agronomy

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Azolla Compost as an Approach for Enhancing Growth, Productivity and Nutrient Uptake of *Oryza sativa* L.

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Abstract: The excessive application of synthetic fertilizers can result in severe environmental risks, while composting green and fresh feedstocks can provide slow-release nutrients. Therefore, the aim of the current investigation was to study the effects of eight individual and combination treatments of azolla compost and NPK synthetic fertilizers (control = no fertilizer and compost; 100% NPK = full recommended dose of synthetic fertilizers as follows: 165 kg N ha^{-1}, 37 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}; 70% NPK; 40% NPK; 100% azolla compost (5 t DM ha^{-1}); 50% NPK + 50% azolla compost; 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost) on rice growth, productivity and nutrient uptake in semi-arid agro-ecosystems. The results indicated that the combination of 40% NPK + 60% azolla compost or 50% NPK + 50% azolla compost resulted in the most optimal growth and the highest yield components. In addition, the application of 40% NPK + 60% azolla compost exhibited similar rice grain yields (10.76 t ha^{-1}) as well as N, P, and K content and uptake compared with the full recommended dose of NPK fertilizer (100% NPK). This study declared that the utilization of azolla compost as an individual or combination application can reduce usage of synthetic fertilizers by up to 60% without significant reduction in the growth and grain productivity of rice.

Keywords: azolla compost; rice; synthetic fertilizers; nutrient uptake; grain yield

Citation: Seleiman, M.F.; Elshayb, O.M.; Nada, A.M.; El-leithy, S.A.; Baz, L.; Alhammad, B.A.; Mahdi, A.H.A. Azolla Compost as an Approach for Enhancing Growth, Productivity and Nutrient Uptake of *Oryza sativa* L. *Agronomy* **2022**, *12*, 416. https://doi.org/10.3390/agronomy12020416

Academic Editors: Maria Angeles Bustamante Muñoz and Raul Moral Herrero

Received: 20 January 2022
Accepted: 5 February 2022
Published: 7 February 2022

1. Introduction

Rice (*Oryza sativa* L.) is considered the second most important cereal crop (after wheat) that is being used as food source for 50% of the world population due to its nourishment [1]. The world's rice cultivated area was about 164.19 M ha with a total annual grains production of 756.74 Mt and 4.60 t grains per ha in 2018 [2]. In order to cultivate such large areas, millions of tons of synthetic fertilizers are needed to produce high grain yields for rapidly growing populations and their food requirements [3,4]. Nevertheless, the incremental application of synthetic fertilizers can cause harmful impacts on soil organic matter that can consequently result in N deficiency [4], and enhance salt accumulation in soil [5]. In 2018–2019 about 188 Mt was the aggregate world consumption of fertilizers, at a cost of about 155.8 billion dollars; this is expected to grow annually by 3.8% until 2024 [6]. Industrialized synthetic N fertilizers require about one-third of the total commercial energy used for different processes in agricultural cultivation, owing to the high levels of energy needed to reduce N_2 into NH_3 during the Haber–Bosch process [7]. Applying synthetic fertilizers into agricultural systems over the long-term can cause soil acidification, reduce soil organic matter, result in nutrient imbalance [7], increase salt accumulation and decrease cation exchange capacity in soils [8]. Thus, the efficient use of all agricultural inputs requires intensive farming approaches to provide adequate and balanced amounts of essential nutrients under the lowest possible rates of synthetic fertilizer use.

To improve soil structure and enhance nutrient recycling, using organic amendments such as composts can potentially save energy compared to using industrialized synthetic fertilizers [9–14]. In addition, applications of soil organic amendments can be optimal alternatives to synthetic fertilizers in order to enhance crop productivity and improve long-term soil fertility [7]. Therefore, sustainable agriculture with high productivity in terms of grain yield are necessary to lessen the threats of hunger and to augment food security while preserving environmental resources [4]. In this respect, composting green and fresh feedstocks can provide slow-release nutrients. In addition, the utilization of composted organic materials can be a benign route towards boosting soil organic matter, enhancing plant acquisition of nutrients and enhancing soil microbial activity, thereby amending soil characteristics and promoting crop production [15–18].

Azolla (*Azolla filiculoides*) is an aquatic small fern that can be found in swamps, pools and lakes where the water is not turbulent. It can fix atmospheric nitrogen by establishing a symbiotic association with Cyanobacteria (i.e., *Anabaena azollae*) which are located in the dorsal lobes of its leaves [19]. Furthermore, azolla has unique uses as a green feedstock and as composted manure due to its nitrogen content that can enhance crop productivity [20–22]. Using azolla compost in agriculture is considered a friendly environmental practice as a result of its desirable influence on suppressing methane emissions and decreasing global warming [23]. Moreover, using azolla as a source of nutrients in agriculture can save non-renewable sources of energy for more sustainable production. Research suggests that compost with a C/N ratio of around 15 indicates stabilization of composting feedstocks [20], while compost with a C/N ratio below 12 indicates mature composts.

The objective of our study was to evaluate combinations of azolla compost and synthetic fertilizers in different proportions to determine which are optimal for enhancing growth, maximizing rice productivity, and nutrient (N, P, and K) uptake in semi-arid agro-ecosystems.

2. Materials and Methods

2.1. Experimental Treatments and Experimental Design

Two field experiments were conducted at the Experimental Farm of Sakha, Kafrelsheikh, Egypt (Latitude: 31°6′ N and Longitude: 30°56′ E) during the summer seasons of 2019 and 2020 to investigate the effects of azolla compost, synthetic fertilizer and their combinations on growth and productivity of rice (*Oryza sativa* L., cv. Sakha super 300) as well as on nutrient uptake in semi-arid agro-ecosystems. The experimental design was a randomized complete block design with four replicates. The plot size was 15 m^2 (5 m in length $\times$ 3 m in width). Treatments of synthetic NPK fertilizer, azolla compost and their combinations included the eight treatments presented in Table 1.

2.2. Azolla Compost Preparation and Analysis

Azolla (*Azolla filiculoides*) was collected and prepared as described by Jumadi et al. [21]. It was thoroughly washed using distilled water, then dried in an oven at 55 °C until the moisture content was stable at around 50%. A mixture with 250 mL of molasses was placed in black plastic and covered with another black plastic cover. Composting mixture processing lasted for one week after which the obtained composted azolla was dried in the oven at a temperature of 55 °C). Finally, the outcome raw material was crushed and then passed through a 2-millimeter sieve. It was merely mixed and distributed with soil homogeneously before transplanting on 0–20 cm depth. Table 2 presents the chemical analysis of azolla compost used during the 2019 and 2020 growing seasons.

Table 1. The details of the treatments.

T1	Control: Synthetic fertilizer and azolla compost were not applied
T2	100% NPK: full recommended dose of NPK synthetic fertilizer (165 kg N ha^{-1}, 37 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}).
T3	70% NPK (115.5 kg N ha^{-1}, 25.9 kg P_2O_5 ha^{-1} and 35.0 kg K_2O ha^{-1})
T4	40% NPK (66.0 kg N ha^{-1}, 14.8 kg P_2O_5 ha^{-1} and 20.0 kg K_2O ha^{-1})
T5	100% azolla compost (5 t DM ha^{-1})
T6	50% NPK (82.5 kg N ha^{-1}, 18.5 kg P_2O_5 ha^{-1} and 25.0 kg K_2O ha^{-1}) + 50% azolla compost (2.5 t DM ha^{-1})
T7	70% NPK + 30% azolla compost (1.5 t DM ha^{-1})
T8	40% NPK + 60% azolla compost (3.0 t DM ha^{-1})

Table 2. The analysis of azolla compost used during the 2019 and 2020 growing seasons.

Season \ Traits	pH	Organic Carbon (%)	N (%)	P (%)	K (%)	C/N Ratio	Zn (ppm)	Fe (ppm)
2019	7.30	34.78	3.10	0.95	1.57	11.21	68.45	570
2020	7.12	35.83	3.17	1.10	1.81	11.30	70.53	614

2.3. Plantation and Crop Management

Rice grains at a rate of 120 kg ha^{-1} were soaked in fresh water for 24 h and then were incubated for another 48 h. On-farm, germinated grains were broadcast in the nursery on 10 and 12 of May during the summer seasons of 2019 and 2020, respectively. All plots, healthy seedlings at the age of 25 days, were transplanted on 5 and 7 June during the summers of 2019 and 2020, respectively. The seedlings were planted with 20 cm of distance between rows and 20 cm of distance between hills.

The recommended synthetic fertilizers (100% NPK) of urea (46% N), calcium superphosphate (15% P_2O_5) and potassium sulfate (48% K_2O) were applied at rates of 165 kg N ha^{-1}, 37 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}, respectively. Urea fertilizer as an N fertilizer source was applied in two doses. The first dose (66.66%) was applied at basal application, while the second dose (33.33%) was applied at panicle initiation. On the other hand, calcium superphosphate and potassium sulfate were applied during land preparation. Zinc sulfate fertilizer ($ZnSO_4$) was broadcast manually at the rate of 24 kg ha^{-1} before transplanting. Five days after transplanting, the pesticide Saturn 50% (at the rate of 5 L ha^{-1}) was used for weeding control.

2.4. Soil Analysis and Climate Data

Bulk soil samples were collected at depths of 0–30 cm before field experiments and soil physicochemical and chemical properties analyses (Table 3), according to Day and Black [24]. Furthermore, meteorological data collected such as maximum and minimum temperatures and humidities during the growing seasons of 2019 and 2020 (June–October) are presented in Table 4. There was no precipitation during the rice growing seasons of the current investigation.

2.5. Measurements

2.5.1. Plant Growth

Rice plants from five hills in each plot were randomly chosen at the flowering stage (BBCH stage 61) [25] during the two growing seasons and used to measure total chlorophyll content, dry matter production (DMP) and leaf area index (LAI). Total chlorophyll content was determined from ten flag leaves using a SPAD chlorophyll meter (Model–SPAD 502, Minolta, Japan). DMP weight (g/hill) was estimated as described by Yoshida et al. [26] and Cock et al. [27]. Leaf area index (LAI) was estimated from the ratio between the leaves areas (cm^2) of the plants divided by the ground area occupied by the plants (cm^2).

Table 3. Physicochemical properties of soil collected from the experimental site during the 2019 and 2020 growing seasons.

Traits \ Season	2019	2020
Physical analysis:		
Texture	Clay	Clay
Sand (%)	13.4	16.3
Silt (%)	32	28
Clay (%)	54.6	55.7
Chemical analysis:		
pH (1:2.5 soil extract)	8.35	8.45
EC (dS m^{-1})	1.9	2.3
Organic matter %	1.51	1.65
Available N (ppm)	17.3	18.2
Available P (ppm)	12.2	14.3
Available K (ppm)	313	318
Available Zn (ppm)	0.85	0.9
Available Mn (ppm)	3.1	3.93
Available Fe (ppm)	2.64	2.96

Table 4. Metrological data for the summer cropping seasons in 2019 and 2020.

Year	Month	Air Temperature (°C)			Relative Humidity (%)		
		Maximum	Minimum	Average	Maximum	Minimum	Average
2019	June	31.9	25.4	28.6	76.4	37.9	57.1
	July	33.5	28.3	30.9	85.2	54.4	69.8
	August	34.2	28.9	31.6	85.7	55.6	70.65
	September	32.4	27.9	30.2	83.4	52.9	68.15
	October	30.3	26.7	28.5	87.3	54.3	70.8
2020	June	32	23.8	27.9	68.9	38.4	53.7
	July	33.7	27.3	30.5	84.2	51.1	67.7
	August	34.6	28.2	31.4	85.3	49.6	67.5
	September	34.2	27.1	30.7	86.7	47.7	67.2
	October	31.5	24.6	28.1	84.7	47.1	65.9

2.5.2. Yield and Its Components

At maturity, ten hills were chosen randomly from the middle of each plot to measure plant height (cm) and number of panicles. Also, ten random panicles were collected to measure panicle length (cm), panicle weight (g), number of filled and unfilled grains/panicle, and 1000-grain weight (g).

An area of 12 m^2 from the middle of each plot was harvested, dried and threshed to estimate grain and biological yields (both straw and grain yield) based on 14% moisture content (t ha^{-1}).

2.5.3. Nutrient Uptake

The nutrient uptake of N, P and K in both grain and rice straw were calculated. Samples were subjected to oven drying (70 °C) in order to obtain constant weights. After this step, samples were ground to powder and digested using H_2SO_4. Using the Micro Kjeldahl method, total N content was determined as described earlier by Jackson [28]. P nutrient content was calorimetrically determined as described by Watanabe and Olsen [29], while K nutrient content was estimated by a flame photometer using atomic absorption according to Peterburgski [30]. Nutrient uptake in both grain and straw parts were calculated in kg/ha as follows:

$$\text{Element uptake (kg/ha DM)} = \text{Element content (g/kg)} \times \text{grains or straw yield (kg/ha)} \times 0.001 \quad (1)$$

2.6. Statistical Analysis

The obtained data from the effects of azolla compost, synthetic fertilizers and their combinations on growth and productivity of rice, as well as on nutrient uptake in grains and straw, were subjected to analyses of variance (ANOVA) according to Gomez and Gomez [31] using SPSS (v. 22, IBM Inc., Chicago, IL, USA). The means of different traits were compared using Duncan's Multiple Range Test [32].

3. Results and Discussions

3.1. Effect of Azolla Compost, Synthetic Fertilizers and Their Combinations on Rice Growth

Data in Table 5 show that all tested growth measurements (chlorophyll content, leaf area index and dry matter production) were significantly affected by the different rates of synthetic fertilizers (NPK), azolla compost and their combinations during the 2019 and 2020 seasons. The main observation indicated that treatment of 50% NPK + 50% azolla compost resulted in the highest chlorophyll content in terms of SPAD values (44.22 and 45.61), LAI (7.70 and 7.61) and DMP (54.16 and 56.28 g/hill) for 2019 and 2020, respectively; these were statistically similar with 70% NPK + 30% azolla compost in both planting seasons. These treatments seemed to provide the required nitrogen levels for rice plants. On the other hand, the 40% NPK + 60% azolla compost and 50% NPK + 50% azolla compost treatments resulted in the highest values for LAI during the growing season of 2019, and the highest DMP values for both the 2019 and 2020 seasons compared to other treatments (Table 5). The lowest values of all tested growth parameters were obtained from unfertilized plants during the first and second seasons. For the LAI and DMP variables, the influence of incorporated azolla compost with synthetic fertilizer may have reinforced the availability of macro and micronutrients. Its positive effects probably enhanced leaf chlorophyll content and cell elongation that occurred in plant cells and thereby resulted in benign photo-assimilates and high accumulations of dry matter [33,34]. The improved growth traits of rice grown with azolla compost applications can be a result of the supplied N and other nutrients, since such applications can provide above 50% of the nitrogen requirements for rice and moreover can beneficially control soil pH [35]. As per the findings of [36], the combined effect of NPK+ azolla compost induced higher photosynthetic rates in rice leaves at different physiological stages as opposed to the application of inorganic NPK alone.

3.2. Effect of Azolla Compost, Synthetic Fertilizers and Their Combinations on Rice Yield and Its Components

The results in Table 6 depict a significant influence of azolla compost application when it was combined with 50% NPK, 70% NPK and 40% NPK. The tallest plants (123.2 and 125.7 cm) were observed under the treatments of 50% NPK + 50% azolla compost followed by 70% NPK + 30% azolla compost. There were no significant differences between them during the first season. The application of 50% NPK + 50% azolla compost produced statistically identical results with 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost during the second season. The co-applied 50% NPK and 50% azolla compost resulted in the highest numbers of panicles/hill (24.11 and 26.00 panicles) and longest panicle lengths (21.45 and 21.10 cm) with statistical matches for 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost in both consecutive seasons. Consequently, combinations of azolla with synthetic fertilizers not only can supply plants with adequate quantities of N, but also can facilitate better use of such nutrients via the mineralization process, resulting in better productivity [35].

Table 5. Effects of azolla compost, synthetic fertilizers and their combinations on chlorophyll content, leaf area index and dry matter production of rice during two growing seasons.

Traits / Treatments	Chlorophyll Content (SPAD Value)		Leaf Area Index (LAI)		Dry Matter Production (g/Hill)	
	2019	2020	2019	2020	2019	2020
Control	30.45 e	30.68 e	4.84 f	5.02 e	21.48 d	22.71 d
100% NPK	41.23 a	45.50 a	7.11 ab	7.34 ab	47.56 b	52.32 a
70% NPK	40.51 b	41.36 c	6.53 d	6.74 c	37.38 c	39.12 c
40% NPK	33.80 d	36.27 d	5.90 e	6.02 d	32.61 c	33.94 c
100% azolla compost	37.95 c	40.25 c	6.43 d	6.61 c	35.22 c	38.30 c
50% NPK + 50% azolla compost	44.22 a	45.61 a	7.61 a	7.70 a	54.16 a	56.28 a
70% NPK + 30% azolla compost	43.53 a	44.80 ab	7.40 a	7.64 a	51.73 a	52.82 a
40% NPK + 60% azolla compost	41.18 b	43.18 b	7.17 ab	7.10 b	49.62 ab	50.03 ab
Significance	**	**	**	**	**	**

** indicates $p \leq 0.01$; Data followed by the same letter were not significantly varied at $p \leq 0.05$.

Table 6. Effects of azolla compost, synthetic fertilizers and their combinations on plant heights, numbers of panicles/hill and panicle lengths of rice during two growing seasons.

Traits / Treatments	Plant Height (cm)		Number of Panicles per Hill		Panicle Length (cm)	
	2019	2020	2019	2020	2019	2020
Control	93.3 d	94.1 d	12.11 d	14.68 d	15.64 d	15.37 c
100% NPK	116.7 b	119.2 ab	22.82 a	25.13 a	20.60 a	20.95 a
70% NPK	111.4 c	115.6 b	19.90 b	21.49 b	18.46 c	17.71 b
40% NPK	97.1 d	99.0 d	15.83 c	17.27 c	16.11 d	16.20 c
100% azolla compost	111.8 c	112.4 bc	16.65 c	19.17 c	17.53 c	16.19 c
50% NPK + 50% azolla compost	123.2 a	125.7 a	24.11 a	26.00 a	21.45 a	21.10 a
70% NPK + 30% azolla compost	121.0 a	123.6 a	24.03 a	23.92 a	20.62 ab	20.94 a
40% NPK + 60% azolla compost	116.9 b	118.8 ab	23.46 a	25.81 a	20.46 ab	20.92 a
Significance	**	**	**	**	**	**

** indicates $p \leq 0.01$; Data followed by the same letter were not significantly varied at $p \leq 0.05$.

Concerning the weights and grain numbers per panicle, in addition to the 1000-grain weights, the same trends were observed in both characters during seasonal planting (Figures 1 and 2). The uppermost values of panicle weight (4.11 and 4.15 g), 1000-grain weight (30.62 and 30.94 g) and grain numbers/panicle (158.26 and 161.87 grains) were produced from rice grown with the 50% NPK + 50% azolla compost application in both cultivated seasons, respectively. Whilst the obtained data did not provide any significant differences between the 50% NPK + 50% azolla compost and 70% NPK + 30% azolla compost applications in the 2019 season with respect to plant height, panicle weights and filled grain numbers had identical statistics between 100% NPK, 70% NPK + 30% azolla compost, 40% NPK + 60% azolla compost and 50% NPK + 50% azolla compost treatments in connection with all previous parameters during the 2020 season. Such improvements for these traits with rice grown using combinations of azolla compost and synthetic fertilizers (current investigation) can be explained by better N use efficiency as a result of reducing N loss and enhancing N uptake by rice plants [37]. Sufficient N availability can preserve green leaf area after heading, and consequently can enhance photosynthesis and improve grain yields [38].

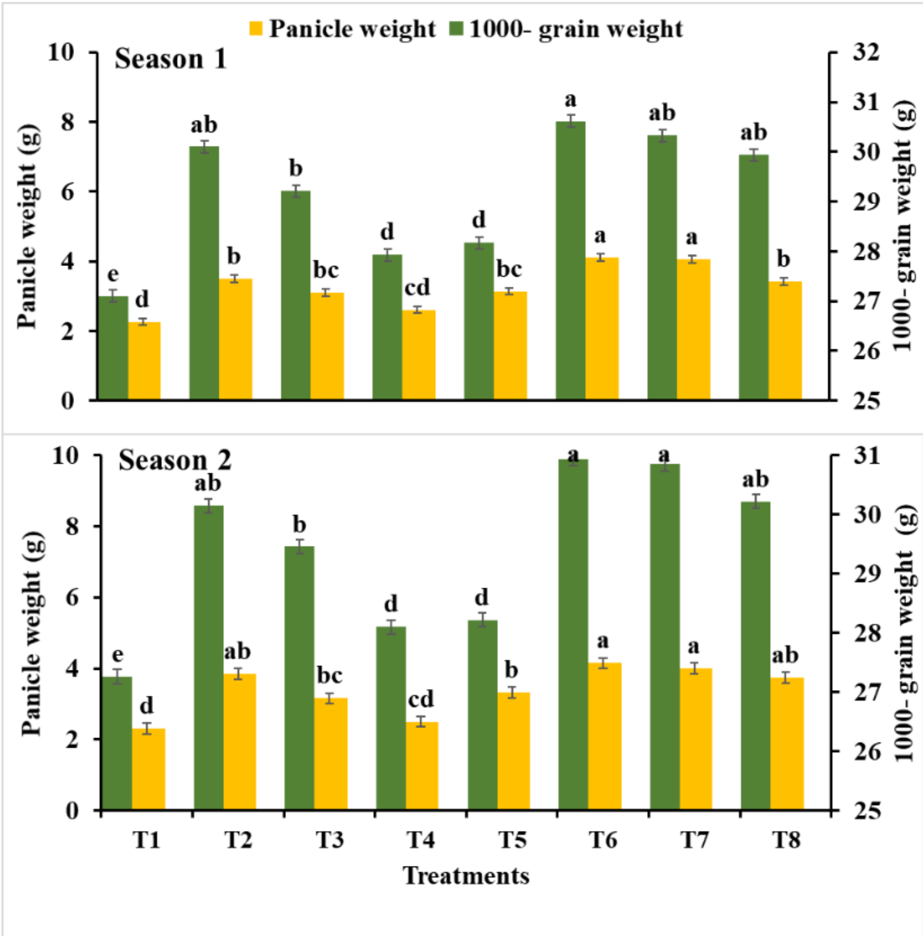

Figure 1. Effects of azolla compost, synthetic fertilizers and their combinations on panicle weight and 1000-grain weight of rice during two seasons. T1 = Control (zero fertilizer and azolla compost); T2 = 100% NPK (full recommended dose of synthetic fertilizers as follows: 165 kg N ha^{-1}, 37 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}); T3 = 70% NPK; T4 = 40% NPK; T5 = 100% azolla compost (5 t DM ha^{-1}); T6 = 50% NPK + 50% azolla compost; T7 = 70% NPK + 30% azolla compost; T8 = 40% NPK + 60% azolla compost. In each parameter, columns followed by the same letter were not significantly varied at $p \leq 0.05$.

The lowest values for plant height (93.3 and 94.1 cm), number of panicles/hill (12.11 and 14.68 panicles), panicle length (15.64 and 15.37 cm), panicle weight (2.26 and 2.31 g), 1000-grain weight (27.10 and 27.26 g) and grain numbers per panicle (102.40 and 98.18 grains) in both the 2019 and 2020 seasons were rendered by the unfertilized treatment (Table 6, Figures 1 and 2). Inversely, the highest empty or un-filled grain numbers (24.66 and 25.30) were obtained from unfertilized treatments. However, the lowest reported values were produced when plants were treated with 100% NPK, 70% NPK + 30% azolla compost, 40% NPK + 60% azolla compost and 50% NPK + 50% azolla compost applications in both the first and second seasons.

Meaningful effects of azolla compost, synthetic fertilizers and their combinations were observed for both grain and biological yields (Figure 3). The maximal weights of biological yield (26.32 and 26.91 t ha^{-1}) and grain yield (10.94 and 11.32 t ha^{-1}) were achieved by the 50% NPK + 50% azolla compost application during both the first and second seasons, respectively. From observations, treatments of 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost presented similar statistics with the 50% NPK + 50% azolla compost application regarding grain and biological yields in both the 2019 and 2020 seasons. The increment of rice grain yield could be caused by efficient uptake of N, P and K which enhanced assimilates translocation from the source to the sink. In addition, increased yields can be attributed to greater biological yield and efficient flag leaf chlorophyll (Table 5 and Figure 3). Moreover, improving grain yield of rice can be a result of high carbon efficiency ratios in soil with azolla compost combined with synthetic fertilizers [33]. However, the minimal values of biological yield (16.73 and 18.05 t ha^{-1}) and grain yield (6.86 and 7.11 t ha^{-1}) were obtained from those unfertilized plants during seasonal planting, respectively. Composts made from different feedstocks involve portions of organic C and N that may enhance soil fertility [39,40] and additionally improve enzyme activity and microbial biomass in treated soil [41]. Consequently, azolla compost can enhance soil microbial activity and thus can improve nutrient recycling in treated soil [21]. Based on the previously mentioned advantages for azolla compost, it can be a beneficial source of nutrients for rice fields.

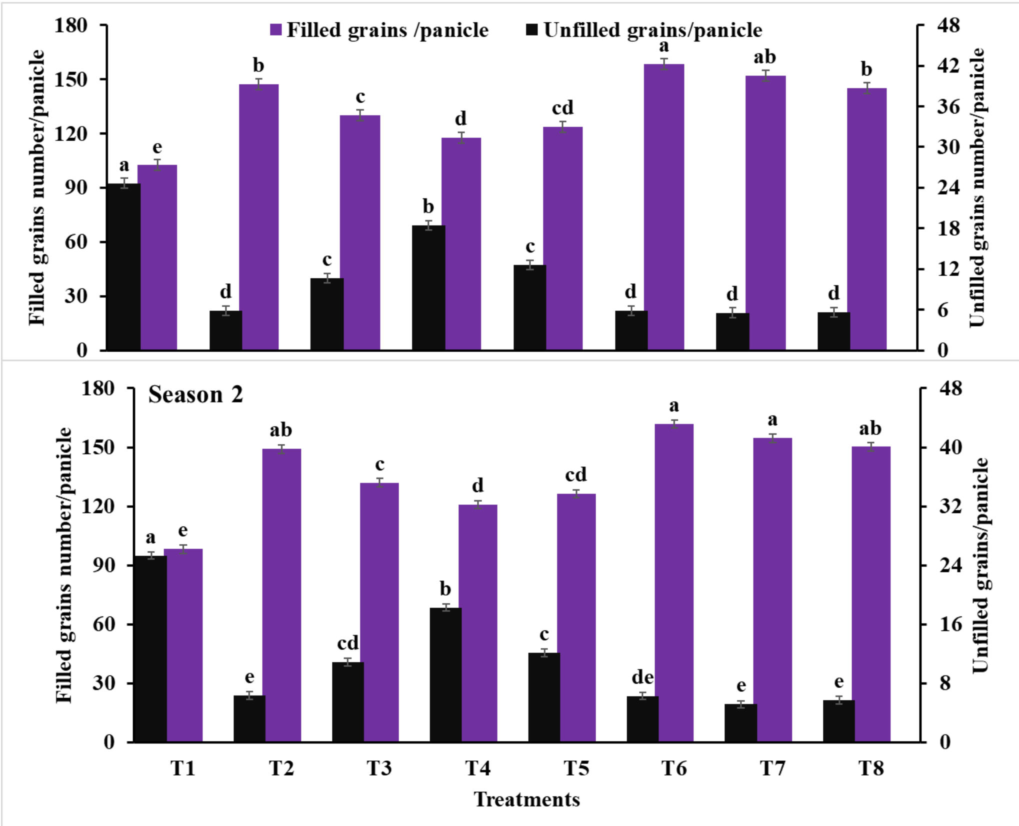

Figure 2. Effects of azolla compost, synthetic fertilizers and their combinations on numbers of filled and unfilled grains/panicle of rice during first (**upper graph**) and second (**lower graph**) growing seasons. For the meanings of T1–T8, please refer to the caption for Figure 1. In each parameter, columns followed by the same letter were not significantly varied at $p \leq 0.05$.

From the given data in this study it can be deduced that azolla compost could help restore adequate nutrient states in the soil under insufficient synthetic fertilizer addition. In general terms, the advanced role of azolla compost under reduced amounts of fertilizers may be caused by its abundance of manifold nutrients (such as N and P nutrients), which feature gradual delivery, organic matter and exchangeable cations [16,42,43]. On the other hand, the addition of azolla compost with a relatively low C/N ratio (about 10) has a rapid-release feature into the soil that enhances the formation of both macro-aggregates and micro-aggregates and additionally increases microbial activity [17,44].

A benign superiority effect on growth traits (relative growth rate, DMP weight, shoot/root ratio, net assimilation rate and LAI) was noted in N-deficient plants versus fully synthetic fertilizer treatment when plants were subjected to foliar application of azolla extract 10% (2.41 g L^{-1}) as mentioned by [45]. These findings concur with those of [21] who asserted that the application of azolla compost yielded evident increases in both plant height (initiated from 21 days after sowing till the harvest) and DMP per plant, and that it could be a proper substitute for urea fertilizer.

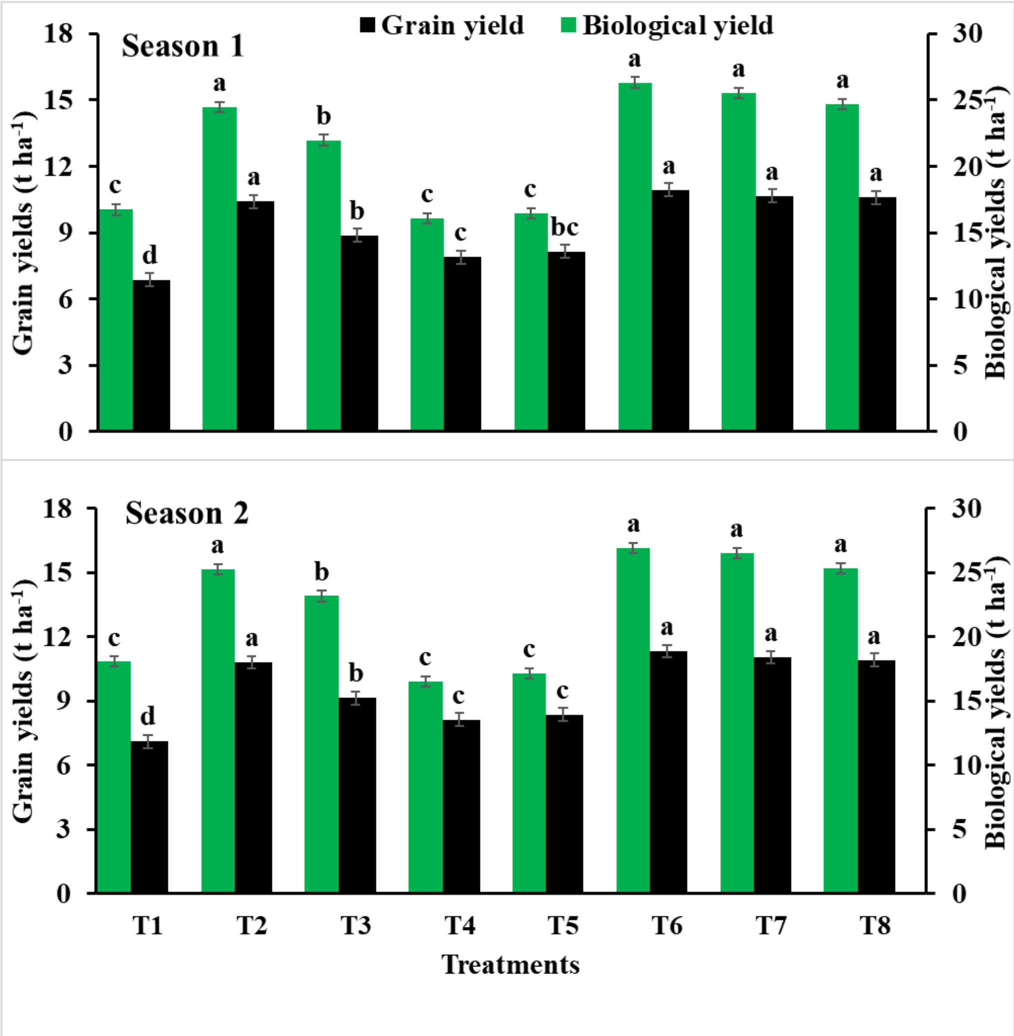

Figure 3. Effects of azolla compost, synthetic fertilizers and their combinations on grain and biological yields of rice during two growing seasons. For the meanings of T1–T8, please refer to the caption for Figure 1. In each parameter, columns followed by the same letter were not significantly varied at $p \leq 0.05$.

Taking that into consideration, reproductive tiller per unit area is a crucially significant morpho-physiological character of paddies that is considered to be a high N content indicator in cultivated soil [46,47]. Furthermore, the spike-bearing numbers/unit area, filled grains number and spike weights are the main determining components for obtaining high grain quantities [48]. In this context, nutrient-enriched soil may pave the way to produce and translocate the pre-sorted assimilates output from source to sink, reflecting an appreciable betterment in yield-causative components such as panicle characteristics (weight and length), percentages of full grains and 1000-grain weights [49,50]. On this basis, both 70% NPK+ 30% azolla compost and 40% NPK + 60% azolla compost applications resulted in remarkable progress concerning yield-associated components (Table 6 and Figures 1–3) despite reducing the recommended NPK fertilizer rates to one-third and two-thirds respectively. These striking results are perhaps attributed to the dual effect of organics and inorganics on providing a nutritious soil for plant growth that achieves generational photosynthetic outputs and more efficient distribution to developmental organs. Our findings were in line with those obtained by [51–54].

Overall, vigorous crop growth is an indication of balanced and sufficient nutrient supplies, resulting in improvements in yield-related attributes and grain yield magnitudes as published earlier by [33,46]. Our study reported that the application of azolla compost contributed to high grain productivity (Figure 3) despite decreasing the amount of synthetic fertilizer (NPK) by 60% (40% NPK + 60% azolla compost). This may be a result of the benign effects of azolla compost properties which ultimately reflect enhanced grain output. These results are compatible with [23] who noted a distinctive increase in grain rice output under the application of azolla compost (2 t ha^{-1}) + NPK fertilizer versus the application of inorganics (NPK) only. Moreover, researchers [16] recorded improvements of rice yields and their components values when azolla compost (5% of soil weight) was applied to the soil underlying water deficiency conditions. Similar findings were obtained by [51] who found benign grain production when cultivated soil was treated with an azolla compost application (at the rate of 5 t ha^{-1}) under a low level of N inorganics treatments.

3.3. Effects of Azolla Compost, Synthetic Fertilizers and Their Combinations on Nutrient Uptake

From all the resultant data, the means of N, P and K uptake in rice grains responded positively to applications of several rates of NPK synthetic fertilizer, azolla compost and their combinations (Figure 4) in both planted seasons. In each season, the 50% NPK + 50% azolla compost application increased accumulated N uptake values by 18.1 and 14.6% compared to 100% NPK, respectively. Nevertheless, in the 2019 and 2020 seasons there were no noticeable statistical differences among 50% NPK + 50% azolla compost, 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost treatments. The same trends were observed concerning the P nutrient uptake values in the 2019 season wherein the treatment of 50% NPK + 50% azolla compost occupied the top rank with identical statistics to 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost treatments (Figure 4). However, what was witnessed in the 2020 season with the treatment of 50% NPK + 50% azolla compost was statistically similar with the 100% NPK, 100% azolla compost, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost applications. The highest mean value of K uptake was obtained under the 50% NPK + 50% azolla compost treatment (increased by 10.4% and 13.5% versus 100% NPK treatment, respectively) which reached statistical conformity with 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost treatments in both seasons. Across both consecutive seasons, the lowest values of N, P and K uptake were obtained from unfertilized plants.

Concerning nutrient uptake (N, P and K) in rice straw, various treatments of NPK synthetic fertilizer, azolla compost and their combination resulted in significant effects on the examined data (Figure 5). Again, in each season, the treatment of 50% NPK + 50% azolla compost occupied the highest rank in enhancing N nutrient uptake by 14.0% and 13.4% compared to 100% NPK, respectively, in rice straw. However, in the 2019 season, no significant differences were observed among the 50% NPK + 50% azolla compost, 100% NPK, 100% azolla compost, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost treatments; however, in the 2020 season the treatment of 100% NPK (full recommended synthetic fertilizers) and 100% azolla compost occupied quadratic levels for N uptake characteristics. A similar trend with the same treatment (50% NPK + 50% azolla compost) was recorded concerning P uptake characteristics which represented the highest increases by 20.2 and 17.5% versus 100% NPK treatment, respectively, in the first and second seasons. In the 2019 season, application of 50% NPK + 50% azolla compost yielded statistically identical results with 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost treatments; however, in the 2020 season there was a statistical match with 50% NPK + 50% azolla compost, 70% NPK + 30% azolla compost, 40% NPK + 60% azolla compost and 100% NPK (Figure 5). Also, the 50% NPK + 50% azolla compost treatment rendered the maximum improvement in K uptake values in comparison to 100% NPK (19.6% and 17.9%, respectively, in both seasons). Meanwhile, across both seasons 50% NPK + 50% azolla compost presented a statistical match with 100% NPK, 70% NPK + 30% azolla compost and 40% NPK + 60% azolla compost treatments. On the contrary, large declines were more predominant for the uptake values of N, P and K nutrients in rice straw of unfertilized plants (control treatment).

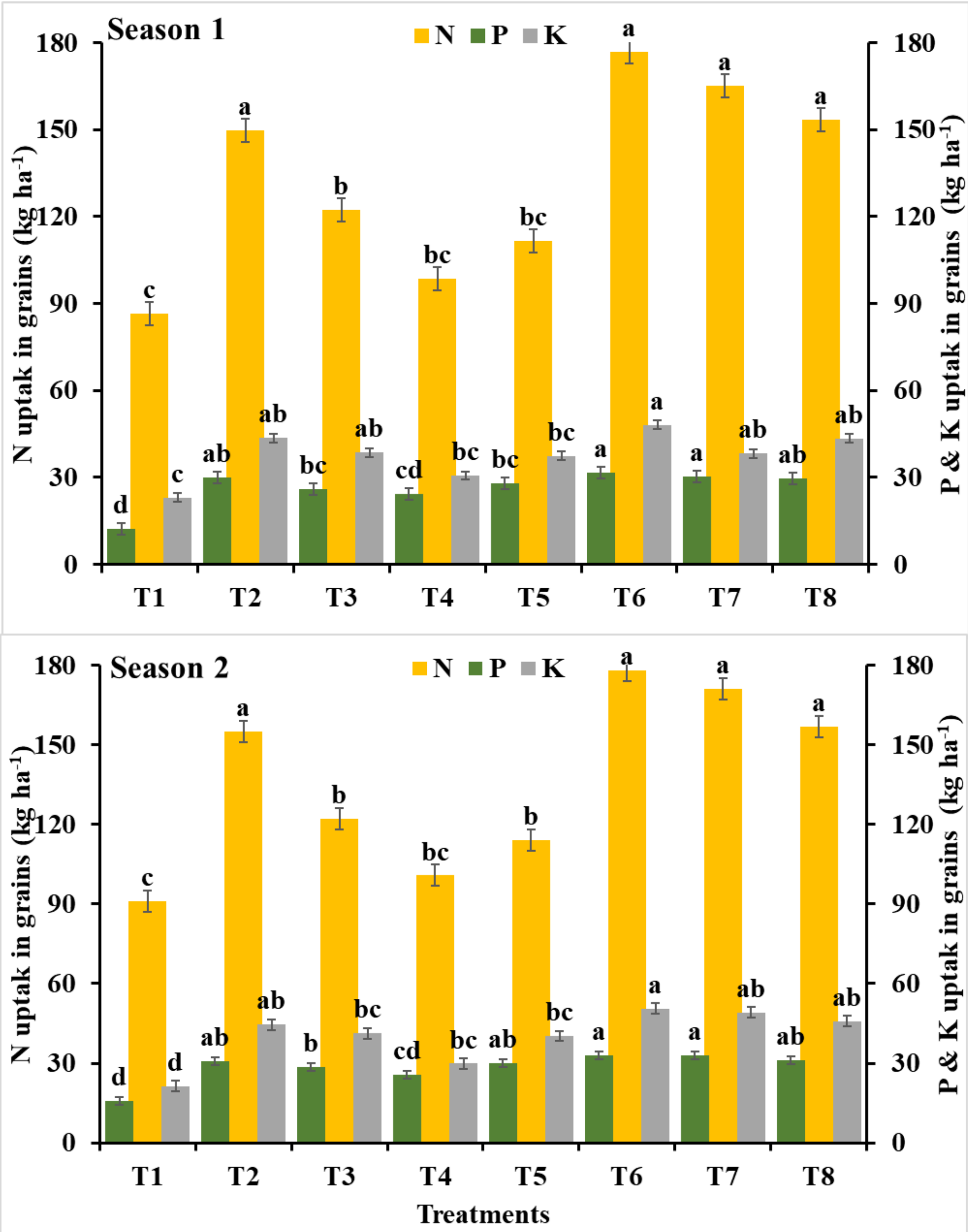

Figure 4. Effects of azolla compost, synthetic fertilizers and their combinations on the uptake of NPK (kg ha^{-1}) by rice grains during both seasons of 2019 and 2020. For the meanings of T1–T8, please refer to the caption for Figure 1. In each parameter, columns followed by the same letter were not significantly varied at $p \leq 0.05$.

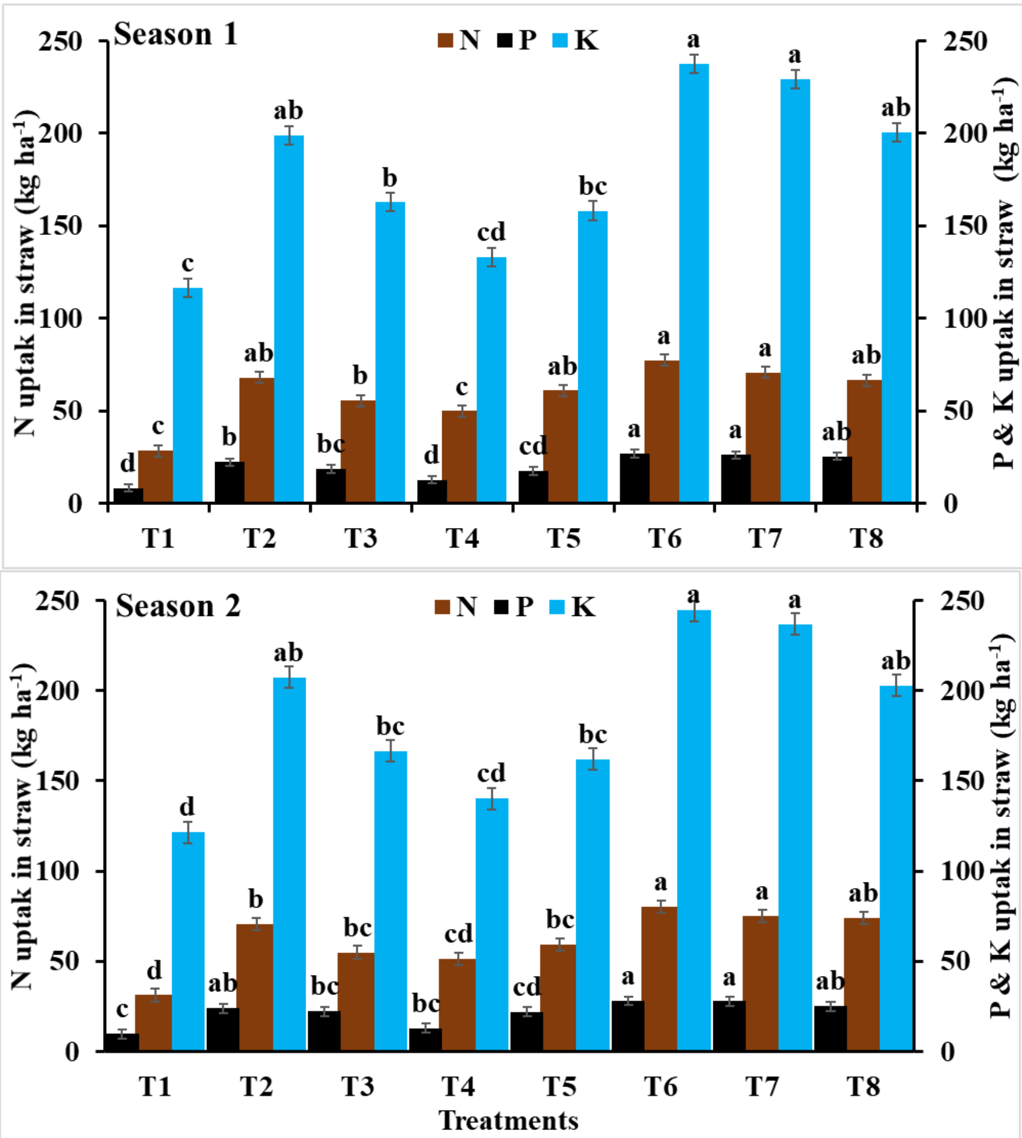

Figure 5. Effects of azolla compost, synthetic fertilizers and their combinations on the uptake of NPK (kg ha^{-1}) by rice straw during both seasons of 2019 and 2020. For the meanings of T1–T8, please refer to the caption for Figure 1. In each parameter, columns followed by the same letter were not significantly varied at $p \leq 0.05$.

From the above discussion, the induction of replenishing plant nutrient uptake is possibly related to the facilitation, richness and adequate nutrients provided by azolla compost applications. Much prior research has articulated the effects of azolla compost applications on nutrient uptake in both rice grain and straw parts. One of these articles documented by [51] noted the highest accumulation amounts of N uptake in both straw and grain parts under azolla compost-treated plots at a rate of 5 t ha^{-1}. Moreover, the authors of [55] indicated that applying azolla compost (at the rate of 5 t ha^{-1}) resulted in increases of available nitrogen and phosphorus (N and P) in cultivated soil which was reflected positively in the enhanced content of both of nutrients inside paddy plants. Similarly to findings in this study, other researchers [56] pointed to the progressive state of N uptake (till 200 kg ha^{-1}) when accompanied by the use of biological and synthetic fertilizers. Furthermore, the authors of [57] asserted that a co-applied amount of half synthetic fertilizer and azolla compost (5 t ha^{-1}) resulted in a remarkable increase in NPK uptake values in corn plants compared to using recommended chemical fertilizer doses, as well as improved soil fertility.

Notably, the addition of azolla improved both N uptake and N-use efficacy, and also reduced N loss in rice plants over the sole application of urea [37]. On the other hand, using azolla compost can provide a continued and slow-release case of both soil ammoniacal nitrogen (NH^{+} -N) and nitrate-nitrogen (NO_3-N) in comparison to the release of these by urea alone [21,58]. Overall, the addition of organic fertilizers results in improved acquisition of NPK nutrients; in contrast, using synthetic fertilizers (as a full recommended dose) is a corollary to achieving NPK status in both plants and their cultivated soil. Moreover, the addition of organic fertilizers can substantially decrease the amounts of synthetic fertilizer required [49,59,60].

4. Conclusions

Azolla compost contains valuable nutrients and therefore is a sustainable soil amendment due to its effects on agronomic aspects. Azolla compost has the potential to reduce the use of NPK synthetic fertilizers by 60% when compared to synthetic fertilizers treatments. Applications of azolla compost in combinations with NPK synthetic fertilizer enhanced rice growth which reflected positively on yield-related components and final grain yields, as well as in nutrient uptake in grains and straw. For instance, the highest grain yields achieved by the applications of 50% NPK + 50% azolla compost (11.13 t ha^{-1}) and 40% NPK + 60% azolla compost (10.76 t ha^{-1}) were without significant differences with the application of 100% NPK (10.60 t ha^{-1}). The lowest grain yield (6.98 t ha^{-1}) was obtained from unfertilized plants. Future investigations are needed for the long-term evaluation of azolla compost as an individual treatment or in combination with other organic amendments in organic farming systems.

Author Contributions: Conceptualization, O.M.E., A.M.N., M.F.S., S.A.E.-l. and A.H.A.M.; data curation: A.H.A.M., B.A.A. and L.B.; investigation: O.M.E., A.M.N., M.F.S., S.A.E.-l., L.B. and B.A.A.; methodology: O.M.E., A.M.N., M.F.S., S.A.E.-l. and A.H.A.M.; resources: O.M.E., A.M.N., M.F.S. and S.A.E.-l.; software: M.F.S., L.B., O.M.E. and A.H.A.M.; writing—original draft: O.M.E., A.M.N., M.F.S. and S.A.E.-l.; writing—review and editing: O.M.E., A.M.N., M.F.S., L.B., S.A.E.-l., B.A.A. and A.H.A.M. 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.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are presented within the article.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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