agronomy

Article

Injected Anhydrous Ammonia Is More Effective Than Broadcast Urea as a Source of Nitrogen for Drill Seeded Rice

Elsayed Naeem [1], Taher Abd El-Megeed [1], Yasmin Emadeldin [2], Asmaa M. Abushady [3,4] and Mohamed Abdelrahman [1,*]

[1] Rice Research and Training Center, Field Crops Research Institute, Agricultural Research Center, Kafrelsheikh 33717, Egypt; naeemlab72@yahoo.com (E.N.); taher_mohamed69@yahoo.com (T.A.E.-M.)
[2] Agricultural Economics Research Institute, Agricultural Research Center, Cairo 12627, Egypt; jasmin_agri_eco@yahoo.com
[3] School of Biotechnology, Nile University, Giza 41516, Egypt; aabushady@nu.edu.eg
[4] Department of Genetic, Faculty of Agriculture, Ain Shams University, Cairo 11566, Egypt
* Correspondence: abdelrahman.rrtc@gmail.com

Abstract: Anhydrous ammonia is a cheaper source of nitrogen (N) fertiliser than granular urea for rice production, but it is not widely used in developing countries. It can only be applied pre-crop with any in-crop applications being applied in the form of urea. This 2-year study conducted in the Nile delta region of Egypt compared pre-crop anhydrous ammonia injected to a depth of 20 cm with broadcast urea as N sources for rice, along with 4 combinations of pre-crop ammonia and in-crop urea. Each treatment supplied a total of 165 kg N/ha. The rice crop was direct seeded rather than transplanted. The highest yields were achieved in the full anhydrous ammonia treatment, which yielded 53% more grain than the nil-N control, while the full urea treatment yielded 22% more than the control; most combination treatments were intermediate. The higher grain yield of the anhydrous ammonia treatment was through a higher panicle density per unit area and more filled grains per panicle. An economic analysis found that the anhydrous ammonia treatment had a net return 70–94% higher than supplying the same quantity of N as urea. Counts of bacteria, fungi and actinomycetes showed a decline by day 2 after injection of anhydrous ammonia, followed by an increase to numbers similar to or above pre-injection levels by day 5. The findings indicated that pre-crop anhydrous ammonia in rice is both economically promising and not deleterious to soil microbes.

Keywords: grain yield; economic analysis; net income; rice; sustainable agriculture; food security

Citation: Naeem, E.; Abd El-Megeed, T.; Emadeldin, Y.; Abushady, A.M.; Abdelrahman, M. Injected Anhydrous Ammonia Is More Effective Than Broadcast Urea as a Source of Nitrogen for Drill Seeded Rice. *Agronomy* **2022**, *12*, 942. https://doi.org/10.3390/agronomy12040942

Academic Editors: Djamilia Skripnuk and Gulnara Romashkina

Received: 6 March 2022
Accepted: 8 April 2022
Published: 14 April 2022

1. Introduction

Globally, rice crops consume around 21–25% of the total world N fertilizer [1]. However, its use efficiency is very low, and the rest of the unconsumed N fertilizer is lost through surface runoff, volatilization or leaching, causing deleterious effects on the environment [2,3]. Additionally, N fertilizer prices have become a burden on farmers' cash-flow during the last decade, affecting their net income. Therefore, exploring effective opportunities to increase production without N fertilizer losses that cause environmental penalties has become a priority for sustainable agriculture production, particularly for the rice crop [4,5].

Acute shortage of labour for paddy rice transplanting has increased the need for direct seeding as an economic solution for growing rice [6]. Direct seeding increases the possibility of mechanizing the crop cultivation. Accordingly, the direct seeded rice planting method is considered a future avenue for increasing rice productivity with lower production costs than transplanted rice [7]. However, the yield is lower under direct seeding than transplanting [6]. There is therefore a need for agronomic research to close the gap between directly seeded and transplanted rice yields.

The development of efficient N management practices could enhance yield production under direct seeded planting and minimise the cost as well as reduce fertilizer losses.

There are several forms of N fertilizers, such as dry urea pellets (46% nitrogen), which is one of these forms and considers the most common forms of N applied to rice fields. Anhydrous ammonia (NH_3) injected in rows below the soil surface prior to crop planting is another form that could be used with the advantage of using a tractor for its application. Anhydrous ammonia has the highest nitrogen content (82%) and the lowest cost per unit of N relative to any other commercial N fertilizer [8]. Furthermore, it is considered the most commonly applied N fertilizer in the United States during the last few years [9]. There are three known processes responsible for the retention of anhydrous NH_3. These processes are NH_4 adsorption onto negatively charged clay minerals, NH_3 absorption by soil organic matter and biological immobilisation of NH_4 by heterotrophic micro-organisms [10–12], some of which may be released to the crop during the growing season [13].

Furthermore, the soil microorganisms contribute to the availability of nutrients for crop production during the growing season [13]. During the last few years, several attempts had been made to optimize the utilization of anhydrous ammonia in rice fields. High profitability from the utilization of anhydrous ammonia was reported when applied to different varieties using transplanting method [14]. The application of anhydrous ammonia has a considerable effect of increasing water use efficiency and saving water, which significantly increased rice yield under water-deficit stress. In the current investigation, we explored the efficacy of anhydrous ammonia in increasing rice grain yield under direct seeding relative to urea. The study also assessed the effect of ammonia injection on soil organisms. This report is intended to support researchers in increasing the utilization of anhydrous ammonia with the directly seeded plantation method in a manner that increases net income for farmers without compromising soil microorganisms.

2. Materials and Methods

2.1. Experimental Site and Soil Properties

Two field experiments were conducted at the experimental farm (31°05′39.8″ N 30°55′13.4″ E) of the Rice Research and Training Center, Sakha, Kafrelsheikh, in the Nile River Delta of Egypt during the rice growing seasons of the years 2017 and 2018. The climate during the rice cropping season was characterized by high temperatures with no rainfall. The soil properties of the two locations were assessed by analysing representative soil samples following the procedures described by [15]. The soil texture of both experiments was clayey with 1.65% organic C at the 2017 site and 1.5% at the 2018 site, and pH 8.05 and 8.2, EC 2.0 and 2.05 dS/m, 13.5 and 12.6 mg/kg NH^{4+} and 10 and 11.8 mg/kg NO_3, respectively.

2.2. Experimental Design and Management

In both seasons, the newly developed high-yielding indica japonica genotype cv. Giza179 (*Oryza sativa*) was utilized in this investigation. For N fertilizer management and sustainability, two different forms of nitrogen fertilizer, namely, urea and anhydrous ammonia, were tested. The 7 different treatments included N as surface-applied urea (T1), anhydrous ammonia (T2), 4 combination treatments (T3 to T6) and an unfertilised control (T7) (Table 1). All the N treatments received a total of 165 kg N/ha. For the treatments with anhydrous ammonia (82% N) application, the fertilizer was injected into the dry soil at a depth of 20 cm 5 days pre-planting by a blade applicator prior to levelling the soil. For treatments with urea (46% N), the fertilizer was surface-applied in 3 equal applications: one-third 25 days after sowing, one-third at 40 days from sowing and the last one-third at panicle initiation. A randomized complete block design arrangement was used with three replications.

Full dose of phosphorus 36.89 kg P_2O_5 ha^{-1} as a superphosphate (15%) was applied as a basal dose before the first ploughing (plowing) and incorporated well into the soil. Potassium was applied as a foliar application at the rate of 2% as potassium sulphate. The first dose was applied after 15 days of the sowing date while the second dose was applied 30 days after the sowing date. All intercultural operations were performed carefully. A thin layer of water (3–5 cm) was kept on the plots from 25 days after sowing until 20 days after the completion of heading. Crop performance under different treatments for leaf area index at heading stage, while measurements at harvest, including dry matter (g m^{-2}), plant height (cm), number of tillers per m^2, number of panicles per m^2, panicle weight (g), number of filled grain per panicle, number of unfilled grains per panicle and 1000-grain weight (g), were assessed. The yield of each plot was harvested separately at full maturity. Plant samples were collected from each plot for the collection of data on plant characters and yield components. The grain and straw yield weight for each plot were recorded after proper sun drying and then converted into ton ha^{-1}. The grain yield is reported for 14% moisture level.

Table 1. Treatments, doses, forms, methods and timing of nitrogen application.

Treatments	N kg ha^{-1}	Forms of Nitrogen	Methods and Time of Application
T1: Urea	165	Urea	Three splits (1/3 basal + 1/3 after two weeks of sowing date + 1/3 at panicle initiation)
T2: NH_3	165	Anhydrous ammonia	Injected into soil 5 days before sowing date
T3: NH_3 + 1/4 urea @ PI	165	Anhydrous ammonia + Urea	3/4 N injected into soil 5 days before sowing date + 1/4 N as urea at panicle initiation
T4: NH_3 + 1/4 urea @ booting	165	Anhydrous ammonia + Urea	3/4 N injected into soil 5 days before sowing date + 1/4 N as urea at late booting
T5: NH_3 + 1/2 urea @ PI	165	Anhydrous ammonia + Urea	1/2 N injected into soil 5 days before sowing date + 1/2 N as urea at panicle initiation
T6: NH_3 + 1/2 urea @ booting	165	Anhydrous ammonia + Urea	1/2 N injected into 5 days before sowing date + 1/2 N as urea at late booting
T7: Nil control	0	—	—

2.3. Statistical Analysis of the Phenotypic Data

Data were analysed by analysis of variance using SAS (version 9.1, SAS Institute, CARY, NC, USA). Differences among the treatment were further compared by multiple comparison tests using Duncan's Multiple Range Test (DMRT) [16].

2.4. Biological Screening of Soil Active Microorganisms' Populations

Soil samples were collected 3 different times in the treatment of full anhydrase ammonia (before treatment, 2 and 5 days after treatments) for the assessment of biological soil microorganisms' activities. Microorganism populations were assessed by dilution plate count technique using specific media for each group of soil microorganism. The total count of microorganisms was determined using soil extract agar for bacteria [17], Martin's medium for Fungi [18] and Jensen's medium for counting soil actinomycetes [19].

2.5. Economic and Net Income Analysis

The economic analysis was conducted based on the collected grain and straw yield data from the treatments. The operation of adding fertilizers costs were kept during the conducting of the two seasons experiments. Other average production costs, rent and prices were collected from unpublished reports of the economic agricultural affairs sector at the Ministry of Agriculture and land reclamation 2017 and 2018 reports. Anhydrous ammonia application was priced at 1207.0 EGP ha^{-1} for the 165 kg N ha^{-1} rate, whereas the full urea treatment was priced at 1434.76 EGP ha^{-1} spread. Anhydrous ammonia was therefore 16% cheaper than urea per unit of N fertiliser spread. Meanwhile, the straw and grain values were 3500 and 35.0 and 3550 and 36.0 EGP ha^{-1}, respectively, for the two seasons. The calculations and economic analysis were conducted based on the formulas stated in [20].

3. Results

3.1. Growth Characteristics Response to the Different N Treatments

In both years, the full anhydrous ammonia treatment (T2) had the greatest biomass at harvest, as well as for leaf area index and plant height at 10 days after heading, the control (T7) had the lowest values and the urea and partial anhydrous ammonia treatments were intermediate (Figure 1, Supplementary Table S1). Among the partial ammonia treatments, it was more effective when urea was applied at the panicle initiation stage than at booting. The same ranking of treatments was also found for the tiller number and the panicle number m^{-2} (Figure 2, Supplementary Table S2).

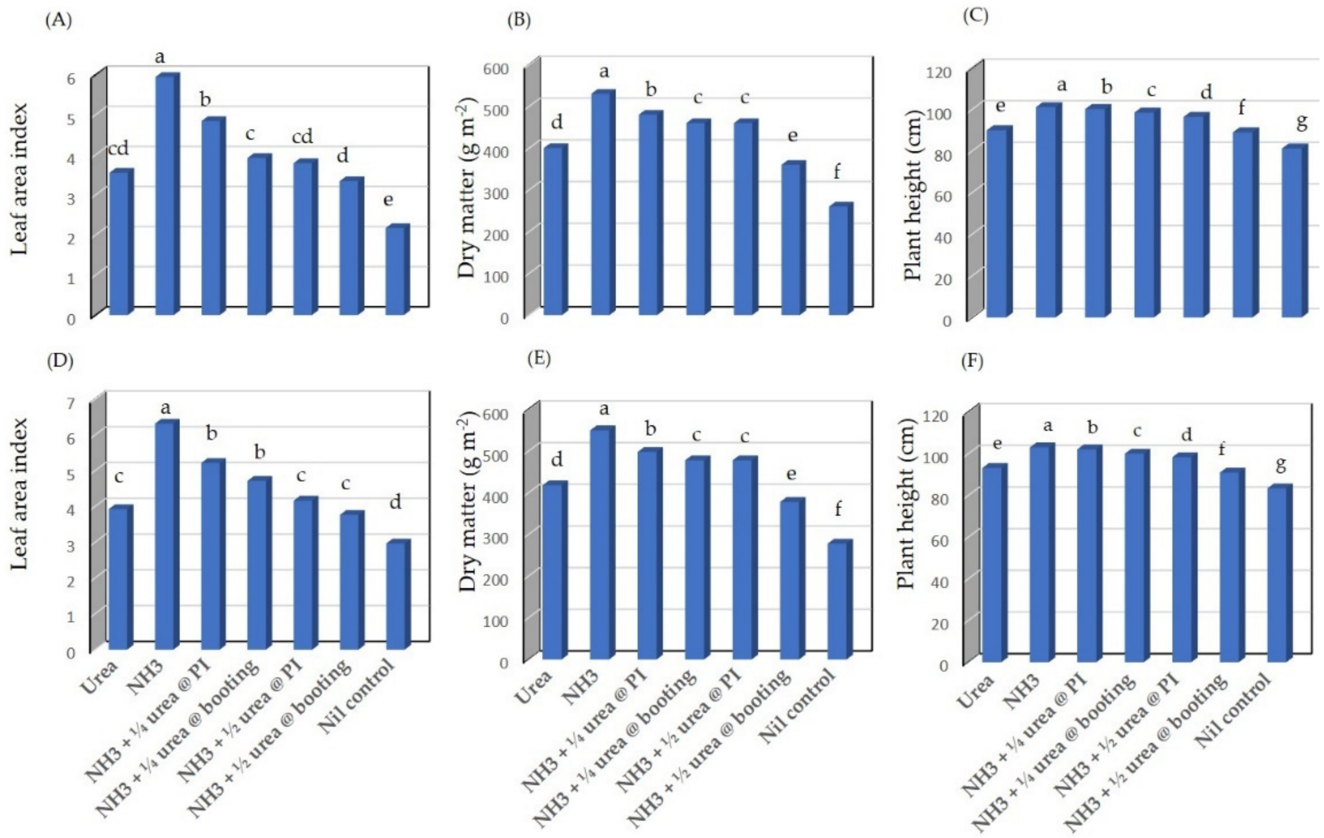

Figure 1. Rice growth characteristics as affected by different N treatments, described in Table 1. Leaf area index: (**A**,**D**); Dry matter (g m^{-2}): (**B**,**E**); and plant height (cm): (**C**,**F**) for the seasons 2017 and 2018, respectively. Values followed by different letters (a, b, c, d, e, f, g) are significantly different according to Duncan's significant difference $P < 0.05$.

3.2. Panicle Characteristics and Yield Attributes as Affected by Different N Treatments

It was observed that the full dose of anhydrous ammonia significantly increased panicle characteristics for panicle weight and filled grain number per panicle in both years (Figure 3, Supplementary Table S3), while, for the unfilled grain number per panicle, the best records for the two seasons were recorded where no nitrogen application was applied (1.60 and 3.60 for the two seasons, respectively). Moreover, no nitrogen application (T7) and the N treatment with half doses of urea and anhydrous ammonia (T6) have the highest values for 1000-grain weight.

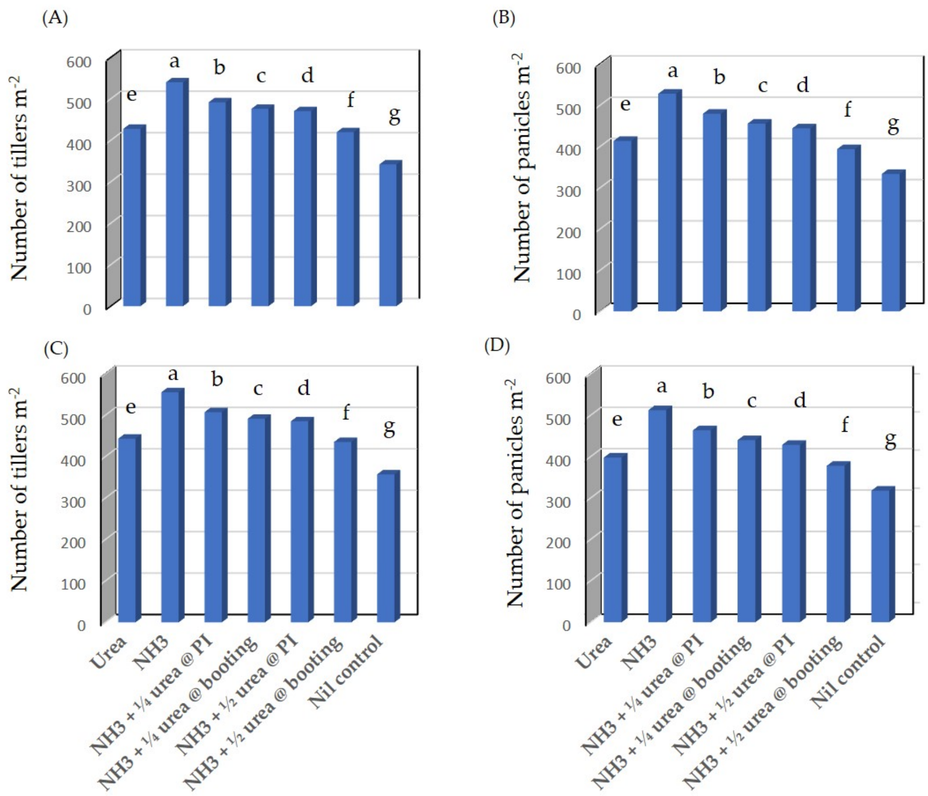

Figure 2. Rice number of tillers (**A**,**C**) and panicles (**B**,**D**) as affected by the different N-treatments described in Table 1 for the seasons 2017 and 2018, respectively. Values followed by different letters (a, b, c, d, e, f, g) are significantly different according to Duncan's significant difference P < 0.05.

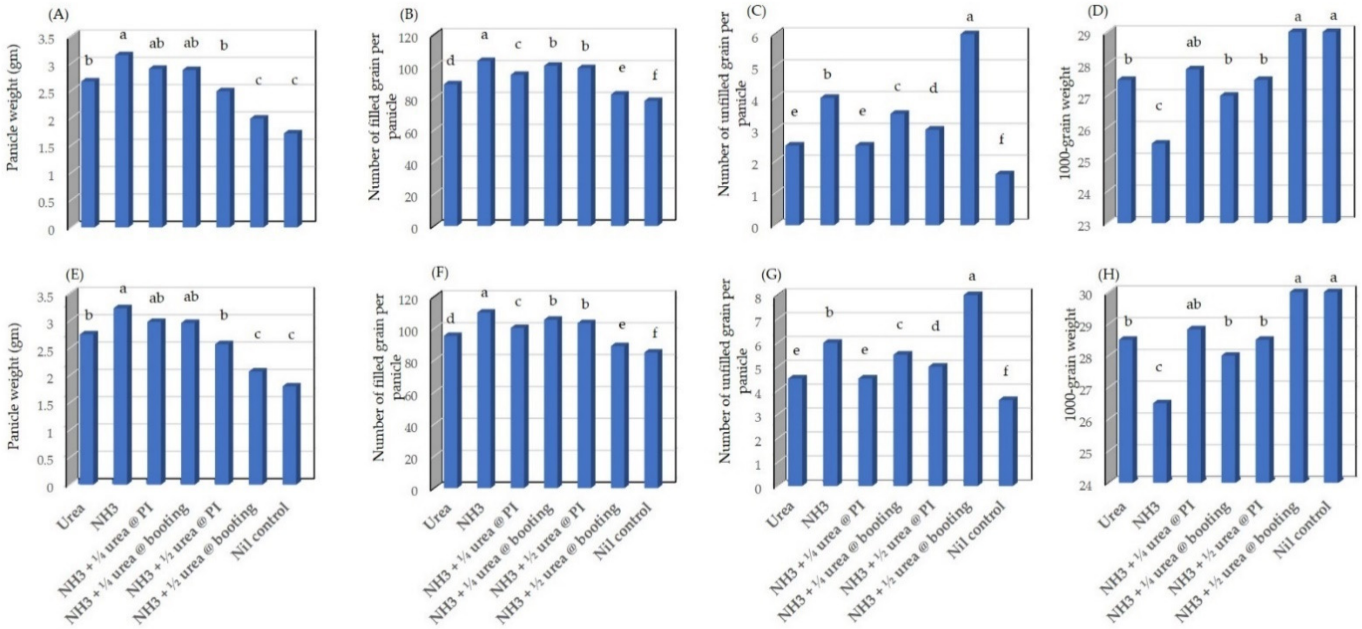

Figure 3. Yield related attributes as affected by the different N-treatments described in Table 1: (**A**,**E**): panicle weight; (**B**,**F**): number of field grain per panicle (g m^{-2}); (**C**,**G**): number of unfilled grains per panicle; and (**D**,**H**): 1000-grain weight (g) for the seasons 2017 and 2018, respectively. Values followed by different letters (a, b, c, d, e, f, g) are significantly different according to Duncan's significant difference P < 0.05.

3.3. Grain Yield and Straw Production in Response to Different N Treatments

Obviously, the full dose of anhydrous ammonia recorded the highest value for both grain and straw yield (Figure 4, Supplementary Table S4). However, the statistical data analysis indicated that the values of treatments (T2) and (T3), where a full dose of anhydrous ammonia application and three-quarters of nitrogen as anhydrous ammonia + one-quarter nitrogen as urea at panicle initiation application, respectively were statistically similar during the two seasons under study. Furthermore, the partial anhydrous ammonia treatment. Zero nitrogen treatment (T7) records were the lowest for grain and straw yield during the two seasons under study.

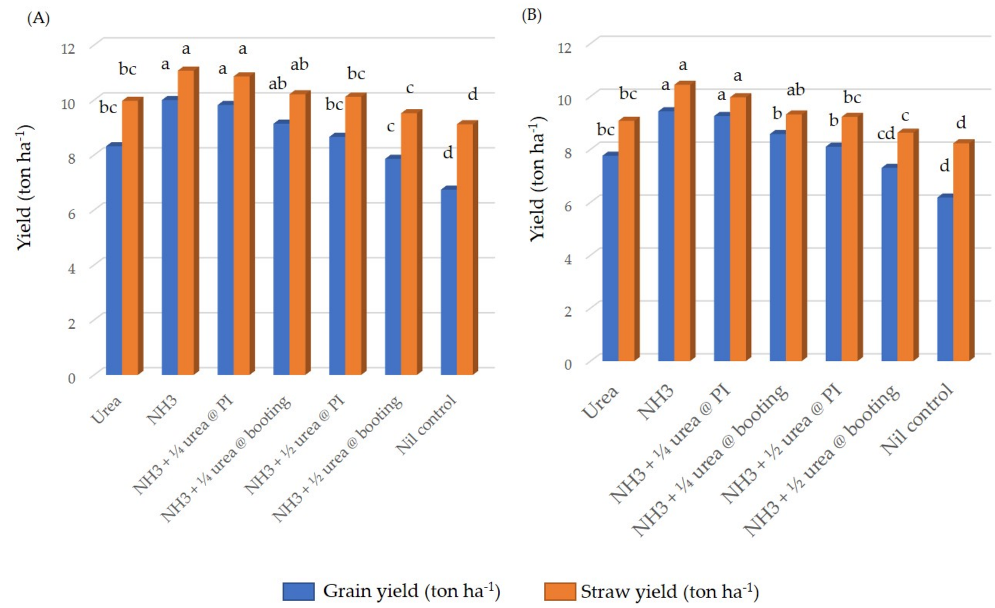

Figure 4. Grain (blue-coloured column) and straw (orange-coloured column) yields as affected by the different N-treatments described in Table 1 for the seasons 2017 (**A**) and 2018 (**B**). Values followed by different letters (a, b, c, d, e, f, g) are significantly different according to Duncan's significant difference $P < 0.05$.

3.4. Economic Analysis of the Increased Yield and Total Revenue as Impacted by the Different N-Treatments

The highest gross and net economic returns were achieved with the full anhydrous ammonia treatments (Table 2), followed by most of the partial treatments. Among these treatments, returns were higher when a higher proportion of N requirements were supplied by pre-crop anhydrous ammonia, and when the balancing urea was supplied at panicle initiation rather than booting.

Table 2. Economic analysis of the different N fertilizer treatments.

Treatments	**Yield Increase (%)**		**Grain Value (EGP ha^{-1})**		**Total Revenue (EGP ha^{-1})**		**Net Return (EGP ha^{-1})**	
	2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Nil control	-	-	21,630	23,927	21,918	24,255	2723	5060
Urea	25.6	23.4	27,160	29,536	27,478	29,895	6697	9115
NH_3	52.8	48.4	33,040	35,500	33,405	35,899	13,003	15,496
$NH_3 + \frac{1}{4}$ urea @ PI	49.8	45.7	32,410	34,861	32,759	35,252	12,250	14,743
$NH_3 + \frac{1}{4}$ urea @ booting	38.8	35.6	30,030	32,447	30,356	32,815	9847	12,306
$NH_3 + \frac{1}{2}$ urea @ PI	31.1	28.5	28,350	30,743	28,673	31,107	8057	10,492
$NH_3 + \frac{1}{2}$ urea @ booting	18.1	16.6	25,550	27,903	25,852	28,246	5236	7630

3.5. Impact of Anhydrous Ammonia on the Populations Count of Soil Microorganisms

The mean values of bacteria, fungi and actinomycetes population counts of the two successive seasons under study combined are presented in Figure 5. The population counts of bacteria, fungi and actinomycetes had decreased by day 2 after injection of ammonia, but by day 5, bacterial and fungal counts had surpassed their count prior to injection.

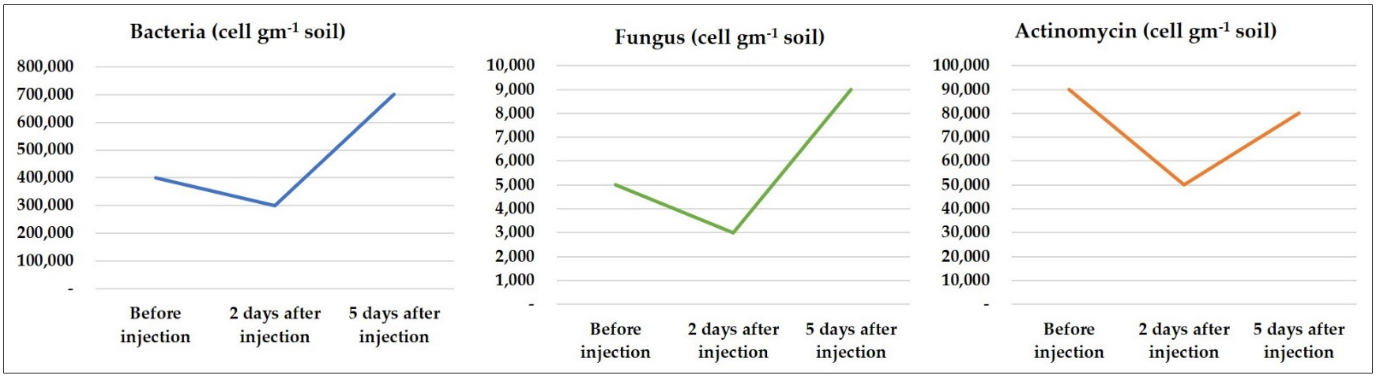

Figure 5. Active microorganisms' populations count during different times before and after treatments.

4. Discussion

Rice is considered one of the most labour-intensive field crops. In the last few years, there has been a gradual decrease in the availability of labourers, which increases the wages paid for labourers incorporated in the agriculture sector in the countries where rice is cultivated [21]. Moreover, N fertilizer application cost becomes a burden on the farmers. In the current study we aimed at investigating the incorporation of the fertilizers with the advantage of possible mechanization as well as to generate the best income for the farmers.

4.1. Anhydrous Ammonia Increased Reproductive Tillers and Enhanced Plant Growth Characteristics

The results indicate that the full dose of anhydrous ammonia significantly provides higher tillering ability for the rice cultivar, which caused a subsequent increase in the number of tillers carrying panicles. The performance of which exceeded even to the treatment with one-half of anhydrous ammonia + one-half urea at panicle initiation. Similar results were obtained by [22], who concluded that the application of anhydrous ammonia has a significant effect on increasing active tillers as compared to the untreated trial.

Furthermore, the presence of an adequate dose of anhydrous ammonia prior to the drill-seeded plantation enhanced the cultivar growth characteristics (plant height, leaf area index and total dry matter values). The addition of urea did not compensate the strength in the growth for the treatments in (T4) and (T5). Previous reports concluded that higher values of the leaf area index have a reasonable association with the rice canopy characteristics such as dry matter and plant height [23–26]. The appropriate application rate of nitrogen ensures that the rice plant canopy will achieve a higher LAI. Leaves are the main organ for the process of photosynthesis; subsequently higher LAI values will increase the photosynthetic capacity [27,28].

4.2. Increased Grain Yield and Yield-Related Characteristics with Full Application of Anhydrous Ammonia

The results indicate that the presence of excess number of tillers increased the number of panicles per unit area with the full dose of anhydrase ammonia. Several investigations reported an increased association between the number of panicles per unit area and grain yield [29–31]. Furthermore, the decrease in anhydrous ammonia fertilizers in the treatments (T3:T6) were accompanied with a reduction in the number of panicles, and the addition of parallel amounts (in the treatments T3:T6) of urea did not compensate for this reduction. Similar results were obtained by [32] when they compared several sources of ammonia fertilizers with urea fertilizer. The full dose of anhydrous ammonia records for number of filled grain per panicle in this study were the highest. These results collectively indicate that the full dose of anhydrous ammonia nitrogen as basal was important for increasing the sink translocation to the grains during the grain filling. Notably, our results indicate that grain yield from anhydrous ammonia was 21.64% higher than the same rate of surface-applied urea. The mechanism of this yield increase was through greater tillering, leading to a higher panicle density and higher records of filled grain number. These results confirm that the injection depth of 20 cm appeared to be deep enough to minimize direct gases losses during injection but also shallow enough for the young rice plants to access during the tillering stage. Moreover, soil moisture content after the winter season and prior to rice crop cultivation was suitable for injection at that depth.

4.3. Economic Impact of the Utilization of Anhydrous Ammonia

Adding N fertilizer in the form of anhydrous ammonia increased most of the yield-related parameters, which finally contributed to potential increase in grain yield. This increase is estimated to be about 52.75% over the no nitrogen treatment. These results were reflected in the economic analysis of the research under study. The costs of fertiliser and application were 24% lower with anhydrous ammonia than urea. The combination of higher yield and lower N cost led to a net economic return from anhydrous ammonia that was 94% higher than urea in 2017 and 70% higher in 2018. Moreover, there was no yield or financial benefit in deferring a portion of the N to an in-crop application. Ref. [14] reported higher net income when anhydrous ammonia application was applied for rice transplanting method.

4.4. Anhydrous Ammonia Did Not Affect the Bacteria, Fungi and Actinomycetes

The existence of a designated treatment that could increase yield and net income for the farmers without side effects on the environment is the key for sustainable agriculture. For this reason, the soil bacteria, fungi and actinomycetes populations were counted in the soil treated with a full dose of anhydrous ammonia. The results indicate that there was a resurgence in the counts of the measured microorganisms. The decrease after 2 days of injection could be attributed to the effect of ammonia, increase in pH and increase in ionic concentration as previously reported by [33,34]. The resurgence in their counts after 5 days could be explained to the rebuilding ability of the microorganisms' populations from the unaffected adjacent area.

5. Conclusions

The form of anhydrous ammonia for supplying rice plants under the direct drill-seeded method with N fertilizer exhibited higher growth characteristics compared to the urea treatment and other treatments combinations. This growth was clearly noticed by higher tillering ability and number of reproduced panicles. Furthermore, the increased number of panicles, filled grain per panicle and panicle weight were the main contributors to the grain yield, which showed around 21.64% and 52.75% yield increases over urea and no nitrogen treatments, respectively. Economically, the injection of a full dose of anhydrous ammonia at basal was higher in terms of total revenue and net return. Nevertheless, treating the soil with such treatment has an immediate effect on the beneficial soil microbe populations, and this effect is localized and not long-lasting. In addition, the utilization of anhydrous ammonia can help solve the problem of late application of fertilizer under drill-seeded rice. The study confidently recommends the full anhydrous ammonia treatment for sustainable rice cultivation, especially with the drill-seeded method.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12040942/s1, Table S1: Growth characteristics of the cultivar Giza179 as affected by different N treatments. Table S2 Number of tillers and panicles for the cultivar Giza179 as affected by the different N-treatments for the seasons 2017 and 2018. Table S3 Performance of Giza179 cultivar for panicle weight (g), number of field grain per panicle, number of unfilled grains per panicle and 1000-grain weight (g) for the seasons 2017 and 2018. Table S4 Grain and straw yields for the cultivar Giza179 as affected by the different N-treatments for the seasons 2017 and 2018.

Author Contributions: Conceptualization, E.N., T.A.E.-M. and M.A.; methodology, E.N. and T.A.E.-M.; software, T.A.E.-M., M.A. and Y.E.; validation, E.N., T.A.E.-M., A.M.A. and M.A.; investigation, T.A.E.-M. and E.N.; writing—original draft preparation, T.A.E.-M., A.M.A. and M.A.; writing—review and editing, E.N. and M.A.; visualization, A.M.A. and M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All the data explained in this paper are available up on request.

Acknowledgments: The authors are grateful to thank all members at RRTC and for the support provided by Field Crops Research Institute, ARC, Egypt.

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

References

1. Prasad, R.; Shivay, Y.S.; Kumar, D. Current status, challenges, and opportunities in rice production. In *Rice Production Worldwide*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 1–32.
2. Ding, W.; Lei, H.; Zhang, J.; Wang, L.; Zhang, J.; Ju, X.; Li, H.; Li, G. One-time N fertilization reduces greenhouse emissions and N leaching while maintaining high yields in a rape-rice rotation system. *Agron. J.* **2021**, *114*, 427–439. [CrossRef]
3. Ma, P.; Lan, Y.; Lyu, T.; Li, F.; Yang, Z.; Sun, Y.; Ma, J. Nitrogen Fate and Efficiency of Fertilizer Application under a Rapeseed–Wheat–Rice Rotation System in Southwest China. *Agronomy* **2021**, *11*, 258. [CrossRef]
4. Abdel-Rahman, M.; El-Denary, M.; Ammar, M.; Abdelkhalik, A.; Draz, A.; Dora, S. QTL validation for grain yield and nitrogen use efficiency under different nitrogen levels in rice. *Egypt. J. Genet. Cytol.* **2015**, *44*, 235–251. [CrossRef]
5. Abdelrahman, M.; Zhao, K. Genome editing and rice grain quality. In *The Future of Rice Demand: Quality Beyond Productivity*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 395–422.
6. Xu, L.; Li, X.; Wang, X.; Xiong, D.; Wang, F. Comparing the grain yields of direct-seeded and transplanted rice: A meta-analysis. *Agronomy* **2019**, *9*, 767. [CrossRef]
7. El-Habet, H.B.; El-Megeed, A.; Hasham, I. Impact of Anhydrous Ammonia and Irrigation Intervals on Rice Yield under Drill Seeded Method. *J. Plant Prod.* **2019**, *10*, 459–468. [CrossRef]
8. Sağlam, C.; Tan, F.; Aktaş, T. Changing of viscosity and thermal properties of olive oil with different harvesting methods and waiting period. *Teh. Glas.* **2018**, *12*, 50–54. [CrossRef]
9. Kovács, P.; Van Scoyoc, G.E.; Doerge, T.A.; Camberato, J.J.; Vyn, T.J. Pre-plant anhydrous ammonia placement consequences on no-till versus conventional-till maize growth and nitrogen responses. *Agron. J.* **2014**, *106*, 634–644. [CrossRef]
10. Jansson, S.; Persson, J. Mineralization and immobilization of soil nitrogen. *Nitrogen Agric. Soils* **1982**, *22*, 229–252.
11. Nommik, H.; Vahtras, K. Retention and fixation of ammonium and ammonia in soils. *Nitrogen Agric. Soils* **1982**, *22*, 123–171.
12. Whiteley, E.L. *An Investigation of Some of the Effects of Anhydrous Ammonia on the Clay Minerals Montmorillonite and Illite*; Texas A&M University: College Station, TX, USA, 1959.
13. Yadav, B.K.; Akhtar, M.S.; Panwar, J. Rhizospheric plant-microbe interactions: Key factors to soil fertility and plant nutrition. In *Plant Microbes Symbiosis: Applied Facets*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 127–145.
14. El-Megeed, A. Effect of Urea and Anhydrous Ammonia Fertilizer on Yield and Yield Component of Rice Plants. *J. Plant Prod.* **2017**, *8*, 425–434. [CrossRef]
15. Cottenia, A.; Camerbynek, R.; Verioo, M.; Dhaere, A. Fractionation and determination on of trace elements in plants. *Soils Sediments Pure Appl. Chem* **1979**, *52*, 145–153.
16. Duncan, D.B. Multiple range and multiple F tests. *Biometrics* **1955**, *11*, 1–42. [CrossRef]
17. Hamaki, T.; Suzuki, M.; Fudou, R.; Jojima, Y.; Kajiura, T.; Tabuchi, A.; Sen, K.; Shibai, H. Isolation of novel bacteria and actinomycetes using soil-extract agar medium. *J. Biosci. Bioeng.* **2005**, *99*, 485–492. [CrossRef] [PubMed]
18. Vieira, F.; Nahas, E. Comparison of microbial numbers in soils by using various culture media and temperatures. *Microbiol. Res.* **2005**, *160*, 197–202. [CrossRef] [PubMed]
19. Allen, O. *Experiments in Soil Bacteriology*; Burgess Publishing, Co.: Minneap, MN, USA, 1959.
20. Debertin, D.L. *Agricultural Production Economics*; CreateSpace Independent Publishing Platform: Scotts Valley, CA, USA, 2012.
21. Duvvuru, N.R.; Motkuri, V. *Declining Labour Use in Agriculture: A Case of Rice Cultivation in Andhra Pradesh*; University Library of Munich: Munich, Germany, 2013.
22. Osman, E.; El-Masry, A.; Khatab, K. Effect of nitrogen fertilizer sources and foliar spray of humic and/or fulvic acids on yield and quality of rice plants. *Adv. Appl. Sci. Res.* **2013**, *4*, 174–183.
23. Din, M.; Zheng, W.; Rashid, M.; Wang, S.; Shi, Z. Evaluating hyperspectral vegetation indices for leaf area index estimation of *Oryza sativa* L. at diverse phenological stages. *Front. Plant Sci.* **2017**, *8*, 820. [CrossRef]

24. Jégo, G.; Pattey, E.; Liu, J. Using Leaf Area Index, retrieved from optical imagery, in the STICS crop model for predicting yield and biomass of field crops. *Field Crops Res.* **2012**, *131*, 63–74. [CrossRef]
25. Maki, M.; Homma, K. Empirical regression models for estimating multiyear leaf area index of rice from several vegetation indices at the field scale. *Remote Sens.* **2014**, *6*, 4764–4779. [CrossRef]
26. Xiong, D.; Wang, D.; Liu, X.; Peng, S.; Huang, J.; Li, Y. Leaf density explains variation in leaf mass per area in rice between cultivars and nitrogen treatments. *Ann. Bot.* **2016**, *117*, 963–971. [CrossRef]
27. Tian, G.; Gao, L.; Kong, Y.; Hu, X.; Xie, K.; Zhang, R.; Ling, N.; Shen, Q.; Guo, S. Improving rice population productivity by reducing nitrogen rate and increasing plant density. *PLoS ONE* **2017**, *12*, e0182310. [CrossRef]
28. Zhang, J.; Tong, T.; Potcho, P.M.; Huang, S.; Ma, L.; Tang, X. Nitrogen Effects on Yield, Quality and Physiological Characteristics of Giant Rice. *Agronomy* **2020**, *10*, 1816. [CrossRef]
29. Huang, M.; Yang, C.; Ji, Q.; Jiang, L.; Tan, J.; Li, Y. Tillering responses of rice to plant density and nitrogen rate in a subtropical environment of southern China. *Field Crops Res.* **2013**, *149*, 187–192. [CrossRef]
30. Li, G.; Xue, L.; Gu, W.; Yang, C.; Wang, S.; Ling, Q.; Qin, X.; Ding, Y. Comparison of yield components and plant type characteristics of high-yield rice between Taoyuan, a 'special eco-site'and Nanjing, China. *Field Crops Res.* **2009**, *112*, 214–221. [CrossRef]
31. Xiong, Q.; Tang, G.; Zhong, L.; He, H.; Chen, X. Response to nitrogen deficiency and compensation on physiological characteristics, yield formation, and nitrogen utilization of rice. *Front. Plant Sci.* **2018**, *9*, 1075. [CrossRef] [PubMed]
32. Chaturvedi, I. Effect of nitrogen fertilizers on growth, yield and quality of hybrid rice (Oryza sativa). *J. Cent. Eur. Agric.* **2005**, *6*, 611–618.
33. Eno, C.F.; Blue, W.G.; Good, J.M., Jr. The effect of anhydrous ammonia on nematodes, fungi, bacteria, and nitrification in some Florida soils. *Soil Sci. Soc. Am. J.* **1955**, *19*, 55–58. [CrossRef]
34. Geisseler, D.; Scow, K.M. Long-term effects of mineral fertilizers on soil microorganisms—A review. *Soil Biol. Biochem.* **2014**, *75*, 54–63. [CrossRef]