mix NPK-Mg [2] | Mix NPK-Mg [2] |
| OSA1 | 2000 * | 40.3 urea | 30 urea + 24 MOP | 18 urea | 18 urea |
| OSA2 | 2000 * | 40.3 urea | 30 urea + 24 MOP | 18 urea | 18 urea |
| OSA3 | 2000 * | 40.3 urea | 30 urea + 24 MOP | 18 urea | 18 urea |
| OSA4 | 2000 * | 40.3 urea | 30 urea + 24 MOP | 18 urea | 18 urea |
| OSA5 | 2000 * | 40.3 urea | 30 urea + 24 MOP | 18 urea | 18 urea |

[1] Mix NPK = 55 g Urea + 50 g TSP + 24 g MOP. [2] Mix NPK-Mg = 18.3 g Urea + 18.7 g TSP + 19.8 g MOP + 1.4 g MgO. Note: TSP = Triple Super Phosphate, MOP = Muriate of Potash. * Application of organic soil amendments was skipped in the third cropping cycle.

### *2.5. Transplanting of Fifteen-Day Seedlings*

The nursed rice seedlings (15-day old) of the MR219 variety in a plastic basin were transported to the rice plot to enable the rice seedlings to adapt to the field condition. The following day, 100 hills (3 seedlings per hill) of the rice seedlings were transplanted into each rice plot (4 $m^2$) as demonstrated in Figure 2. Afterwards, they were monitored until maturity (98 days to 120 days after transplanting). Figure 2 demonstrates the growth of rice plants at one, forty, and eighty days as affected by treatments, respectively.

### *2.6. Weed and Pest Control*

Manual weeding was carried out to control weeds from outcompeting the rice plants' growth, whereas Halex Malathion 84 EC was used to control insect pests such as grasshoppers, stem borers, and caterpillars.

### *2.7. Harvesting of Rice Plants at Maturity*

A day before harvest, 10 rice plant hills were randomly selected (excluding border plants) and harvested using a knife for the rice plant growth and grain yield measurements. The rice plant height was measured from the soil surface to the tip of the tallest leaf using a measuring tape. The number of tillers and number panicles per hill were counted from the 10 harvested hills and subsequently 10 panicles were randomly harvested and placed into separate plastic bags for total grain per panicle, percentage of grain filling, and weight of 1000 grains determination. Thereafter, another 10 rice plant hills were harvested for determination of dry matter weight and nutrient contents. The following day, the remaining panicles were harvested using a pair of scissors, followed by air-drying at room temperature and grain removal.

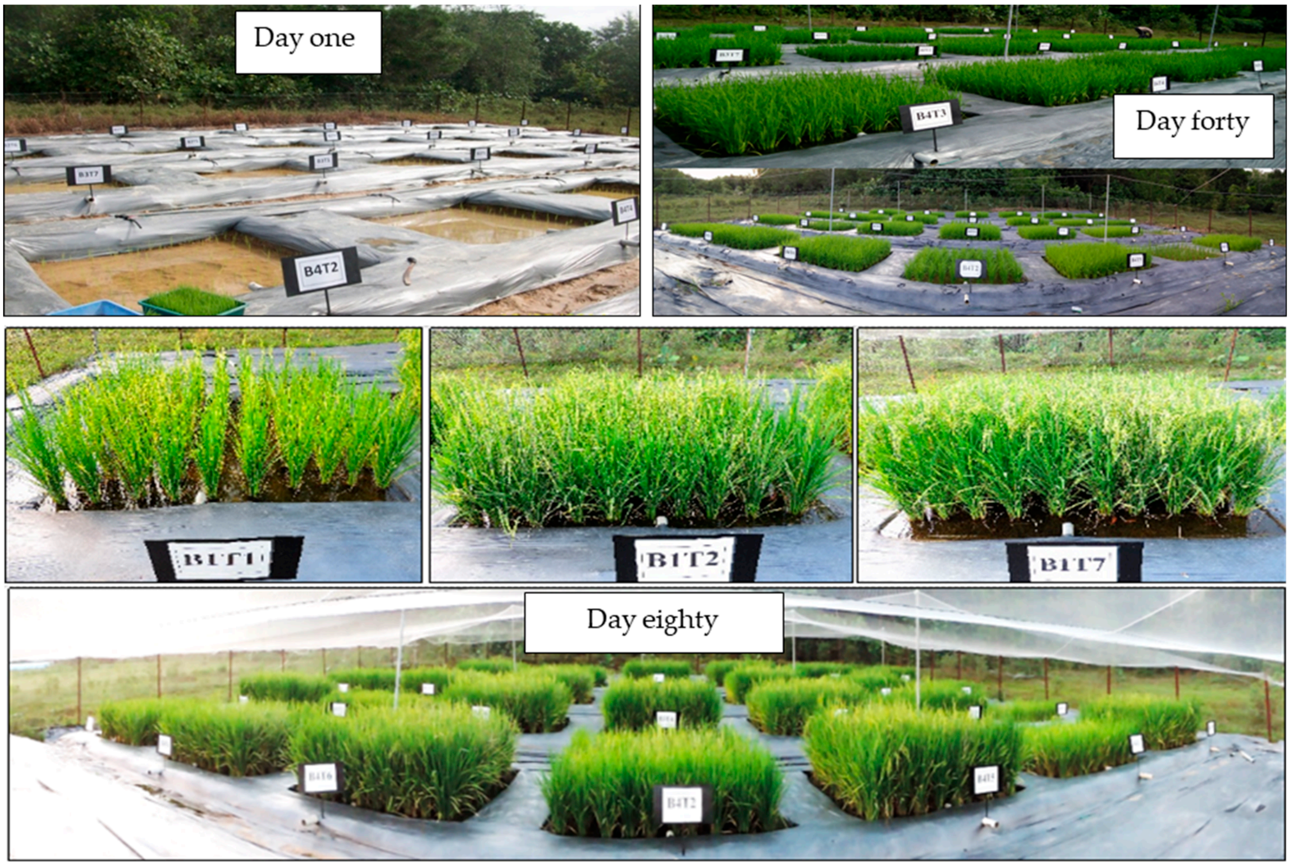


**Figure 2.** Rice seedlings in relation to treatments at different growth stages after transplanting.

*2.8. Soil Sampling and Analysis*

The soils in each rice plot were sampled immediately after harvesting at five points into separate plastic containers using the diagonal method, after which the soil samples were air-dried, manually crushed, and sieved to pass through a 2 mm sieve for chemical analyses. Soil pH was determined in a 1:2.5 (soil: distilled water or 1 mol dm$^{-3}$ KCl) suspension using a digital pH meter [18]. Soil total organic matter was determined using the loss on ignition method, and soil total C was calculated as 58% of the organic matter [19]. Soil cation exchange capacity (CEC) was determined using the leaching method [20]. Soil total N was determined using the Kjeldahl method [21,22], whereas inorganic N ($NO_3^-$ and $NH_4^+$) were determined using the method described by Keeney and Nelson [23]. Soil total P was extracted using the aqua regia method [22], whereas soil available P was extracted using Mehlich's No.1 double-acid method [24]. Thereafter, soil total and available P were determined using Ultraviolet-visible Spectrophotometry (Lambda 25, Perkin Elmer, Shelton, CT, USA) after blue color development [25]. Soil exchangeable acidity, $H^+$, and $Al^{3+}$ were determined using acid–base titration method [26]. The initial chemical properties of Nyabau series soil (*Typic Paleudults*) are presented in Table 4.

**Table 4.** Initial chemical properties of Nyalau series (*Typic Paleudults*).

| Soil Properties | Value Determined (Mean ± S.E. [1]) |
|---|---|
| $pH_{water}$ | 5.11 ± 0.02 |
| $pH_{KCl}$ | 3.97 ± 0.02 |
| (%) | |
| Total Organic Matter | 4.40 ± 0.12 |
| Total Organic Carbon | 2.55 ± 0.07 |
| Total N | 0.10 ± 0.01 |
| ($mg\ kg^{-1}$) | |
| Exchangeable $NH_4^+$ | 9.34 ± 0.47 |
| Available $NO_3^-$ | 2.57 ± 0.23 |
| Total P | 58.29 ± 0.51 |
| Available P | 3.00 ± 0.19 |
| ($cmol_{(+)}\ kg^{-1}$) | |
| Exchangeable $K^+$ | 0.19 ± 0.003 |
| Exchangeable $Ca^{2+}$ | 1.55 ± 0.02 |
| Exchangeable $Mg^{2+}$ | 0.001 ± 0.000 |
| Exchangeable $Na^+$ | 1.40 ± 0.03 |
| Exchangeable $Fe^{2+}$ | 48.31 ± 0.06 |
| Exchangeable $Mn^{2+}$ | 0.083 ± 0.001 |
| Exchangeable $Cu^{2+}$ | 0.52 ± 0.01 |
| Exchangeable $Zn^{2+}$ | 2.25 ± 0.10 |
| Cation exchange capacity | 4.40 ± 0.12 |
| Exchangeable acidity | 1.42 ± 0.01 |
| Exchangeable $Al^{3+}$ | 0.75 ± 0.01 |
| Exchangeable $H^+$ | 0.67 ± 0.01 |

[1] S.E. = Standard error.

### 2.9. Organic Soil Amendments and above Ground Biomass Analysis

The organic soil amendments and above ground biomass samples were digested using the single dry ashing method [20] to extract P and cations such as K, Ca, Mg, Mn, Zn, Fe, and Cu. The cation concentrations were determined using Atomic Absorption Spectrometry (AAS), whereas P was determined using the blue method [25]. Total N was determined using the Kjeldahl method followed by steam distillation [21,22]. The nutrient concentrations were multiplied by the dry weight of above ground biomass for nutrient uptake determination.

### 2.10. Total Grain Yield Determination

Total grain yield was determined using the following formula which is described by Matsushirna and Tanaka [27]:

$$\text{Yield}\left(\text{t ha}^{-1}\right) = \frac{\text{weight of 1000 grains} \times \text{spikelet} \times \text{\% filled grain}}{10000\ \text{m}^2 \times 1000\ \text{grains}} \quad (1)$$

where the area of one hectare = 10,000 $m^2$ was used to express the yield per hectare basis.

### 2.11. Weight of 1000 Grains Determination

A total of 1000 matured rice grains from the 10 selected panicles were placed in a clean crucible after separating filled and unfilled grains. The grains were oven dried at 60 °C until constant weight was attained, followed by keeping in a desiccator to enable the samples to equilibrate with room temperature. The dried grains were weighed and the dry weight of one grain was determined using the following formula:

$$\text{Dry weight of one grain (g)} = \frac{\text{dry weight of 1000 rice grains}}{1000\ \text{grains}} \quad (2)$$

### *2.12. Percentage of Total Grain Filling and Number of Spikelet*

The percentage total grain filling was determined by dividing the number of filled grains with total number of grains from the 10 selected panicles. Thereafter, the number of spikelets was determined by multiplying the number of panicles per hill with percentage of total grain filling, followed by dividing with the area per hill.

$$\text{Percentage of total grain filling } (\%) = \frac{\text{Total number of filled grains}}{\text{Total number of grain}} \times 100 \quad (3)$$

$$\text{Number of spikelet} = \frac{\text{number of panicles per hill } \times \text{ \% total grain filling}}{\text{area per hill}} \quad (4)$$

### *2.13. Statistical Analysis*

The collected data were subjected to analysis of variance (ANOVA) to detect the treatment effects, followed by mean comparisons using Tukey's HSD test at $p \leq 0.05$. The statistical software used was Statistical Analysis System version 9.2 [28].

## **3. Results and Discussion**

### *3.1. Effects of Organic Soil Amendments on Soil Chemical Properties*

The organic soil amendments such as biochar, animal manures, and plant residuals do not only improve soil productivity but they also stabilize yields over time and encourage farmers to increase rice cultivation. Effects of the organic soil amendments on the soil chemical properties after the first cropping cycle of rice cultivation are presented in Table 5. Amending the acidic soil with organic soil amendments in the first cropping cycle had significantly increased pH in water of OSA1 (4.78), OSA2 (4.77), and OSA5 (4.73) compared with that of S0 (3.97), NPK-Mg (4.18), OSA3 (4.60), and OSA4 (4.39). Similarly, the pH in KCl of OSA5 (3.87), OSA1 (3.83), and OSA2 (3.80) was significantly higher compared with that of S0 (3.38), NPK-Mg (3.71), OSA3 (3.72), and OSA4 (3.64). This was due to the alkaline nature of the organic amendments (Table 2). The use of organic soil amendments significantly increased soil total C of OSA5 compared with that of NPK-Mg and S0. The application of organic soil amendments did not increase soil total N compared with that of S0 and NPK-Mg. This was due to the low N in the organic amendments. There were no significant differences in the soil available $NO_3^-$ between the soils with the organic amendments (OSA1 to OSA5) compared with that of NPK-Mg, except for soil without amendment (S0). The exchangeable $NH_4^+$ of NPK-Mg, OSA2, and OSA5 were similar but significantly higher than that of S0, OSA3, and OSA4, whereas the soil total P of OSA1 and OSA5 were significantly higher than those of other treatments. After the first cropping cycle, the incorporation of organic soil amendments (OSA1 to OSA5) significantly improved available P to a range of 161.71 mg kg$^{-1}$ to 349.54 mg kg$^{-1}$ compared with that of S0 (25.34 mg kg$^{-1}$) and NPK-Mg (129.63 mg kg$^{-1}$). This was due to the residual effect of the applied soil organic amendments in addition to that of the second application. The use of organic soil amendments significantly suppressed soil exchangeable acidity and $Al^{3+}$ of OSA1 to OSA5 compared with that of S0 and NPK-Mg. This was due to the high affinity of the organic amendments towards Al and Fe. After the first cropping cycle, OSA5 had the highest soil CEC (3.75 cmol$_{(+)}$ kg$^{-1}$), followed by OSA1 (2.90 cmol$_{(+)}$ kg$^{-1}$), OSA2 (2.35 cmol$_{(+)}$ kg$^{-1}$), OSA3 (2.37 cmol$_{(+)}$ kg$^{-1}$), and OSA4 (2.43 cmol$_{(+)}$ kg$^{-1}$), whereas S0 and NPK-Mg demonstrated the lowest CEC of 1.70 cmol$_{(+)}$ kg$^{-1}$ and 1.65 cmol$_{(+)}$ kg$^{-1}$, respectively. These findings indicate that the organic soil amendments improved the chemical properties of Nyalau series soil compared with the prevailing fertilization method (NPK-Mg), except for soil total C, total N, available $NO_3^-$, and exchangeable $NH_4^+$.

**Table 5.** Effects of organic soil amendments on chemical properties of Nyalau series soil after the first cropping cycle of rice cultivation.

| Soil Chemical Properties | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | **S0** | **NPK-Mg** | **OSA1** | **OSA2** | **OSA3** | **OSA4** | **OSA5** |
| pH in water | 3.97 b ± 0.12 | 4.18 ab ± 0.04 | 4.78 a ± 0.09 | 4.77 a ± 0.13 | 4.60 ab ± 0.19 | 4.39 ab ± 0.30 | 4.73 a ± 0.10 |
| pH in KCl | 3.38 b ± 0.09 | 3.71 ab ± 0.08 | 3.83 a ± 0.04 | 3.80 a ± 0.04 | 3.72 ab ± 0.05 | 3.64 ab ± 0.11 | 3.87 a ± 0.08 |
| | | | | % | | | |
| Total C | 2.49 bc ± 0.07 | 2.18 bc ± 0.11 | 2.46 ab ± 0.04 | 2.39 abc ± 0.08 | 2.56 ab ± 0.12 | 2.40 abc ± 0.07 | 2.80 a ± 0.05 |
| Total N | 0.10 ab ± 0.01 | 0.11 a ± 0.01 | 0.07 ab ± 0.01 | 0.06 b ± 0.01 | 0.08 ab ± 0.01 | 0.09 ab ± 0.01 | 0.08 ab ± 0.01 |
| | | | | mg $kg^{-1}$ | | | |
| Avail. $NO_3^-$ | 2.50 b ± 0.17 | 4.58 a ± 0.11 | 3.85 a ± 0.20 | 4.03 a ± 0.18 | 4.55 a ± 0.20 | 4.38 a ± 0.18 | 4.55 a ± 0.20 |
| Exch. $NH_4^+$ | 2.13 c ± 0.03 | 2.73 ab ± 0.07 | 2.28 bc ± 0.18 | 2.90 a ± 0.10 | 2.13 c ± 0.03 | 2.10 c ± 0.01 | 2.68 ab ± 0.13 |
| Total P | 143.13 d ± 7.81 | 249.96 c ± 9.57 | 415.25 a ± 6.93 | 336.13 b ± 18.17 | 341.5 b ± 11.11 | 347.00 b ± 19.37 | 420.74 a ± 15.13 |
| Available P | 25.34 f ± 0.17 | 129.63 e ± 7.20 | 333.00 ab ± 8.75 | 314.50 b ± 9.38 | 161.71 d ± 5.66 | 248.77 c ± 6.64 | 349.54 a ± 3.28 |
| | | | | $cmol_{(+)}$ $kg^{-1}$ | | | |
| Exch. acidity | 1.53 a ± 0.06 | 1.27 b ± 0.04 | 0.60 de ± 0.03 | 0.56 e ± 0.03 | 0.77 c ± 0.03 | 0.78 c ± 0.02 | 0.73 cd ± 0.03 |
| $Al^{3+}$ | 0.81 a ± 0.02 | 0.69 a ± 0.07 | n.d. | n.d. | n.d. | n.d. | n.d. |
| $H^+$ | 0.73 abc ± 0.04 | 0.57 cd ± 0.06 | 0.60 bcd ± 0.03 | 0.56 d ± 0.03 | 0.77 a ± 0.04 | 0.76 ab ± 0.02 | 0.73 abc ± 0.03 |
| CEC | 1.70 d ± 0.18 | 1.65 d ± 0.17 | 2.90 b ± 0.06 | 2.35 c ± 0.17 | 2.37 c ± 0.10 | 2.43 bc ± 0.13 | 3.75 a ± 0.16 |

Means with different letters within a row indicate significant difference using Tukey's test at $p \leq 0.05$. Data are presented as mean of four replicates ± standard error. Note: n.d. = not detectable.

The soil chemical properties preceding the second cropping cycle of MR219 rice cultivation through the use of organic soil amendments are demonstrated in Table 6. The results showed that soil pH (in both water and KCl) and total N of all the soils following the application of organic soil amendments (OSA1 to OSA5) were significantly higher than those of S0 and NPK-Mg. On the other hand, organic soil amendments (OSA1 to OSA5) significantly lowered soil total acidity and exchangeable $Al^{3+}$. Soil total C of OSA1 (2.73%), OSA2 (2.90%), OSA3 (2.93%), and OSA5 (2.70%) was significantly higher compared with that of OSA4 (2.49%), S0 (2.18%), and NPK-Mg (2.00%). The use of organic soil amendments in the second cropping cycle also contributed to the improved availability of $NO_3^-$ in OSA4 compared with that of other treatments (S0, NPK-Mg, OSA1, OSA2, OSA3, and OSA5). Enhanced exchangeable $NH_4^+$ availability after the second cropping cycle was observed in OSA2, OSA4, and OSA5, compared with that of S0, NPK-Mg, OSA1, and OSA3. The soil total and available P of OSA5 were significantly higher than those of other treatments. Notably, exchangeable $Al^{3+}$ was negligible in the soils with the organic soil amendments. Application of the organic soil amendments significantly increased the soil CEC of OSA1, OSA2, OSA4, and OSA5 compared with those of S0, NPK-Mg, and OSA3. The pattern of these results was similar and consistent with those in the first cropping cycle. However, the soil chemical properties in the second cropping cycle were slightly higher than those of the first cropping cycle because of the residual effects of the organic soil amendments. This suggests that continued application of these organic soil amendments can improve the chemical properties of Nyalau series soil over time.

The residual effects of organic soil amendments on chemical properties of Nyalau series after the third cropping cycle are summarized in Table 7. The soil pH in water of OSA2 and OSA3 was higher compared with that of other treatments. It is observed that OSA2 demonstrated the highest pH in KCl of 4.19, which was higher than that of other treatments. Soil total N of OSA3 (0.11%), OSA5 (0.11%), and NPK-Mg (0.09%) were statistically similar, followed by OSA4 (0.08%), OSA1 (0.07%), and OSA2 (0.07%), whereas S0 had the lowest soil total N of 0.04%. Soil total Cand CEC of the soils treated with organic soil amendments (OSA1 to OSA5) were significantly higher compared with those of S0 and NPK-Mg. OSA2 demonstrated lower soil available $NO_3^-$ and exchangeable $NH_4^+$ compared with those of the other treatments with organic soil amendments (OSA1, OSA3, OSA4, and OSA5) and the prevailing method (NPK-Mg). Similar to the two preceding cropping cycles, the organic soil amendments (OSA1 to OSA5) consistently reduced the soil total acidity and exchangeable $Al^{3+}$. The soil total P of OSA2 (501.13 mg $kg^{-1}$) and OSA3 (500.63 mg $kg^{-1}$) were the highest, followed by OSA5 (400.38 mg $kg^{-1}$), OSA4 (399.69 mg $kg^{-1}$), NPK-Mg

(372.08 mg kg$^{-1}$), and OSA1 (309.05 mg kg$^{-1}$), whereas soil without amendments (S0) had the lowest total P of 139.10 mg kg$^{-1}$. The application of organic soil amendments (OSA1 to OSA5) significantly increased available P to a range of 236.77 mg kg$^{-1}$ to 370.75 mg kg$^{-1}$ compared with S0 (28.95 mg kg$^{-1}$). Consistent with the two previous cropping cycles, it is noteworthy that the exchangeable $Al^{3+}$ was negligible in the soils amended with the organic soil amendments (OSA1 to OSA5). Our findings demonstrate that application of the organic soil amendments in the two preceding cropping cycles consistently improved the soil fertility when no organic soil amendments were applied in the third cropping cycle. This is because the organic soil amendments consistently improved soil total C, available $NO_3^-$, exchangeable $NH_4^+$, and CEC in addition to reducing exchangeable acidity and $Al^{3+}$, which can result in optimum rice plant growth, nutrient uptake, and improved rice grain yield.

**Table 6.** Effects of organic soil amendments on chemical properties of Nyalau series soil after the second cropping cycle of rice cultivation.

| Soil Chemical Properties | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | S0 | NPK-Mg | OSA1 | OSA2 | OSA3 | OSA4 | OSA5 |
| pH in water | 4.41 b ± 0.14 | 4.57 b± 0.20 | 5.60 a± 0.17 | 5.84 a ± 0.09 | 5.86 a ± 0.07 | 5.74 a ± 0.17 | 5.85 a ± 0.05 |
| pH in KCl | 3.78 b ± 0.08 | 3.88 b ± 0.07 | 4.93 a ± 0.65 | 5.07 a ± 0.01 | 5.07 a ± 0.05 | 4.96 a ± 0.05 | 5.15 a ± 0.06 |
| | | | | % | | | |
| Total C | 2.18 cd ± 0.06 | 2.00 d ± 0.03 | 2.73 ab ± 0.07 | 2.90 a ± 013 | 2.93 a ± 0.09 | 2.49 bc ± 0.07 | 2.70 ab ± 0.06 |
| Total N | 0.06 b ± 0.002 | 0.06 b ± 0.003 | 0.09 a ± 0.002 | 0.09 a ± 0.003 | 0.08 a ± 0.001 | 0.09 a ± 0.002 | 0.08 a ± 0.001 |
| | | | | mg kg$^{-1}$ | | | |
| Avail. $NO_3^-$ | 3.40 bc ± 0.10 | 3.08 c ± 0.17 | 3.33 bc ± 0.18 | 3.68 abc ± 0.18 | 4.03 abc ± 0.18 | 4.58 a ± 0.45 | 4.45 ab ± 0.17 |
| Exch. $NH_4^+$ | 3.33 b ± 0.18 | 3.33 b ± 0.34 | 3.33 b ± 0.18 | 4.85 a ± 0.26 | 4.28 ab ± 0.07 | 4.48 a ± 0.17 | 4.45 a ± 0.17 |
| Total P | 140.51 d ± 9.33 | 349.58 c ± 14.71 | 426.81 bc ± 15.02 | 437.17 bc ± 14.76 | 509.42 b ± 27.61 | 347.50 c ± 19.10 | 668.50 a ± 35.21 |
| Available P | 34.85 e ± 1.20 | 143.21 d ± 10.75 | 331.13 b ± 12.65 | 277.00 c ± 13.26 | 328.38 b ± 10.14 | 353.75 b ± 8.29 | 448.77 a ± 12.00 |
| | | | | $cmol_{(+)}$ kg$^{-1}$ | | | |
| Exch. acidity | 1.69 a ± 0.07 | 1.52 a ± 0.03 | 0.71 b ± 0.02 | 0.73 b ± 0.05 | 0.74 b ± 0.03 | 0.75 b ± 0.05 | 0.51 c ± 0.04 |
| $Al^{3+}$ | 1.01 a ± 0.04 | 0.74 b ± 0.03 | n.d. | n.d. | n.d. | n.d. | n.d. |
| $H^+$ | 0.68 a ± 0.04 | 0.79 a ± 0.03 | 0.71 a ± 0.02 | 0.73 a ± 0.05 | 0.74 a ± 0.03 | 0.75 a ± 0.05 | 0.51 b ± 0.04 |
| CEC | 3.45 b ± 0.13 | 3.80 b ± 0.32 | 5.20 a ± 0.18 | 5.03 a ± 0.31 | 3.78 b ± 0.28 | 5.80 a ± 0.15 | 5.80 a ± 0.20 |

Means with different letters within a row indicate significant difference using Tukey's test at $p \leq 0.05$. Data are presented as mean of four replicates ± standard error. Note: n.d. = not detectable.

**Table 7.** Residual effects of organic soil amendments on chemical properties of Nyalau series soil after the third cropping cycle of rice cultivation.

| Soil Chemical Properties | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | S0 | NPK-Mg | OSA1 | OSA2 | OSA3 | OSA4 | OSA5 |
| pH in water | 4.42 c ± 0.05 | 4.51 bc ± 0.16 | 4.87 abc ± 0.06 | 5.00 a ± 0.06 | 5.22 a ± 0.20 | 4.92 ab ± 0.08 | 4.80 abc ± 0.01 |
| pH in KCl | 3.94 b ± 0.05 | 4.01 ab ± 0.05 | 4.04 ab ± 0.05 | 4.19 a ± 0.06 | 4.14 ab ± 0.04 | 4.08 ab ± 0.05 | 4.12 ab ± 0.03 |
| | | | | % | | | |
| Total C | 1.98 b ± 0.08 | 2.09 b ± 0.11 | 2.58 a ± 0.06 | 2.53 a ± 0.06 | 2.52 a ± 0.10 | 2.58 a ± 0.07 | 2.64 a ± 0.10 |
| Total N | 0.04 d ± 0.003 | 0.09 ab ± 0.004 | 0.07 c ± 0.002 | 0.07 c ± 0.003 | 0.11 a ± 0.005 | 0.08 bc ± 0.002 | 0.11 a ± 0.004 |
| | | | | mg kg$^{-1}$ | | | |
| Avail. $NO_3^-$ | 2.10 b ± 0.04 | 2.73 a ± 0.05 | 2.83 a ± 0.02 | 2.15 b ± 0.05 | 2.68 a ± 0.07 | 2.70 a ± 0.07 | 2.93 a ± 0.08 |
| Exch. $NH_4^+$ | 4.38 b ± 0.10 | 4.98 a ± 0.08 | 5.13 a ± 0.13 | 4.25 b ± 0.05 | 4.91 a ± 0.05 | 4.88 a ± 0.03 | 5.00 a ± 0.10 |
| Total P | 139.10 d ± 6.16 | 372.08 b ± 9.06 | 309.05 c ± 5.85 | 501.13 a ± 7.27 | 500.63 a ± 7.95 | 399.69 b ± 3.33 | 400.38 b ± 9.73 |
| Available P | 28.95 e ± 0.79 | 232.39 d ± 6.27 | 236.77 cd ± 4.38 | 276.19 bc ± 15.74 | 370.75 a ± 8.73 | 255.79 cd ± 8.09 | 313.58 b ± 9.16 |
| | | | | $cmol_{(+)}$ kg$^{-1}$ | | | |
| Exch. acidity | 1.56 a ± 0.08 | 1.58 a ± 0.06 | 0.71 b ± 0.04 | 0.68 b ± 0.04 | 0.68 b ± 0.02 | 0.69 b ± 0.02 | 0.75 b ± 0.01 |
| $Al^{3+}$ | 0.82 a ± 0.11 | 0.69 b ± 0.08 | n.d. | n.d. | n.d. | n.d. | n.d. |
| $H^+$ | 0.74 a ± 0.14 | 0.89 a ± 0.13 | 0.71 a ± 0.04 | 0.68 a ± 0.04 | 0.68 a ± 0.02 | 0.69 a ± 0.02 | 0.75 a ± 0.01 |
| CEC | 3.03 c ± 0.17 | 3.60 c ± 0.11 | 5.83 a ± 0.14 | 4.64 b ± 0.23 | 5.00 b ± 0.16 | 5.40 ab ± 0.11 | 6.05 a ± 0.18 |

Means with different letters within a row indicate significant difference using Tukey's test at $p \leq 0.05$. Data are presented as mean of four replicates ± standard error. Note: n.d. = not detectable.

Apart from the buffering capacity of the amendments, the improvement in the soil chemical properties after amending the soil with the organic soil amendments was due to replacement of leached cations, especially Mg and Ca [29]. This was possible because the organic soil amendments formed complexes with Al and Fe [30]. There was an increase in soil pH because of proton exchange between the soil and organic soil amendments. The organic soil amendments have phenolic and humic-like compounds which are capable of increasing soil pH because of the occurrence of deprotonation [31]. The humic compounds of the organic soil amendments were absorbed onto the hydrous surfaces of Al oxides thereby releasing $OH^-$ to increase soil pH [32]. Additionally, the organic matter especially in the biochar, animal manures, and plants residues are able to increase soil's ability to adsorb and desorb essential plant nutrients because of increased negatively charged functional groups [29].

The organic soil amendments produced from *LLeucaena*, forest litter, chicken manure, and cow dung co-composted with chicken litter biochar increased the soil pH. Moreover, the organic soil amendments increased the soil nutrient availability because of reduction in the soil P and K fixing capacity. This explains why skipping or reducing P and K applications, respectively, in this present study did not adversely affect the productivity of the soil and rice plants [16,33]. The results of this present study further suggest that most of the Al in the soil were neutralized following the application of the organic soil amendments. The increase in pH by NPK-Mg in the first cropping cycle was due to urea hydrolysis which resulted in more $OH^-$ ions. The use of these amendments reduced the soil acidity. This confirms the findings of several studies that organic soil amendment use increases soil pH [33–35]. The variation of the pH among the soil organic soil amendments used was due to their unique properties [35]. During the first and second cropping cycles, the organic soil amendments improved the soil exchangeable acidity and buffering capacity. This resulted in the increase in the soil pH. However, this increase in soil pH was temporary because the soil pH decreased in this cropping cycle. This process is, however, slow and depends largely on the amount of organic amendment used and its physicochemical properties [36].

The soil available nutrients at harvest (for the cropping cycles), especially after the third cropping cycle, were due to slow release of the nutrients and decomposition of the organic soil amendments [37]. Unlike N, which is mobile in soils, the mobility of P is significantly reduced in mineral soils particularly the highly weathered soils such as Utisols and Oxisols which are commonly high in Al and Fe [38]. The higher affinity of the organic soil amendments for Al and Fe reduced iron and aluminum-bound P and this reaction increases P availability [39]. Maru et al. [16] found that the use of 5 t $ha^{-1}$ chicken litter biochar alone provided sufficient amount of P for MR219 rice plants and this finding is confirmed in this present study because P, MgO, and trace elements were 100% reduced in all the three cropping cycles. Generally, using local organic agro-wastes through co-composting *LLeucaena*, forest litter, chicken manure, and cow dung with chicken litter biochar as amendments can be cost-effective. In addition, the use of these soil organic amendments can mitigate environmental pollutions such as forest residue slash pile burning and facilitate suitable disposal of animal wastes.

### *3.2. Effects of Organic Soil Amendments on Total Nitrogen and Nutrient Uptake of Rice Plants*

The effects of the organic soil amendments on total N and nutrient uptake of the rice plants during the first cropping cycle are presented in Table 8. During the first cropping cycle, total N and P uptake by the rice plants of OSA4 were significantly higher compared with those of other treatments. Additionally, the rice plants which were harvested on the soil without amendments (S0) had the lowest N content and P uptake. The K uptake of rice plants in OSA4 (477.05 mg hill $^{-1}$) was significantly higher compared with OSA5 (428.76 mg hill $^{-1}$), OSA2 (413.64 mg hill $^{-1}$), OSA3 (346.25 mg hill $^{-1}$), OSA1 (163.60 mg hill $^{-1}$), and NPK-Mg (109.46 mg hill $^{-1}$), whereas S0 had the lowest K uptake (413.64 mg hill $^{-1}$). The rice plants with the organic soil amendments (OSA1 to OSA5) improved Ca and Na uptake compared with the rice plants with the prevailing fertilization method (NPK-Mg) and without application of amendments (S0). The Mg, Fe, and Cu uptake of rice plants with OSA5 were higher compared with those of other treatments, whereas the rice plants with OSA1 and OSA5 had the higher Mn uptake compared with those of other treatments. The Zn uptake in rice plants of OSA2 (2.66 mg hill $^{-1}$) was the highest, followed by OSA5 (2.46 mg hill $^{-1}$), OSA4 (2.28 mg hill $^{-1}$), OSA1 (2.09 mg hill $^{-1}$), and OSA3 (1.89 mg hill $^{-1}$) whereas S0 (0.36 mg hill $^{-1}$) had the lowest Zn uptake. Our findings suggest that the nutrient uptake of the rice plants was enhanced by the application of organic soil amendments. The nutrient variation among the treatments during the first cropping cycle was due to translocation of the nutrients for grain yield.

**Table 8.** Total nitrogen and nutrients uptake by MR219 rice plants as affected by organic soil amendments during the first cropping cycle.

| Nutrient | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | **S0** | **NPK-Mg** | **OSA1** | **OSA2** | **OSA3** | **OSA4** | **OSA5** |
| N (%) | 1.15 d ± 0.06 | 3.53 c ± 0.21 | 5.55 c ± 0.30 | 8.65 b ± 0.47 | 8.30 b ± 1.14 | 11.70 a ± 0.44 | 8.42 b ± 0.38 |
| Nutrient uptake | mg hill$^{-1}$ | | | | | | |
| P | 0.87 d ± 0.06 | 5.21 c ± 0.32 | 7.12 c ± 0.29 | 17.35 b ± 0.36 | 15.33 b ± 1.78 | 20.74 a ± 0.58 | 15.54 b ± 0.24 |
| K | 18.06 d ± 1.93 | 109.46 c ± 10.31 | 163.60 c ± 6.71 | 413.64 ab ± 19.08 | 346.25 b ± 40.67 | 477.05 a ± 9.21 | 428.76 ab ± 16.65 |
| Ca | 18.25 c ± 1.41 | 99.18 b ± 3.94 | 148.91 a ± 8.98 | 142.81 a ± 2.09 | 139.43 a ± 2.44 | 152.02 a ± 5.99 | 136.22 a ± 4.45 |
| Na | 3.19 c ± 0.16 | 10.79 b ± 1.04 | 16.87 a ± 2.07 | 19.23 a ± 0.77 | 16.03 a ± 0.92 | 17.68 a ± 0.38 | 17.94 a ± 0.35 |
| Mg | 10.95 d ± 0.48 | 51.51 c ± 1.73 | 80.40 b ± 4.10 | 84.72 b ± 3.07 | 79.70 b ± 2.38 | 88.51 ab ± 1.97 | 98.05 a ± 2.96 |
| Fe | 2.08 d ± 0.22 | 7.02 c ± 0.29 | 8.44 abc ± 0.75 | 8.58 ab ± 0.32 | 7.21 bc ± 0.20 | 8.04 bc ± 0.11 | 9.78 a ± 0.11 |
| Cu | 0.02 e ± 0.001 | 0.10 d ± 0.002 | 0.13 cd ± 0.011 | 0.15 bc ± 0.007 | 0.14 bc ± 0.004 | 0.17 ab ± 0.003 | 0.19 a ± 0.011 |
| Mn | 3.79 c ± 0.13 | 14.60 b ± 0.59 | 24.70 a ± 1.68 | 16.68 b ± 0.66 | 14.83 b ± 0.60 | 18.30 b ± 0.88 | 24.66 a ± 0.54 |
| Zn | 0.36 f ± 0.03 | 1.13 e ± 0.04 | 2.09 cd ± 0.14 | 2.66 a ± 0.15 | 1.89 d ± 0.06 | 2.28 bc ± 0.08 | 2.46 ab ± 0.06 |

Means with different letters within a row indicate significant difference using Tukey's test at $p \leq 0.05$. Data are presented as mean of four replicates ± standard error.

The effects of organic soil amendments on total N and nutrient uptake of rice plants during the second cropping cycle are demonstrated in Table 9. During the second cropping cycle, the addition of organic soil amendments (OSA1 to OSA5) also increased total N and nutrient uptake in rice plants. The N content, P, K, Ca, and Mn uptakes of the rice plants for OSA5 were significantly higher compared with those of OSA1, OSA2, OSA3, OSA4, NPK-Mg, and S0. These results can be due to higher nutrients in the chicken manure and *Leucaena* co-composted with chicken litter biochar. The Na uptake of the rice plants with OSA1 was the highest, followed by the other organic soil amendments (OSA2 to OSA5) and the prevailing fertilizer method (NPK-Mg). The rice plants in S0 had the lowest Na uptake. The Fe uptake of the rice plants with NPK-Mg, OSA1, and OSA2 were lower compared with those of OSA3, OSA4, and OSA5 whereas the rice plants in S0 had the lowest Fe uptake. The Mg and Cu uptakes of the rice plants with the organic soil amendments (OSA1 to OSA5) were significantly higher than those grown on the soil with the chemical fertilizers (NPK-Mg) and without the amendments (S0). The Zn uptake of rice plants with OSA2, OSA3, and OSA5 was significantly higher compared with those of OSA1, OSA4, NPK-Mg, and S0.

Effects of the organic soil amendments on total N and nutrient uptake of the rice plants during the third cropping cycle are summarized in Table 10. After the second cropping cycles, the residual effects of the organic soil amendments (OSA1 to OSA5) significantly increased total N and P uptake of the rice plants compared with those on S0. In addition, the N and P uptake of the rice plants with the organic soil amendments (OSA1 to OSA5) were similar to those of the prevailing fertilization regime (NPK-Mg). This suggests that the organic soil amendments used in this study have the potential to replace the use of chemical fertilizers in rice cultivation. The uptakes of K, Ca, Cu, Mn, and Zn of rice plants in OSA5 were significantly higher than those of other treatments. The highest Na uptake in rice plants was observed in OSA2 (57.31 mg hill $^{-1}$), OSA5 (54.57 mg hill $^{-1}$), and OSA3 (46.15 mg hill $^{-1}$), followed by OSA4 (31.20 mg hill $^{-1}$), and OSA1 (28.02 mg hill $^{-1}$), whereas NPK-Mg (17.56 mg hill $^{-1}$) and S0 (6.79 mg hill $^{-1}$) had the lowest Na uptake.

The highest Mg uptake of the rice plants was observed in OSA2 compared with that of the other treatments.

**Table 9.** Total nitrogen and nutrients uptake by MR219 rice plants as affected by organic soil amendments during the second cropping cycle.

| Nutrient | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | S0 | NPK-Mg | OSA1 | OSA2 | OSA3 | OSA4 | OSA5 |
| N (%) | 0.70 d ± 0.03 | 1.83 d ± 0.13 | 4.28 bc ± 0.35 | 3.79 bc ± 0.21 | 3.5 c ± 0.19 | 4.97 ab ± 0.40 | 6.10 a ± 0.36 |
| Nutrient uptake | mg hill$^{-1}$ | | | | | | |
| P | 7.01 d ± 0.40 | 40.69 c ± 0.47 | 78.35 b ± 3.91 | 88.19 ab ± 5.86 | 81.46 b ± 0.320 | 87.62 ab ± 4.01 | 96.06 a ± 4.42 |
| K | 169.16 e ± 5.85 | 291.34 d ± 17.43 | 608.04 c ± 7.71 | 742.35 b ± 26.52 | 604.48 c ± 11.82 | 688.68 bc ± 24.55 | 903.78 a ± 18.64 |
| Ca | 12.72 d ± 0.89 | 33.73 c ± 1.67 | 78.23 ab ± 2.20 | 87.12 ab ± 3.81 | 83.66 b ± 3.94 | 80.04 b ± 0.32 | 97.77 a ± 2.52 |
| Na | 4.82 d ± 0.20 | 16.74 c ± 1.22 | 27.35 a ± 0.97 | 22.85 b ± 0.79 | 20.49 bc ± 0.76 | 21.28 b ± 0.51 | 21.40 b ± 0.74 |
| Mg | 24.05 d ± 1.57 | 91.43 c ± 3.67 | 155.33 ab ± 5.95 | 164.97 a ± 3.09 | 147.10 ab ± 1.95 | 137.81 b ± 1.85 | 162.78 a ± 8.62 |
| Fe | 0.13 e ± 0.01 | 0.40 d ± 0.02 | 0.51 cd ± 0.03 | 0.59 bc ± 0.03 | 0.66 ab ± 0.03 | 0.76 a ± 0.03 | 0.77 a ± 0.02 |
| Cu | 0.06 c ± 0.005 | 0.12 bc ± 0.009 | 0.27 a ± 0.035 | 0.27 a ± 0.014 | 0.33 a ± 0.050 | 0.23 ab ± 0.030 | 0.26 a ± 0.011 |
| Mn | 0.04 d ± 0.002 | 0.08 c ± 0.004 | 0.13 b ± 0.005 | 0.14 b ± 0.005 | 0.13 b ± 0.005 | 0.14 b ± 0.004 | 0.23 a ± 0.011 |
| Zn | 0.41 d ± 0.02 | 1.15 c ± 0.02 | 1.52 b ± 0.05 | 1.77 a ± 0.03 | 1.84 a ± 0.03 | 1.22 c ± 0.04 | 1.84 a ± 0.04 |

Means with different letters within a row indicate significant difference using Tukey's test at $p \leq 0.05$. Data are presented as mean of four replicates ± standard error.

**Table 10.** Total nitrogen and nutrients uptake by MR219 rice plants as affected by residual organic soil amendments during the third cropping cycles.

| Nutrient | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | S0 | NPK-Mg | OSA1 | OSA2 | OSA3 | OSA4 | OSA5 |
| N (%) | 0.67 b ± 0.08 | 7.94 a ± 0.83 | 8.71 a ± 0.43 | 9.28 a ± 1.49 | 7.96 a ± 0.79 | 9.01 a ± 0.85 | 10.84 a ± 0.52 |
| Nutrient uptake | mg hill$^{-1}$ | | | | | | |
| P | 3.72 b ± 0.25 | 29.61 a ± 2.18 | 28.20 a ± 2.82 | 41.69 a ± 4.12 | 36.33 a ± 3.54 | 29.76 a ± 1.55 | 35.71 a ± 3.10 |
| K | 166.01 e ± 11.48 | 203.44 de ± 5.33 | 306.95 bc ± 21.07 | 269.71 cd ± 25.93 | 216.32 ed ± 18.50 | 374.85 b ± 20.06 | 511.62 a ± 38.99 |
| Ca | 12.98 e ± 0.62 | 43.80 d ± 1.09 | 60.33 cd ± 5.63 | 84.62 ab ± 5.70 | 62.64 cd ± 8.64 | 71.24 bc ± 5.42 | 98.48 a ± 5.24 |
| Na | 6.79 d ± 0.29 | 17.56 cd ± 0.27 | 28.02 bc ± 1.90 | 57.31 a ± 3.56 | 46.15 a ± 3.64 | 31.20 b ± 1.82 | 54.57 a ± 4.54 |
| Mg | 26.86 d ± 0.48 | 113.24 c ± 8.81 | 121.16 bc ± 1.76 | 168.47 a ± 7.32 | 149.93 ab ± 6.11 | 147.66 ab ± 11.31 | 154.05 ab ± 10.04 |
| Fe | 0.15 b ± 0.01 | 0.53 a ± 0.02 | 0.56 a ± 0.02 | 0.66 a ± 0.05 | 0.55 a ± 0.05 | 0.51 a ± 0.03 | 0.56 a ± 0.03 |
| Cu | 0.07 c ± 0.00 | 0.24 b ± 0.01 | 0.24 b ± 0.02 | 0.30 ab ± 0.04 | 0.34 ab ± 0.04 | 0.25 b ± 0.02 | 0.42 a ± 0.03 |
| Mn | 0.05 e ± 0.00 | 0.11 d ± 0.01 | 0.16 bc ± 0.01 | 0.20 b ± 0.01 | 0.17 bc ± 0.01 | 0.15 cd ± 0.01 | 0.24 a ± 0.02 |
| Zn | 0.47 d ± 0.05 | 1.18 c ± 0.07 | 1.20 c ± 0.09 | 1.77 b ± 0.03 | 1.67 bc ± 0.16 | 1.37 bc ± 0.15 | 2.40 a ± 0.19 |

Means with different letters within a row indicate significant difference using Tukey's test at $p \leq 0.05$. Data are presented as mean of four replicates ± standard error.

Nitrogen and P uptake under OSA4 were higher in the first cropping cycle due to the higher rates of *Leucaena* used. However, in the second cropping cycle, the N content and P uptake of the rice plants in OSA5 increased but were similar to those of OSA4. This demonstrates that the organic soil amendments produced from the chicken litter biochar with *Leucaena* and chicken manure can enhance N and P for uptake. The *Leucaena* and chicken litter (OSA5) stimulated N and K availability and their absorption by the rice plants. For S0 and NPK-Mg, the higher Al and Fe concentrations impeded the rice plants' growth is because of the reduction in the rice plants'' roots elongation. This is related to the direct and indirect effects on the rice plant metabolism [40]. The stress significantly reduced the rice plants' roots nutrient adsorption thereby reducing the growth of rice plants [40]. For example, higher concentrations of Al impede P availability because Al binds or prevents P from being absorbed and this results in lower plant nutrient uptake and rice yields [40]. However, the soil data in this present study suggest that the adverse effects of Al and Fe were averted.

Generally, the quality of the organic soil amendments is related to lignin content and C:N ratio. The lower C:N ratio of materials (less than 20:1) leads to higher decomposition because of higher microbial growth [41,42]. Degradation of these organic soil amendments is important in terms of release of plant nutrients originally bound in organic biomass [36]. In mineralization, materials which have simpler nutrients, especially N compounds, are mineralized more rapidly than complex materials with higher lignin content [43,44]. Lignin-rich materials such as chicken litter biochar, chicken litter, and forest litter are resilient to microbial attack. Additionally, these materials may cause physical protection of soil, improve rice plant roots development, and enhance chemical fertilizer use efficiency [45,46].

Among the organic soil amendments used in this study, the treatments with *Leucaena* significantly increased the rice plants' nutrients uptake. However, addition of the chicken manure to *Leucaena* resulted in the release of more nutrients for the rice plants. These nutrients might have been released from the chicken manure because of the reduction of high C:N ratio following the addition of *Leucaena* [47]. The lower C:N ratio of the chicken litter biochar and the chicken manure with *Leucaena* might have increased the decomposition of the chicken manure. Carbon-rich materials such as chicken litter biochar, chicken manure, forest litter, cow dung, leaves, straw, and wood chips tend to be dry and difficult to decompose [48]. Lower decomposition results in a minimum release of important nutrients for plants uptake. Nitrogen rich materials such as *Leucaena*, fresh grass clippings, and food waste cause release of excess ammonia if they are used without treating them with other materials. Thus, the use of organic soil amendments (OSA1, OSA2, and OSA3) had the capacity to significantly improve total N and nutrients uptake of the rice plants compared with those of the rice plants with the prevailing fertilization recommendation (NPK-Mg) and without amendments (S0), but not as high as the addition of *Leucaena* (OSA4 and OSA5). Hence, mixing *Leucaena* with other carbon-rich materials can optimize the release of nutrients in C rich materials such as biochar and chicken manure.

### *3.3. Effects of Organic Soil Amendments on Rice Growth and Grain Yield*

The effects of organic soil amendments on rice growth and grain yield after the first cropping cycle are presented in Figure 3. The organic soil amendments used in this study enabled the rice plants to translocate most of the absorbed nutrients for desirable growth and yield. Application of the organic soil amendments (OSA1 to OSA5) significantly improved grain yield, dry matter, plant height, and total grain filling per panicle compared with those of NPK-Mg and S0 (Figure 3a–d). The number of panicles and number of tillers per hill of the rice plants with organic soil amendments (OSA1 to OSA5) were similar to those of the prevailing fertilization method (NPK-Mg) but significantly higher than the rice plants without the amendments (S0) (Figure 3e,f). These results were consistent with the higher soil nutrients availability and uptake of rice plants.

Effects of the organic soil amendments on rice plants' growth and grain yield after the second cropping cycle are demonstrated in Figure 4. It is observed that the continued application of the organic soil amendments during the second cropping cycle further improved the translocation of most of the absorbed nutrients and it resulted in enhanced growth and yield of the rice plants. Similar to the first cropping cycle, the use of the organic soil amendments (OSA1 to OSA5) significantly improved grain yield, dry matter, plant height, and total grain filling per panicle compared with those of NPK-Mg and S0 (Figure 4a–d). Notably, the number of panicles and number of tillers per hill of the rice plants in OSA3 and OSA5 significantly increased compared with those of the prevailing fertilization method (NPK-Mg) (Figure 4e,f). The MR219 rice plants grown on the soil without amendments (S0) revealed the lowest numbers of panicles and tillers per hill. These results suggest that the rice plant growth and grain yield during the second cropping cycle were generally higher than those of the first cropping cycle because of the residual effects of organic soil amendments.

Effects of the organic soil amendments on the rice plants growth and grain yield after the third cropping cycle are summarized in Figure 5. Although application of the organic amendments was skipped in the third cropping cycle, the residual effects of the organic soil amendments (OSA1 to OSA5) significantly improved the rice grain yield (Figure 5a). The number of tillers per hill of the rice plants with the organic soil amendments (OSA1 to OSA5) were similar to those of the prevailing fertilization method (NPK-Mg) but significantly higher than the rice plants grown on the soil without the amendments (S0) (Figure 5f). The dry matter yield and rice plant height of OSA5 were the highest compared with those of other treatments (Figure 5b,c). The total filled grain per panicle of OSA1 OSA2, and OSA5 were significantly higher than those of OSA3, OSA4, S0, and NPK-Mg (Figure 5d). The pattern of these results was similar to those in the second cropping cycle. However, the rice grain yield slightly decreased compared with the two earlier cropping cycles.

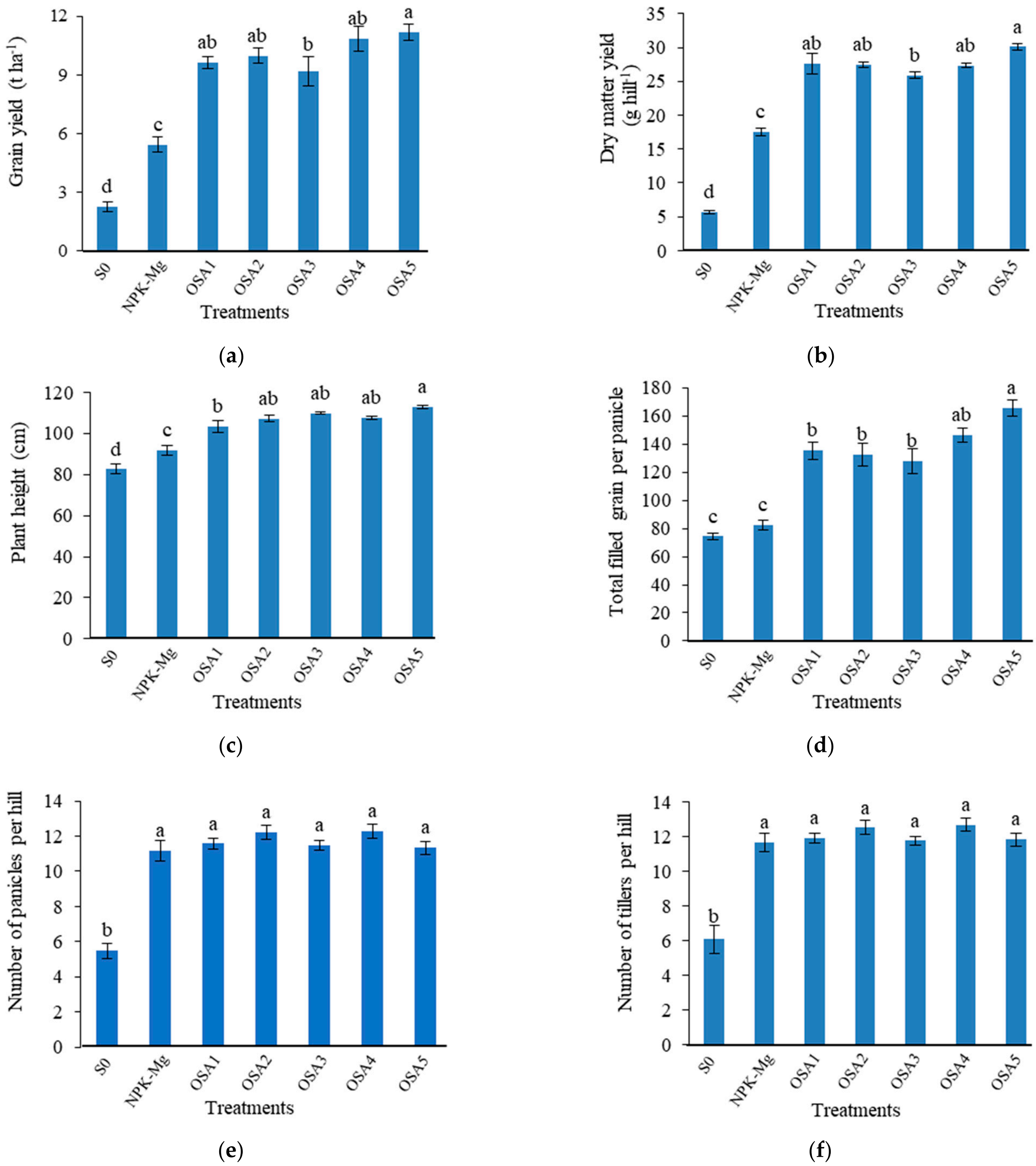


**Figure 3.** (**a**) Grain yield, (**b**) dry matter yield, (**c**) plant height, (**d**) total filled grain per panicle, (**e**) number of panicles per hill, and (**f**) number of tillers per hill of rice plants in relation to the addition of chemical fertilizers and organic soil amendments after the first cropping cycle. Means with different letters indicate significant difference using Tukey's test at $p \leq 0.05$ and error bars represent standard error.

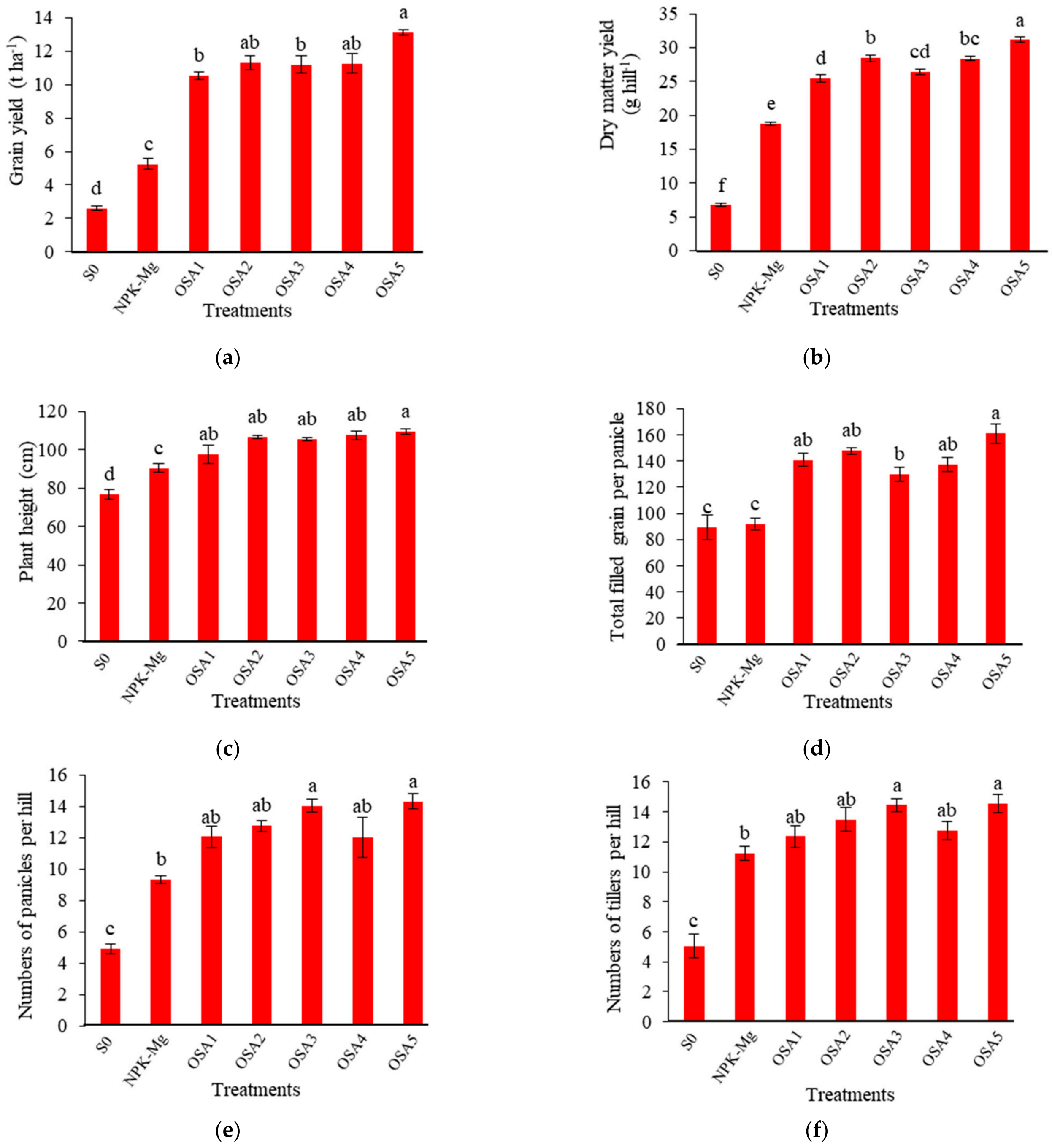


**Figure 4.** (**a**) Grain yield, (**b**) dry matter yield, (**c**) plant height, (**d**) total filled grain per panicle, (**e**) number of panicles per hill, and (**f**) number of tillers per hill of rice plants in relation to the addition of chemical fertilizers and organic soil amendments after the second cropping cycle. Means with different letters indicate significant difference using Tukey's test at $p \leq 0.05$ and error bars represent standard error.

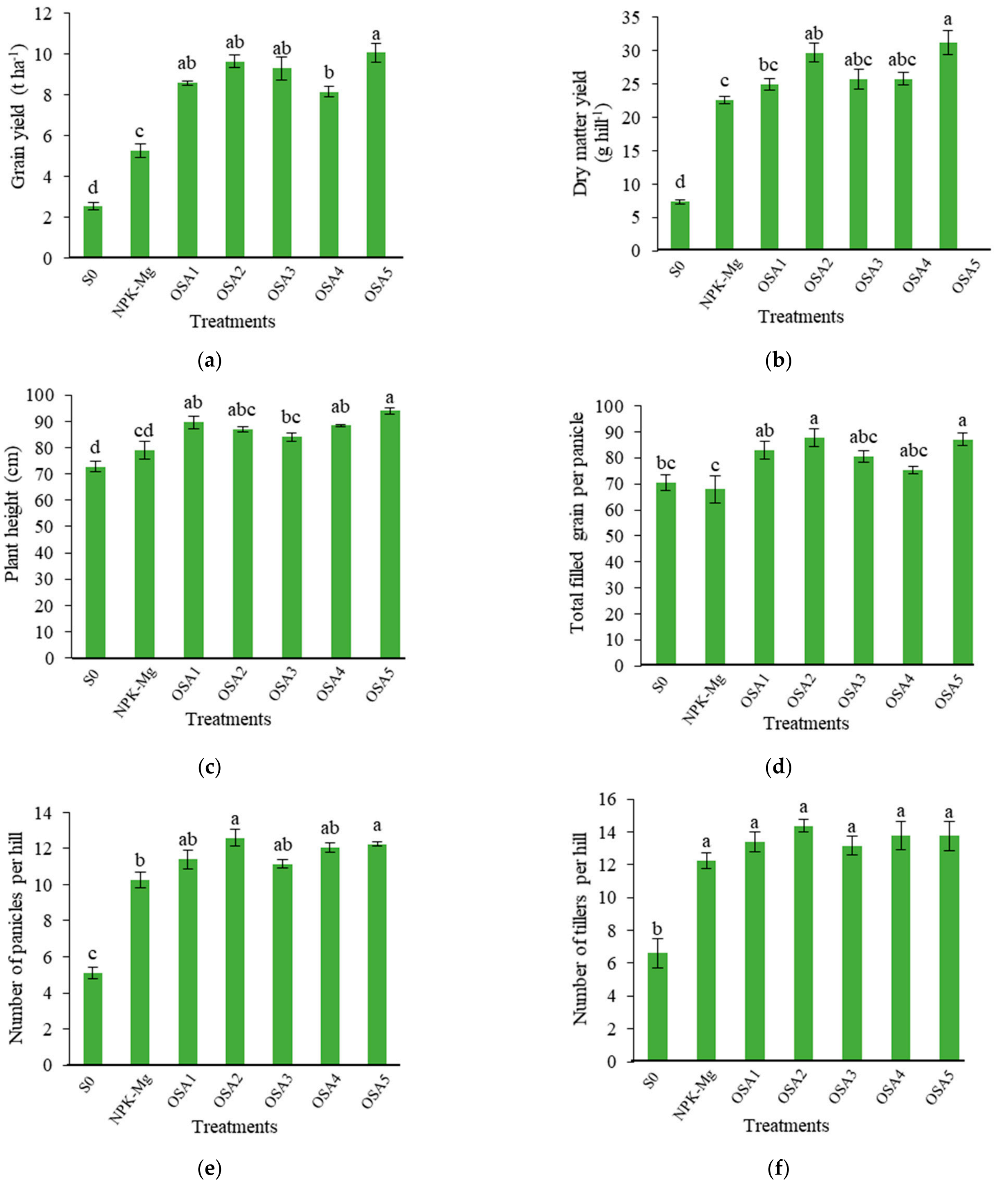


**Figure 5.** (**a**) Grain yield, (**b**) dry matter yield, (**c**) plant height, (**d**) total filled grain per panicle, (**e**) number of panicles per hill, and (**f**) number of tillers per hill of rice plants in relation to the addition of chemical fertilizers and organic soil amendments after the third cropping cycle. Means with different letters indicate significant difference using Tukey's test at $p \leq 0.05$ and error bars represent standard error.

The rice grain yields at the end of the first and second cropping cycles indicate that the continued application of the co-composted chicken litter biochar and the chemical fertilization (75% N and 34% K) significantly increased rice yield [16]. The organic soil amendments used in this study reduced the inorganic fertilizers application of N, P, K, MgO, and trace elements by 25%, 100%, 64%, 100%, and 100%, respectively [16]. The organic soil amendments used in this study also improved rice grain yields in the first (9 t $ha^{-1}$ to 11 t $ha^{-1}$), second (11 t $ha^{-1}$ to 13 t $ha^{-1}$), and third cropping cycles (8 t $ha^{-1}$ to 10 t $ha^{-1}$). Although the rice yield in the third cropping cycle decreased relative to those of the first and second cropping cycles, the residual effects of the organic soil amendments significantly improved the rice grain yield compared with the existing rice yield in Malaysia [48].

Among the treatments with the organic soil amendments, OSA5 significantly improved the rice grain yield. This finding is related to the integrated application of organic soil amendments and inorganic fertilizer (N and K), which enhanced stomata conductance and the photosynthetic rate of the rice plants [49]. These primary physiological processes are responsible for the production of rice plant dry matter yield, number of tillers, and number of panicles [50,51]. The similarity in the yields of the treatments with different organic soil amendments suggests the efficient utilization of nutrients [52]. The results of S0 and NPK-Mg on the other hand suggest that continued rice cultivation without organic soil amendments leads to yield reduction.

The improved rice grain yield over three cropping cycles through the use of the organic soil amendments was also due to the balanced fertilization. This suggests that our approach facilitates effective translocation of nutrients to improve grain formation and filling, thus, resulting in the improved rice grain yield [53]. Herencia et al. [54] reported that the use of organic soil amendments provides a conducive environment for optimum rice growth, thus resulting in a higher grain yield. Sathish et al. [55] also reported that the combined use of organic and inorganic fertilizers can increase rice yield over time because the gradual decomposition of organic soil amendments could slowly release nutrients for crop uptake throughout the cropping cycle.

## 4. Conclusions

The combined use of co-composted *Leucaena*, forest litter, chicken manure, and cow dung with chicken litter biochar (OSA1 to OSA5) as organic soil amendments with chemical fertilizers can improve soil chemical properties, nutrients content and uptake, rice growth, and grain yield compared with those of the prevailing fertilization method (NPK-Mg). The organic soil amendments used in this study improved the rice grain yields in the first (9 t $ha^{-1}$ to 11 t $ha^{-1}$), second (11 t $ha^{-1}$ to 13 t $ha^{-1}$), and third cropping cycles (8 t $ha^{-1}$ to 10 t $ha^{-1}$). Among organic soil amendments used, OSA5 (Chicken litter biochar: Leucaena: chicken litter compost = 2:1:1) is the most recommended organic soil amendment because it demonstrated the highest rice grain yields at the first (11.17 t $ha^{-1}$), second (13.11 t $ha^{-1}$), and third (10.06 t $ha^{-1}$) cropping cycles in addition to significantly improved soil chemical properties, nutrients content and uptake, and rice growth. The application of inorganic fertilizers N, P, K, MgO, and trace elements were reduced by 25%, 100%, 64%, 100%, and 100%, respectively because *Leucaena* improves mineralization, soil nutrient availability, and nutrient uptake of the rice plants especially when chicken litter biochar, chicken manure, and *Leucaena* are co-composted (OSA5). The residual effects of the organic soil amendments (OSA1 to OSA5) suggest that the nutrients content and uptake, rice growth, and grain yield were slightly reduced compared with those of the two earlier cropping cycles but significantly higher than those of prevailing fertilization method (NPK-Mg). Reduction of P, K, MgO, and trace elements by 100%, 64%, 100%, and 100%, respectively, were maintained; however, the application of N could not be reduced because of higher demand of N by rice plants and lower N supply by the residual organic soil amendments. Generally, the use of organic soil amendments from *Leucaena*, forest litter, chicken manure, and cow dung co-composted with chicken litter biochar does not only improve sustainable productivity of rice on tropical acid soil, but it also mitigates other environmental pollutions such as forest residue slash pile burning and facilitates suitable disposal of animal wastes. Thus, it is possible to transform organic agro-wastes into organic soil amendments to sustainably improve mineral acid soil and rice productivity.

**Author Contributions:** Conceptualization, O.H.A.; methodology, M.A.; validation, O.H.A. and M.B.J.; formal analysis and visualization, M.A. and J.F.N.; investigation, M.A.; resources, O.H.A.; writing—original draft preparation, M.A.; writing—review and editing, O.H.A., M.B.J. and J.F.N.; supervision, O.H.A. and W.C.P.; project administration, O.H.A., M.B.J. and A.A.M.; funding acquisition, O.H.A., M.B.J. and A.A.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Ministry of Higher Education, Malaysia with grant number (FRGS/1/2016/WAB01/UPM/02/2).

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to acknowledge Ministry of Higher Education, Malaysia, for financial assistance and Universiti Putra Malaysia for providing research facilities. Our appreciation also goes to colleagues and staff of Universiti Putra Malaysia, Universiti Islam Sultan Sharif Ali, Universiti Malaysia Sabah, Management and Science University, and University of Ghana for their technical support and collaboration.

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

## References

1. Von Uexküll, H.R.; Mutert, E. Global extent, development and economic impact of acid soils. *Plant Soil* **1995**, *171*, 1–15. [CrossRef]
2. Brady, N.C.; Weil, R.R. *The Nature and Properties of Soils*, 14th ed.; Pearson Education: Upper Saddle River, NJ, USA, 2008.
3. Simonson, R.W. Soil classification. In *Handbook of Soils and Climate in Agriculture*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2018; pp. 103–130.
4. Saenya, J.; Anusontpornperm, S.; Thanachit, S.; Kheoruenromne, I. Potential of Paddy Soils for Jasmine Rice Production in Si Sa Ket Province, Northeast Thailand. *Asian J. Crop Sci.* **2015**, *7*, 34–47. [CrossRef]
5. Dressler, W.H.; Wilson, D.; Clendenning, J.; Cramb, R.; Keenan, R.; Mahanty, S.; Bruun, T.B.; Mertz, O.; Lasco, R.D. The impact of swidden decline on livelihoods and ecosystem services in Southeast Asia: A review of the evidence from 1990 to 2015. *Ambio* **2017**, *46*, 291–310. [CrossRef] [PubMed]
6. Blumenschein, T.G. Effects of Deep Vertical Placement of Lime on Corn and Soybean Response and Soil Chemical Properties in Conservation Tillage Systems. Master's Thesis, University of Missouri, Columbia, MO, USA, 2016.
7. Department of Agriculture. Booklet Statistik Tanaman (Sub-sektor Tanaman Makanan) 2021. Available online: http://www.doa.gov.my/index/resources/aktiviti_sumber/sumber_awam/maklumat_pertanian/perangkaan_tanaman/booklet_statistik_tanaman_2021.pdf (accessed on 18 March 2022).
8. Bruinsma, J. *World Agriculture: Towards 2015/2030. Summary Report*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2002.
9. Smith, P.; House, J.I.; Bustamante, M.; Sobocká, J.; Harper, R.; Pan, G.; West, P.C.; Clark, J.M.; Adhya, T.; Rumpel, C.; et al. Global change pressures on soils from land use and management. *Glob. Chang. Biol.* **2016**, *22*, 1008–1028. [CrossRef] [PubMed]
10. Che Omar, S.; Shaharudin, A.; Tumin, S.A. *The Status of the Paddy and Rice Industry in Malaysia Key Findings of the Report*; Khazanah Research Institute: Kuala Lumpur, Malaysia, 2019; ISBN 978-967-16335-7-1.
11. Chandini, K.R.; Kumar, R.; Prakash, O. The impact of chemical fertilizers on our environment and ecosystem. In *Research Trends in Environmental Sciences*; Akinik Publications: New Delhi, India, 2019; pp. 69–86.
12. Scotti, R.; Bonanomi, G.; Scelza, R.; Zoina, A.; Rao, M. Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. *J. Soil Sci. Plant Nutr.* **2015**, *15*, 333–352. [CrossRef]
13. Manyi-Loh, C.E.; Mamphweli, S.N.; Meyer, E.L.; Makaka, G.; Simon, M.; Okoh, A.I. An Overview of the Control of Bacterial Pathogens in Cattle Manure. *Int. J. Environ. Res. Public Health* **2016**, *13*, 843. [CrossRef]
14. Ghosh, P.K.; Palsaniya, D.R.; Kiran Kumar, T. Resource conservation technologies for sustainable soil health management. In *Adaptive Soil Management: From Theory to Practices*; Springer: Singapore, 2017; pp. 161–187.
15. Meena Devi, V.N.; Ariharan, V.N.; Nagendra Prasad, P. Nutritive value and potential uses of *Leucaena leucocephala* as biofuel—A mini review. *RJPBCS* **2013**, *4*, 5515–5521.
16. Maru, A.; Haruna, O.A.; Charles Primus, W. Coapplication of chicken litter biochar and urea only to improve nutrients use efficiency and yield of *Oryza sativa* L. cultivation on a tropical acid soil. *Sci. World J.* **2015**, *2015*, 943853. [CrossRef]
17. Maru, A. Improvement of Acid Soils and Rice (*Oryza sativa* L.) Productivity Using Organic Amendments from Organic Wastes. Doctoral Thesis, Universiti Putra Malaysia, Serdang, Selangor, Malaysia, June 2019.
18. Peech, H.M. Hydrogen-ion activity. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*; Norman, A.G., Ed.; American Society of Agronomy and Soil Science Society of America: New York, NY, USA, 1965; Volume 1, pp. 914–926.

19. Chefetz, B.; Hatcher, P.G.; Hadar, Y.; Chen, Y. Chemical and Biological Characterization of Organic Matter during Composting of Municipal Solid Waste. *J. Environ. Qual.* **1996**, *25*, 776–785. [CrossRef]
20. Cottenie, A. Soil testing and plant testing as a basis of fertilizer recommendation. *FAO Soils Bull.* **1980**, *38*, 70–73.
21. Bremner, J.M.; Keeney, D.R. Steam distillation methods for determination of ammonium, nitrate and nitrite. *Anal. Chim. Acta* **1965**, *32*, 485–495. [CrossRef]
22. Tan, K.H. *Soil Sampling, Preparation, and Analysis*, 2nd ed.; CRC Press, Taylor and Francis Group: Boca Raton, FL, USA, 2005; Volume 154–174, pp. 1–623.
23. Keeney, D.R.; Nelson, D.W. Nitrogen-Inorganic Forms. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, 2nd ed.; Page, A.L., Ed.; American Society of Agronomy and Soil Science Society of America: New York, NY, USA, 1982; Volume 1, pp. 643–698.
24. Mehlich, A. *Determination of P, Ca, Mg, K, Na, NH4*; Short Test Methods Used in Soil Testing Division, Department of Agriculture: Raleigh, NC, USA, 1953; Volume 1, p. 8. Available online: http://www.ncagr.gov/agronomi/pdffiles/mehlich53.pdf (accessed on 4 November 2022).
25. Murphy, J.; Riley, J.P. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* **1962**, *27*, 31–36. [CrossRef]
26. Rowell, D.L. Soil acidity and alkalinity. In *Soil Science: Methods and Applications*, 1st ed.; Pearson Education Limited: New York, NY, USA, 1994; Volume 1, pp. 153–174.
27. Matsushima, S.; Takayuki, T. Analysis of Developmental Factors Determining Yields and Its Application to Yield Prediction and Culture Improvement of Lowland Rice: LV. Early discrimination of non-fertilized rice-grains. *Jpn. J. Crop Sci.* **1960**, *28*, 365–366. [CrossRef]
28. SAS. SAS/STAT Software. In *SAS Institute*, 2nd ed.; SAS Institute Inc.: Cary, NC, USA, 2013.
29. Havlin, J.L.; Beaton, J.D.; Tisdale, S.L.; Nelson, W.L. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*; Pearson Prentice Hall: Upper Saddle River, NJ, USA, 2005; Volume 515, pp. 97–141.
30. Ch'ng, H.Y.; Ahmed, O.H.; Majid, N.M.A. Biochar and compost influence the phosphorus availability, nutrients uptake, and growth of maize (*Zea mays* L.) in tropical acid soil. *Pak. J. Agric. Sci.* **2014**, *51*, 797–806.
31. Hamidi, N.H.; Ahmed, O.H.; Omar, L.; Ch'ng, Y.H.; Johan, P.D.; Paramisparam, P.; Jalloh, M.B. Acid Soils Nitrogen Leaching and Buffering Capacity Mitigation Using Charcoal and Sago Bark Ash. *Agronomy* **2021**, *13*, 11808. [CrossRef]
32. Smebye, A.; Alling, V.; Vogt, R.D.; Gadmar, T.C.; Mulder, J.; Cornelissen, G.; Hale, S.E. Biochar amendment to soil changes dissolved organic matter content and composition. *Chemosphere* **2016**, *142*, 100–105. [CrossRef]
33. Lim, S.L.; Wu, T.Y.; Lim, P.N.; Shak, K.P.Y. The use of vermicompost in organic farming: Overview, effects on soil and economics. *J. Sci. Food Agric.* **2015**, *95*, 1143–1156. [CrossRef]
34. Agegnehu, G.; Bass, A.M.; Nelson, P.N.; Bird, M.I. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Sci. Total Environ.* **2016**, *543*, 295–306. [CrossRef]
35. Yousaf, B.; Liu, G.; Wang, R.; Zia-ur-Rehman, M.; Rizwan, M.S.; Imtiaz, M.; Murtaza, G.; Shakoor, A. Investigating the potential influence of biochar and traditional organic amendments on the bioavailability and transfer of Cd in the soil–plant system. *Environ. Earth Sci.* **2016**, *75*, 374. [CrossRef]
36. Awasthi, M.K.; Pandey, A.K.; Bundela, P.S.; Wong, J.W.C.; Li, R.; Zhang, Z. Co-composting of gelatin industry sludge combined with organic fraction of municipal solid waste and poultry waste employing zeolite mixed with enriched nitrifying bacterialbconsortium. *Bioresour. Technol.* **2016**, *213*, 181–189. [CrossRef]
37. Lehmann, J.; Kleber, M. The contentious nature of soil organic matter. *Nature* **2015**, *528*, 60–68. [CrossRef] [PubMed]
38. Daly, K.; Styles, D.; Lalor, S.; Wall, D.P. Phosphorus sorption, supply potential and availability in soils with contrasting parent material and soil chemical properties. *Eur. J. Soil Sci.* **2015**, *66*, 792–801. [CrossRef]
39. Ch'ng, H.Y.; Ahmed, O.H.; Majid, N.M.A. Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. *Sci. World J.* **2014**, *2014*, 506356. [CrossRef] [PubMed]
40. Parihar, P.; Singh, S.; Singh, R.; Singh, V.P.; Prasad, S.M. Effect of salinity stress on plants and its tolerance strategies: A review. *Environ. Sci. Pollut. Res. Int.* **2015**, *22*, 4056–4075. [CrossRef] [PubMed]
41. McDaniel, M.D.; Tiemann, L.K.; Grandy, A.S. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecol. Appl.* **2014**, *24*, 560–570. [CrossRef] [PubMed]
42. Turmel, M.S.; Speratti, A.; Baudron, F.; Verhulst, N.; Govaerts, B. Crop residue management and soil health: A systems analysis. *Agric. Syst.* **2015**, *134*, 6–16. [CrossRef]
43. Pascault, N.; Cécillon, L.; Mathieu, O.; Hénault, C.; Sarr, A.; Lévêque, J.; Farcy, P.; Ranjard, L.; Maron, P.-A. In Situ Dynamics of Microbial Communities during Decomposition of Wheat, Rape, and Alfalfa Residues. *Microb. Ecol.* **2010**, *60*, 816–828. [CrossRef]
44. Fanin, N.; Bertrand, I. Aboveground litter quality is a better predictor than belowground microbial communities when estimating carbon mineralization along a land-use gradient. *Soil Biol. Biochem.* **2016**, *94*, 48–60. [CrossRef]
45. Kleber, M. What is recalcitrant soil organic matter? *Environ. Chem.* **2010**, *7*, 320–332. [CrossRef]
46. Marin-Spiotta, E.; Chaopricha, N.T.; Plante, A.F.; Diefendorf, A.F.; Mueller, C.W.; Grandy, A.S.; Mason, J.A. Long-term stabilization of deep soil carbon by fire and burial during early Holocene climate change. *Nat. Geosci.* **2014**, *7*, 428–432. [CrossRef]
47. Hernandez-Muciño, D.; Sosa-Montes, E.; Ceccon, E. Leucaena macrophylla: An ecosystem services provider? *Agrofor. Syst.* **2015**, *89*, 163–174. [CrossRef]

48. Morrone, V.; Snapp, S.S. Building Soil for Organic and Sustainable Farms: Where to Start? In *Extension Bulletin E-3144 New*; Michigan State University: East Lansing, MI, United States, January 2011.
49. Akhtar, S.S.; Andersen, M.N.; Liu, F. Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agric. Water Manag.* **2015**, *158*, 61–68. [CrossRef]
50. Wei, W.; Yan, Y.; Cao, J.; Christie, P.; Zhang, F.; Fan, M. Effects of Combined Application of Organic Amendments and Fertilizers on Crop Yield and Soil Organic Matter: An Integrated Analysis of Long-Term Experiments. *Agric. Ecosyst. Environ.* **2016**, *225*, 86–92. [CrossRef]
51. Zhao, J.T.N.; Lia, J.; Lua, Q.; Fanga, Z.; Huang, Q.; Lia, R.Z.R.; Shen, B.; Shena, Q. Effects of organic-inorganic compound fertilizer with reduced chemical fertilizer application on crop yields, soil biological activity and bacterial community structure in a rice–wheat cropping system. *Appl. Soil Ecol.* **2016**, *99*, 1–12. [CrossRef]
52. Mi, W.; Wu, L.; Brookes, P.C.; Liu, Y.; Zhang, X.; Yang, X. Changes in soil organic carbon fractions under integrated management systems in a low-productivity paddy soil given different organic amendments and chemical fertilizers. *Soil Tillage Res.* **2016**, *163*, 64–70. [CrossRef]
53. Keerthi, M.M.; Babu, R.; Joseph, M.; Amutha, R. Optimizing plant geometry and nutrient management for grain yield and economics in irrigated greengram. *Am. J. Plant Sci.* **2015**, *6*, 1144. [CrossRef]
54. Herencia, J.F.; Ruiz-Porras, J.C.; Melero, S.; Garcia-Galavis, P.A.; Morillo, E.; Maqueda, C. Comparison between organic and mineral fertilization for soil fertility levels, crop macronutrient concentrations, and yield. *Agron. J.* **2007**, *99*, 973–983. [CrossRef]
55. Sathish, A.; Gowda, V.; Chandrappa, H.; Kusagur, N. Long term effect of integrated use of organic and inorganic fertilizers on productivity, soil fertility and uptake of nutrients in rice-maize cropping system. *Int. J. Sci. Nat.* **2011**, *2*, 84–88.