Journal of Global Ecology and Environment

Volume 20, Issue 3, Page 1-12, 2024; Article no.JOGEE.12282
ISSN: 2454-2644

Effect of Arbuscular Mycorrhizal Fungi on the growth and Yield of Rice (*Oryza sativa* L.) in Bauchi, Nigeria

Musa Ibrahim [a], Ahmad Abdulhameed [b*], A. J. Nayaya [b] and A. G. Ezra [b]

[a] Department of Biology, University of Maiduguri, P. M. B. 1069, Maiduguri, Borno State, Nigeria.
[b] Department of Ecology, Abubakar Tafawa Balewa University, P. M. B. 0248, Bauchi, Bauchi State, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.56557/jogee/2024/v20i38797

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.ikprress.org/review-history/12282

Original Research Article

Received: 20/05/2024
Accepted: 24/07/2024
Published: 31/07/2024

ABSTRACT

Rice (*Oryza sativa* L.) is one of the most important staple foods considered in many countries around the world, including Nigeria. This aim of the study is to determine the effect of Arbuscular mycorrhizal fungi on the growth and yield of rice. The experiment was conducted in a screen house using a complete randomize design (CRD). Two rice varieties (Nerica and Jamila) were grown in a one litre pods, filled with sterilized soil and three seeds were sown into each pod at a depth of 2 cm until germination, then reduced to one seedling. Different Arbuscular mycorrhizal fungi (AMF) dose (10 g, 20 g, 30 g, and 40 g) was inoculated at the time of seed sowing and non-inoculated pods as control. Various parameters were taken into consideration like plant height, number of leaves,

**Corresponding author: E-mail: gesunnam.aa@gmail.com;*

***Cite as:** Ibrahim, Musa, Ahmad Abdulhameed, A. J. Nayaya, and A. G. Ezra. 2024. "Effect of Arbuscular Mycorrhizal Fungi on the Growth and Yield of Rice (Oryza Sativa L.) in Bauchi, Nigeria". Journal of Global Ecology and Environment 20 (3):1-12. https://doi.org/10.56557/jogee/2024/v20i38797.*

panicle length and panicle number while shoot dry biomass, root dry biomass and yield attributes were taken at harvest. According to the results, the effects on growth indices and yield attributes increases with increased in AMF dose. Although, yield attributes were significantly higher, in the order control<10 g<20 g< 30 g< 40 g. Thus, suggesting the beneficial utilization of AMF as a potential biofertilizer.

Keywords: Oryza sativa L.; arbuscular mycorrhizal fungi; Complete Randomize Design (CRD); biofertilizer.

ABBREVIATIONS

AMF : Arbuscular mycorrhizal fungi
C : Carbon
CRD : Completely randomized design
DSAAT : Digital situational awareness assessment and training
SOM : Soil organic matter
MGR : Mycorrhizal Growth Response
N : Nitrogen
NCRI : National Cereal Research Institute
P : Phosphorus

1. INTRODUCTION

Rice is one of the most vital cereal crops grown in many countries globally, with more than half of the global population depending on it as part of essential family diet [1,2,3,4]. Farmers need to scaled up production in other to meet global market demand for rice. These rising demands for agricultural products has introduced many techniques and processes of attaining higher yield through the use of advanced machineries, synthetic and inorganic fertilizer, improved cultivars and pesticides [5,6,7]. Consequently, multiple constraints arising from policy changes has led to a ban and restriction of many agrochemical brands used by farmers across the country leading to a significant dropped in rice production in recent years. Nevertheless, the effect of synthetic agrochemicals on both humans and the environment due to massive rice cultivation cause great concerned [8]. Therefore, exploring better alternative cultivation method that minimize the use of agrochemicals and synthetic fertilizer becomes necessary towards ameliorating their negative impacts on the environment.

Arbuscular mycorrhizal fungi (AMF)have coexisted with plants in various ecosystems long ago [9]. AMF exist in almost all soils forming symbiotic association between the plant root and the fungi. These symbiotic association is established as the host plant supply the fungi with carbon in the form of sugar and lipid while the fungi supply nutrients, minerals and water to the host plant [10,11,12]. According to Xu et al., [13] revealed that AMF ability to enhance both growth and development through absorption and utilization of required nutrients, essential minerals and water, increase overall plant tolerance to both biotic and abiotic stress, improving soil physical and chemical properties have been reported by many scholars. AMF have positive impact on cell regeneration and root development of the host plant by enhancing the root absorption capacity, thereby maintaining both ion and osmotic balance and also, robust strengthening of the plant antioxidant productive system [14]. The influence of AMF towards reduction of oxidative processes and reducing soil organic matter have led to reduction of the amount of soil based carbon-dioxide (CO_2) emission resulting from organic carbon stock in the soil [14,15,16].

Few research have reported little or no AMF colonization of rice root in paddy field under flood regime [17,18,19] while numerous research have reported the presence of AMF colonisation in paddy field worldwide [20,21,17,22,23]. Therefore, the aim of the study is to determine the effect of arbuscular mycorrhizal fungi on the growth and yield of rice (*Oryza sativa*) in Bauchi, Bauchi State, Nigeria.

2. MATERIALS AND METHODS

2.1 Site Description

The experiment was conducted in the Screen house of Abubakar Tafawa Balewa University in

Bauchi, Bauchi State, Nigeria. The area is lies in the tropical savanna climatic zone between latitude N 10º 16.520' and N 10º 17.02' and longitude E 009º 49.02' and E 009º 49.433'.

2.2 Source of Rice Seeds and AMF Inoculum

Two varieties of rice (Nerica and Jamila) were purchased from National Cereal Research Institute (NCRI), Badeggi, Niger State, Nigeria. Viability test of seeds was carried out according to Goyal et al., [24]. The AMF inoculum was sourced from University of Aberdeen, Department of Biological Sciences, Aberdeen, Scotland.

2.3 Soil Analysis

The pre-planting soil was collected in a transparent Ziplock polythene bag and taken to University of Maiduguri, Department of Soil Science for physical and chemical analysis. The parameters analysed includespH (H_2O), Electrical Conductivity (dsm^{-1}), Exchangeable Acidity (cmol kg^{-1}), Ca^{2+} (cmol kg^{-1}), Mg^{2+} (cmol kg^{-1}), K^+ (cmol kg^{-1}), Na^+ (cmol kg^{-1}), Cation Exchange Capacity (cmol kg^{-1}), Total Exchangeable Base (cmol kg^{-1}), Base Saturation (%), N (%), Organic Carbon (%), Organic Matter (%), Carbon to Nitrogen, Available Phosphorus (mg kg^{-1}), Clay, Sand, Silt, and Texture were all determine according to American Public Health Association (APHA) (2008).

2.4 Experimental Treatment and Design

Different concentration of AMF *Glomus intraradices* (10g, 20g, 30g and 40g) were inoculated and non-inoculated pot as control. The experiment was set-up in a completely randomized design (CRD) using 1 litre pots filled with 5 mm sieved soil. Three rice seeds were planted into each pot at a depth of 2 cm which after germination others were removed, maintaining one at each pot. The inoculation of AMF (10g, 20g, 30g and 40g i.e. average of 40 spores per 10 g) were done at the time of sowing.

2.5 Data Collection

Plant height, number of leaves, panicle length and panicle number were recorded at two weeks intervals while root biomass, shoot biomass, weight of seeds and number of seeds per plant were recorded at harvest i.e. at thirteen weeks.

2.6 Statistical Analysis

Data collected from growth indices (plant height, number of leaves, panicle length, panicle number, root biomass, shoot biomass and yield) were analysed using Data Science and Advanced Analytics Statistics (DSAASTAT) statistical software on Microsoft excel and GraphPad Prism version 8.0 software. The significances of treatment means were determined at $P \leq 0.05$ with Duncan's Multiple Range Test.

3. RESULTS

Fig. 1A shows the number of leaves of *Oryza sativa* variety (Nareca) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between 10g,30g and 40g at harvest. There is significant difference between control (0g), and 30g at harvest and of which 30g has the highest leave number. Fig. 1B shows number of leaves of *Oryza sativa* (Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between 10g, 20g and 30g at harvest. There is significant difference between 40g and other treatments, of which40g has the highest leave number while control (0g) record least number of leaves.

Fig. 2A shows the plant height of *Oryza sativa* variety (Nareca) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between 30g and 40g at harvest. Similarly, there is no significant difference between 10g and 20g at harvest while there is significant difference between control (0g) and other treatments. Fig. 2B shows plant height of *Oryza sativa* (Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between control (0g), 10g, and 20g at harvest. There is no significant difference between 30g and 40g at harvest and 40g has the highest leave number.

Fig. 3 shows the shoot dry biomass of *Oryza sativa* varieties (Nareca-8 and Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF). For Nerica-8, there is no significant difference between 20g, 30g and 40g at harvest while there is significant difference between control (0g) and other treatments. Similarly, Jamila variety shows no significant difference between control (0g), 10g, 20g, and 30g at harvest.

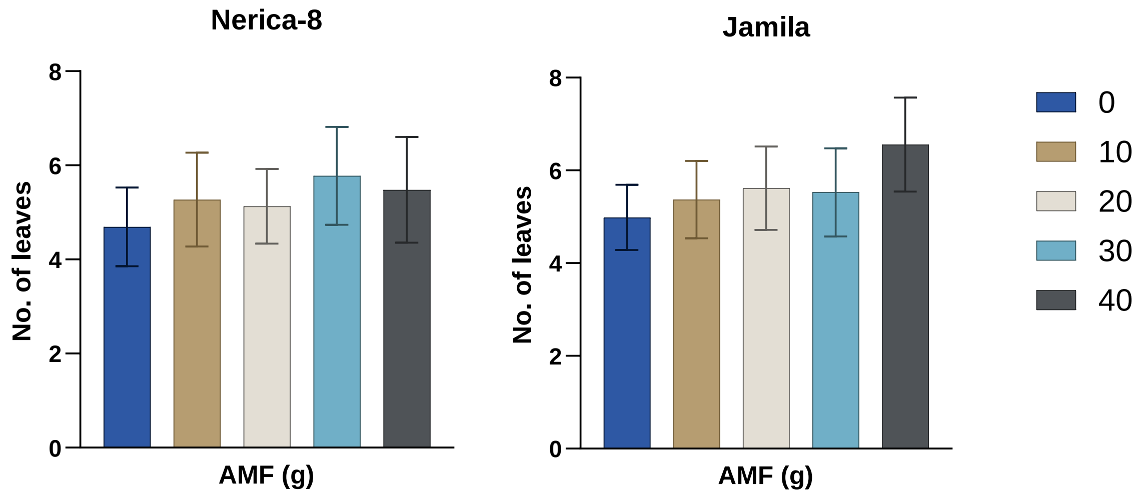

Fig. 1. A - Effect of AMF (*Glomus intraradices)* on number of leaves of *Oryza sativa* (Nerica)B - Effect of AMF (*Glomus intraradices)* on number of leaves of *Oryza sativa* (Jamila)

(A) **(B)**

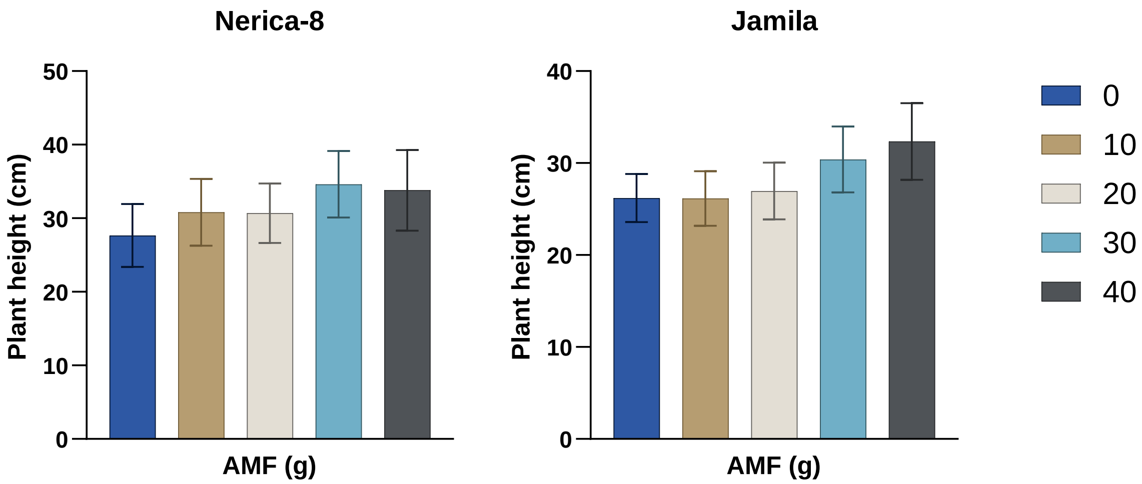

Fig. 2. A - Effect of AMF (*Glomus intraradices)* on plant height of *Oryza sativa* (Nerica)B - Effect of AMF (*Glomus intraradices)* on plant height of *Oryza sativa* (Jamila)

Fig. 4 shows the root dry biomass of *Oryza sativa* varieties (Nareca-8 and Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF). For Nerica-8, the result shows there is no significant difference between 20g, 30g and 40g at harvest while there is significant difference between control (0g), 10g and 20g AMF at harvest. The result for Jamila variety shows that there is no significant difference between control (0g), 10g, and 20g AMF at harvest.

Fig. 5 shows the yield of *Oryza sativa* varieties (Nerica-8 and Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF). The two varieties have response to AMF inoculation positively when compared with their respective controls (0g). Jamila (40g AMF) has the best yield as compared to Nerica-8.

Fig. 6A shows the panicle length of *Oryza sativa* variety (Nareca) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between control (0g), 10g, 20g and 30g AMF at harvest while 40g has the highest panicle length. Fig. 6B shows panicle length of *Oryza sativa* (Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between control (0g), 10g, 20g and 30g AMF at harvest while there is significant difference between 40g AMF and other retreatments. Similarly, 40g has the highest panicle length in both Nerica-8 and Jamila.

Table 1. Physical and chemical properties of the pre-planting soil

Soil property	Value
pH (H_2O)	6.79
EC (dsm^{-1})	0.23
EA ($cmol\ kg^{-1}$)	1.40
Ca^{2+} ($cmol\ kg^{-1}$)	18.0
Mg^{2+} ($cmol\ kg^{-1}$)	3.80
K^+ ($cmol\ kg^{-1}$)	0.18
Na^+ ($cmolkg^{-1}$)	0.41
CEC ($cmol\ kg^{-1}$)	22.4
TEB ($cmol\ kg^{-1}$)	23.8
Base Sat. (%)	94.1
N (%)	0.15
OC (%)	0.59
OM (%)	1.02
C:N	3.93
AP ($mg\ kg^{-1}$)	29.0
Clay	60.3
Sand	60.3
Silt	10.7
Texture	Sandy clay loam

EC-Electrical conductivity, EA-Exchangeable acidity, Ca^{2+} -Calcium, Mg^{2+} -Magnesium, K^+ -Potassium, Na^+ -Sodium, CEC- Cation exchange capacity, TEB- Total exchangeable base, Base sat- Base saturation, N-Nitrogen, OC- Organic carbon, OM- Organic matter, C:N- Carbon to Nitrogen, and AP- Available Phosphorus.

Fig. 7A shows the number of tillers of *Oryza sativa* variety (Nareca-8) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between 20g and 30g at harvest while there is significant difference between 40g AMF and other treatments. Fig. 7B shows number of tillers of *Oryza sativa* (Jamila) inoculated with different dose of arbuscular mycorrhiza fungi (AMF) of which, there is no significant difference between control (0g), and 10g, AMF at harvest. Similarly, there is no significant difference between 20g and 30g, AMF at harvestwhile there is significant difference between 40g AMF and other treatments. And, 40g has the highest number of tillers in both Nerica-8 and Jamila.

4. DISCUSSION

The inoculation AMF have shown positive impact on the two rice varieties as compared to the non-inoculated ones, a phenomenon known as Mycorrhizal Growth Response (MGR) [25,26]. The AMF inoculated plants performed higher due the symbiotic association between AMF and the host plant. Several studies have reported the positive effects of AMF on the growth and yield of rice [27,28,29]. These AMF-plant association induce plant growth and yield by improving nutrients, minerals, and water uptake of the plant and in return, the host plant supply the fungi with protein for their growth and development [27,30]. Plant height were significantly higher in plants inoculated with high dose of AMF which agrees with the studies of Karunarathna et al., [31] and Michel et al., [32]. Shoot and root biomass were significantly higher in plants with high AMF dose which agree with study of Miora et al., [33]. Similarly, yield of the plants increases with increased in AMF dose which agrees with studies of Chareesri et al., [34] and Huanhe et al., [35].

High yield may be attributed to increased in P and N uptake induce by the high root colonization by AMF. Plants inoculated with high AMF dose exhibit high root colonization which result due to availability of soil nutrient particularly P [33,36]. During grain filling stage, high nutrients supply to panicle particularly P and N could also be the reason for attaining high yield in the inoculated plants [37]. Low P availability in plant result in more carbon allocationto AMF in other to grow more hyphae, reaching new areas [38,39]. The presence of AMF is also known to improved N uptake by the host plant [40,41]. The colonization of rice root by AMF usually occurred at the vegetative stage [42] of the rice growth not at the matured stage [43,44] of the rice plant, indicating early support by AMF to the host plant.

AMF exert positive influence on microbial communities in the soil through improving soil structure, stimulating root growth, enhancing root exudate in the rhizosphere, and rapid production of glomalin [45,46,47,48]. Similarly, the enhancement of soil nutrient bioavailability, increasing plant developmental hormones and improving host plant growth are among the few positive affect of soil microbial communities on AMF [46,49,50]. The role of rice plant towards limiting plant pathogens in the soil are attained through the secretion of different range of root exudate in to the soil which attracts wide range of microorganisms thereby, establishing mutualistic association with the rice plant [51,52,53].

The established symbiotic association have clearly revealed the complete dependent of AMF on photosynthetic fixed C for their growth and development [54,23]. Similarly, high AMF colonization lead to increase photosynthetic rate in the host plant [55,56]. According to Wang et al., [23] reported that AMF have gradually evolves trait that circumvent defence mechanisms which are strictly controlled in the immune system of the host plant. In contrast, AMF have exhibited the ability to improve sustainable rice production through enhance nutrient uptake.

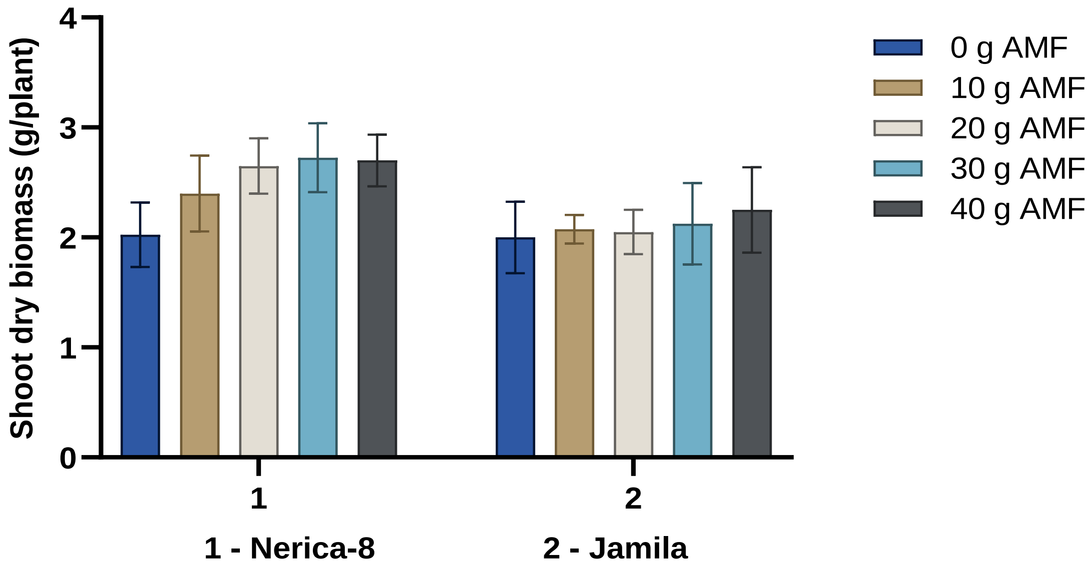

Fig. 3. Effect of AMF (*Glomus intraradices)* on shoot dry biomass of *Oryza sativa* varieties (Nerica and Jamila)

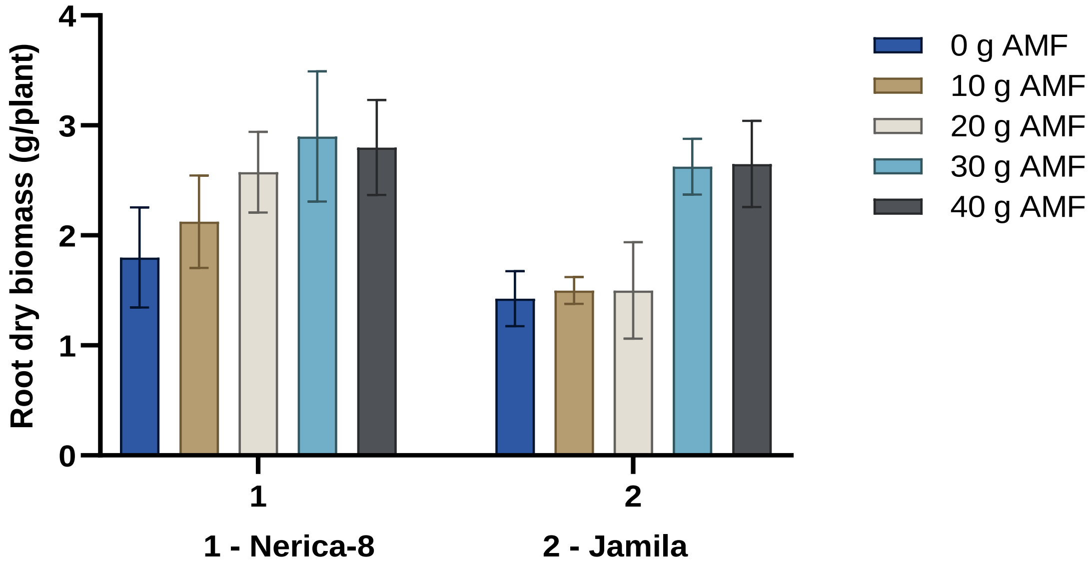

Fig. 4. Effect of AMF (*Glomus intraradices)* on root dry biomass of *Oryza sativa* varieties (Nerica and Jamila)

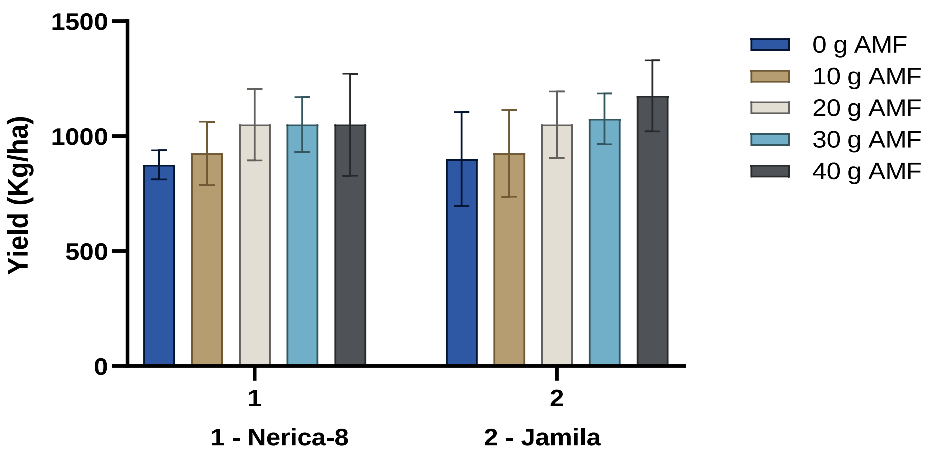

Fig. 5. Effect of AMF (*Glomus intraradices)* on yield of *Oryza sativa* varieties (Nerica-8 and Jamila)

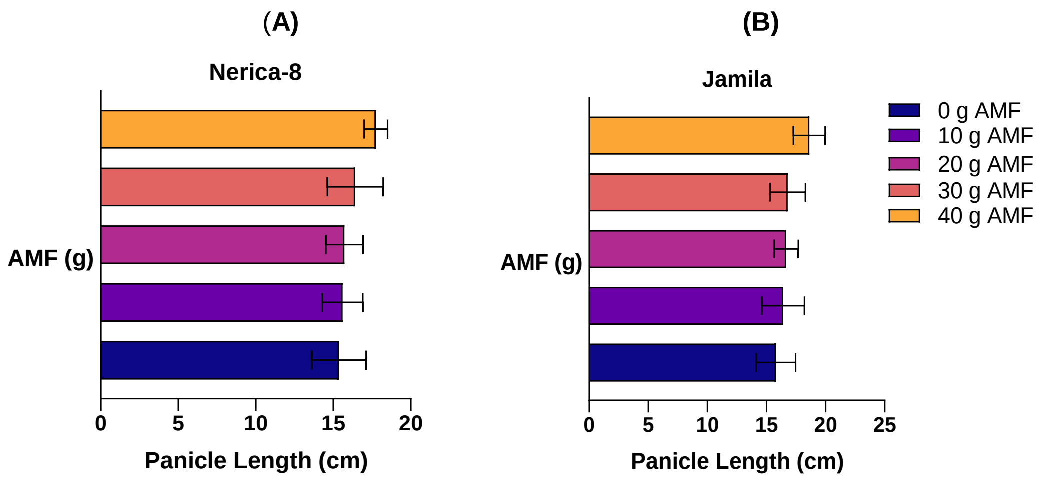

Fig. 6. A- Effect of AMF (*Glomus intraradices)* on panicle length of *Oryza sativa* (Nerica)B - Effect of AMF (*Glomus intraradices)* on panicle length of *Oryza sativa* (Jamila)

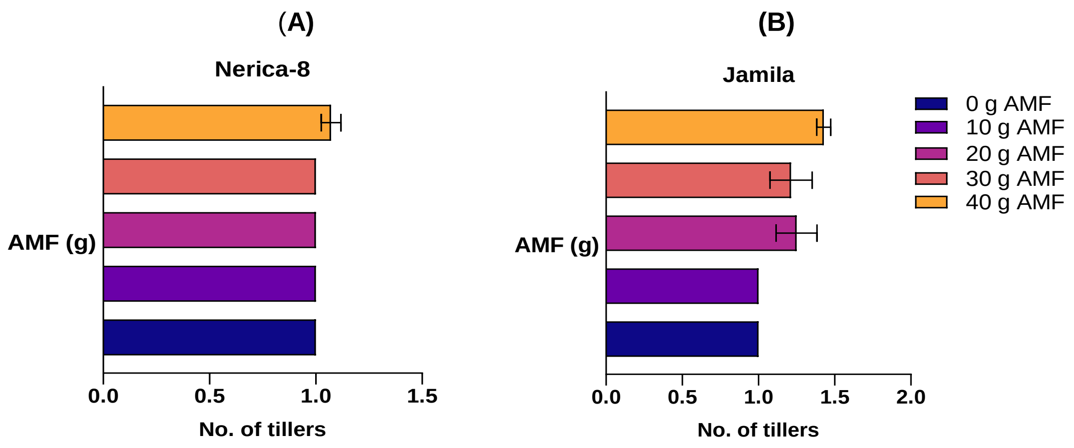

Fig. 7. A- Effect of AMF (*Glomus intraradices)* on number of tillers of *Oryza sativa* (Nerica-8) B - Effect of AMF (*Glomus intraradices)* on number of tillers of *Oryza sativa* (Jamila)

5. CONCLUSION

In conclusion, AMF shown greater potential to improve growth development leading to increased rice productivity and higher grain yield under favourable condition. The result validates the influence of AMF on the growth and yield of rice varieties (Nerica-8 and Jamila) and Jamila has the best performance with AMF inoculation then Nerica-8. It reveals that high yield attributes were observed with increased AMF dose in both varieties of rice which relates to high AMF colonization around the roots, thereby increasing both water and nutrient uptake by the plant.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Alabi OO, Aluwong JS, Atteh PA, Dirisu HI, Yusuf FM, Popoola LA, Agada LF, Haruna OE. Economic Efficiency of Rice Production among the Smallscale Women Farmers in the Federal Capital Territory , Nigeria. Agricultural Sciences. 2024;16 (40):1–16. Available:https://doi.org/10.22620/agrisci.2024.40.006
2. Dzarma ED, Degla NN, Guy D. Modelling and optimization of rice production in Nigeria : bibliometric analysis and future research. International Journal of Physical Sciences. 2024;19(1):46–57. Available:https://doi.org/10.5897/IJPS2023.5040
3. Sen Y, Zhenmin W, Houqing Z, Wenlong S. Rice Variety Classification Based on Optimized Near-Infrared Spectral Classification Model. Rice Science. 2024; 31(1):6–9. Available:https://doi.org/10.1016/j.rsci.2023.11.003
4. Vallejos-torres G, Gaona-jimenez N, Ordoñez-sánchez L, Lozano C, Tuanama J, Marín C. Effects of arbuscular mycorrhizal fungi , poultry manure compost , and cadmium on plant growth and nutrient absorption of *Oryza sativa*. Chilean Journal of Agricultural Research. 2023;83(6):656–665. Available:https://doi.org/10.4067/S0718-58392023000600656
5. Singh H, Pal S, Kumar D, Kumar A, Verma A, Sachan R. Effect of Integrated Nutrient Management on Productivity and Quality of Rice. International Journal of Environment and Climate Change. 2024;14(2):646–651. Available:https://doi.org/10.9734/IJECC/2024/v14i23979
6. Waththe K, Madhushan A, Karunarathna SC, Mudiyanselage D. Dissanayake D, Devage T, Priyadarshani C, Kankanamalage A, Priyashantha H, Dai D, Yapa PN. Effect of Arbuscular Mycorrhizal Fungi on Lowland Rice Growth and Yield (*Oryza sativa* L .) under Different Farming Practices. Agronomy. 2023;13(2803):1–13.
7. Yu TI, Jing AN, Jiaxin SUN, Aixia LI, Mengzi Wang NI, Xue GO, Lili WA, Liya LIU, Fengzhong, WA, Litao TO. Effects of Milling Methods on Rice Flour Properties and Rice Product Quality : A Review. Rice Science. 2024;31(1):33–46. Available:https://doi.org/10.1016/j.rsci.2023.11.002
8. Ashim NH, Li MMA, Ahadi MRM, Bdullah AFA, Ayayok AW, Saufi M, Assim MK. Smart Farming for Sustainable Rice Production : An Insight into Application , Challenge , and Future Prospect. Rice Science. 2024;31(1):47–61. Available:https://doi.org/10.1016/j.rsci.2023.08.004
9. Bernaola L, Stout MJ. Effects of arbuscular mycorrhizal fungi on rice-herbivore interactions are soil-dependent. Scientific Reports. 2019;9(14037):1–13. Available:https://doi.org/10.1038/s41598-019-50354-2
10. Bernaola L, Cange G, Way MOW, Ore JG, Ardke JH, Tout MS. ScienceDirect Natural Colonization of Rice by Arbuscular Mycorrhizal Fungi in Different Production Areas. Rice Science. 2018;25(3):169–174. Available:https://doi.org/10.1016/j.rsci.2018.02.006
11. Luginbuehl L, Guillaume M, Smita K, Harrie VE, Guru R, Andrew B, Giles O, Peter E. Fatty acids in arbuscular mycorrhizal fungi are synthesized by the host plant. Science. 2017;356(6343):1175–1178.

12. Xu H, Shi Y, Chen C, Pang Z, Zhang G, Zhang W, Kan H. Arbuscular Mycorrhizal Fungi Selectively Promoted the Growth. Plants. 2024;13(1678):1–12.
13. Xu Y, Tu Y, Feng J, Peng Z, Peng Y, Huang J. Arbuscular Mycorrhizal Fungi Mediate the Acclimation of Rice to Submergence. Plants. 2024;13(1908):1–15.
14. Gökhan B, Caner Y, Talip Ç, Üstün Ş, Semra D. Effects of Arbuscular Mycorrhizal Fungi on Carbon Dioxide (CO2) and Water (H2O) Emissions in Turfgrass Soil under Different Salinity Irrigation Levels E. Environmental Engineering and Management Journal. 2023;22(6):1081–1090. Available:https://doi.org/10.30638/eemj.2023.089
15. Ordi MK, Arrokhi NF, Anul MIPECH, Hmadikhah AA. Rice Husk at a Glance : From Agro-Industrial to Modern Applications. Rice Science. 2024;31(1):14–32. Available:https://doi.org/10.1016/j.rsci.2023.08.005
16. Zhou J, Zang H, Loeppmann S, Gube M, Kuzyakov Y, Pausch J. Arbuscular mycorrhiza enhances rhizodeposition and reduces the rhizosphere priming effect on the decomposition of soil organic matter. Soil Biology and Biochemistry. 2020;140: 107641. Available:https://doi.org/10.1016/j.soilbio.2019.107641
17. Guigard L, Jobert L, Busset N, Moulin L, Czernic P. Symbiotic compatibility between rice cultivars and arbuscular mycorrhizal fungi genotypes affects rice growth and mycorrhiza-induced resistance. Frontiers in Plant Science. 2023;14(1278990):1–17. Available:https://doi.org/10.3389/fpls.2023.1278990
18. Umini ERL, Allino MAV, Lguacil MAMA, Omani MAR. Different farming and water regimes in Italian rice fields affect arbuscular mycorrhizal fungal soil communities. Ecological Applications. 2011;21(5):1696–1707.
19. Vallino M, Fiorilli V, Bonfante P. Rice flooding negatively impacts root branching and arbuscular mycorrhizal colonization , but not fungal viability. Plant, Cell and Environment. 2014;37:557–572. Available:https://doi.org/10.1111/pce.12177
20. Barro M, Wonni I, Simonin M, Kassankogno AI, Klonowska A, Moulin L, Béna G, Somda I, Brunel C, Tollenaere C. The impact of the rice production system (irrigated vs lowland) on root-associated microbiome from farmer ’ s fields in western Burkina Faso. FEMS Microbiology Ecology. 2022;28:1–17. Available:https://doi.org/10.1093/femsec/fiac085
21. Chialva M, Ghignone S, Cozzi P, Lazzari B, Bonfante P, Abbruscato P, Lumini E, Loc E, Codazza C, Lodi I. Water management and phenology influence the root-associated rice field microbiota. FEMS Microbiology Ecology. 2020;96:1–16. Available:https://doi.org/10.1093/femsec/fiaa146
22. Shuxuan Z, Ghulam R, Xiangping G, Liang S, Kewen C. Effects of Different Irrigation Methods on Environmental Factors, Rice Production, and Water Use Efficiency. Water. 2020;12(2239): 1–14. Available:https://doi.org/doi:10.3390/w12082239
23. Wang Y, Bao X, Li S. Effects of Arbuscular Mycorrhizal Fungi on Rice Growth Under Different Flooding and Shading Regimes. Frontiers in Microbiology. 2021;12:1–15. Available:https://doi.org/10.3389/fmicb.2021.756752
24. Goyal G, Shukla S, Shubham S, Anand D, Sanjay T, Jitender B, Pradip K. The Study Evaluated the Potential Viability of Seeds from Various Types of Rice (*Oryza sativa* L .). Journal of Experimental Agriculture International. 2024;46(6):693–698.
25. Johnson NC, Wilson GWT, Wilson JA, Miller RM, Bowker MA. Mycorrhizal phenotypes and the Law of the Minimum. New Phytologist. 2015;205:1473–1484.
26. Singh J, Singh KK, Robock A, Xia L. Future Climate Change Impacts on Rice in Uttar Pradesh , India ’ s Most Populous Agrarian State Earth ’ s Future. Advancing Earth and Space Science. 2024;1(1):1–22. Available:https://doi.org/10.1029/2023EF004009
27. Campo S, Martín-cardoso H, Olivé M, Pla E, Catala-forner M, Martínez-eixarch M, Segundo BS. Effect of Root Colonization by Arbuscular Mycorrhizal Fungi on Growth , Productivity and Blast Resistance in Rice. Rice. 2020;13(42):1–14. Available:https://doi.org/doi.org/10.1186/s12284-020-00402-7

28. Diedhiou AG, Mbaye FK, Mbodj D, Gaye S, Kane A, Laplaze L, Manneh B. Field Trials Reveal Ecotype-Specific Responses to Mycorrhizal Inoculation in Field Trials Reveal Ecotype-Specific Responses to Mycorrhizal Inoculation in Rice. PLOS ONE. 2016;11(2):1–18. Available:https://doi.org/10.1371/journal.pone.0167014
29. Zheng W, Lehmann A, You Z, Rillig MC. Arbuscular mycorrhizal fungi increase grain yields : a. New Phytologist. 2019;222: 543–555. Available:https://doi.org/10.1111/nph.15570
30. Gehlot Y, Lal B, Yadav SS, Bhagwatrao S, Sharma SK, Trivedi SK. Effect of Biochar Application on Performance of Rice in a Vertisol of Central India. Journal of Experimental Agriculture International. 2024;46(6):317–322. Available:https://doi.org/10.9734/JEAI/2024/v46i62483
31. Karunarathna SC, Mudiyanselage D, Dissanayake D, Devage T, Priyadarshani C, Stephenson SL, Elgorban A, Dawoud TM, Kankanamalage A, Priyashantha H, Karunarathna SC, Scholar G. Effect of Arbuscular Mycorrhizal Fungi on Lowland Rice Growth and Effect of Arbuscular Mycorrhizal Fungi on Lowland Rice Growth and Yield (*Oryza sativa* L .) under Different Farming Practices. Preprints. 2023;1–12. Available:https://doi.org/10.20944/preprints202309.1980.v1
32. Michel RS, Armada E, Aroca R, Azcón R. Azospirillum and arbuscular mycorrhizal colonization enhance rice growth and physiological traits under well-watered and drought conditions. Journal of Plant Physiology. 2011;168:1031–1037. Available:https://doi.org/10.1016/j.jplph.2010.12.019
33. Miora N, Njaramanana R, Rahetlah VB, Trap J. Field arbuscular mycorrhizal inoculation increased plant performance without phosphorus fertilizer supply of four promoted upland rice varieties in Madagascar. Experimental Agriculture. 2022;58(57):1–14. Available:https://doi.org/10.1017/S0014479722000527
34. Chareesri A, Deyn GB, De Sergeeva L, Polthanee A, Kuyper TW. Increased arbuscular mycorrhizal fungal colonization reduces yield loss of rice (*Oryza sativa* L .) under drought. Mycorrhiza. 2020;30:315–328. Available:https://doi.org/https://doi.org/10.1007/s00572-020-00953-z
35. Huanhe WEI, Xiaoyu GENG, Xiang ZH, Wang ZHU, Xubin ZH, Yinglong CHEN, Zhongyang H UO, Guisheng ZHOU, Tianyao MENG, Qigen DAI. Grain Yield , Biomass Accumulation , and Leaf Photosynthetic Characteristics of Rice under Combined Salinity-Drought Stress. Rice Science. 2024;31(1):118–128. Available:https://doi.org/10.1016/j.rsci.2023.06.006
36. Trinuran E., Joy B, Raidasari F. Effect of Combination of Soil Improvers NP, K Fertilizer on Organic C , Total N , Uptake N , and Yield of Lowland Rice (*Oryza sativa* L .) in Inceptisols from Jatinangor , West Java , Indonesia. International Journal of Plant & Soil Science. 2024;36(3):142–149. Available:https://doi.org/10.9734/IJPSS/2024/v36i34409
37. Yooyongwech S, Tisaru R., Samphumphuang T, Phisalaphong M, Cha S. Integrated strength of osmotic potential and phosphorus to achieve grain yield of rice under water deficit by arbuscular mycorrhiza fungi. Scientific Reports. 2023;13(5999):1–13. Available:https://doi.org/10.1038/s41598-023-33304-x
38. Jyothsna K, Meghana P, Akash A, Setty J. Impact of Temperature Variations on Rice Production. Journal of Experimental Agriculture International. 2024;14(5) :1–9. Available:https://doi.org/10.9734/IJECC/2024/v14i54166
39. Zhang S, Wang L, Ma F, Bloomfield KJ. Is resource allocation and grain yield of rice altered by inoculation with arbuscular mycorrhizal fungi ? Journal of Plant Ecology. 2015;8(4):436–448. Available:https://doi.org/10.1093/jpe/rtu025
40. Lei S, Xu C, Qianya Z, Tianlei Z, Qian Y, Lianmeng L, Shiwen H, Ling W. Effects of Nitrogen-Regulating Gene AreA on Growth , Pathogenicity , and Fumonisin Synthesis of Fusarium proliferatum. Rice Science. 2024;31(1):10–13. Available:https://doi.org/10.1016/j.rsci.2023.11.001
41. Ryan MH, Graham JH. Tansley review Little evidence that farmers should consider abundance or diversity of arbuscular mycorrhizal fungi when

managing crops. New Phytologist. 2018; 220:1092–1107.
Available:https://doi.org/10.1111/nph.15308

42. Sarkodee-addo E, Yasuda M, Lee CG, Kanasugi M, Fujii Y, Omari RA, Abebrese SO, Bam R, Asuming-brempong S, Mohammad K, Dastogeer G. Arbuscular Mycorrhizal Fungi Associated with Rice (*Oryza sativa* L .) in Ghana : E ff ect of Regional Locations and Soil Factors on Diversity and Community Assembly. Agronomy. 2020;10 (559):1–19.
Available:https://doi.org/doi:10.3390/agronomy1004055

43. Wang Y, Li T, Li Y, Björn O, Rosendahl S, Olsson A, Li S. Community Dynamics of Arbuscular Mycorrhizal Fungi in High-Input and Intensively Irrigated Rice Cultivation Systems. Applied and Environmental Microbiology. 2015;81(8):1–8.
Available:https://doi.org/10.1128/AEM.03769-14

44. Xinli DONG, Yang ZHOU, Yaqi ZH, Fuxi RONG, Jiahong DU, Zheyuan HONG, Peisong HU, Yusong LÜ. OsbZIP01 Affects Plant Growth and Development by Regulating OsSD1 in Rice. Rice Science. 2024;31(1):77–86.
Available:https://doi.org/10.1016/j.rsci.2023.11.007

45. Al-maliki S, Ebreesum H. Rhizosphere Changes in soil carbon mineralization , soil microbes , roots density and soil structure following the application of the arbuscular mycorrhizal fungi and green algae in the arid saline soil. Rhizosphere. 2020;14: 100203.
Available:https://doi.org/10.1016/j.rhisph.2020.100203

46. Bao X, Zou J, Zhang B, Wu L, Yang T, Huang Q. Arbuscular Mycorrhizal Fungi and Microbes Interaction. Agronomy. 2022;12(1277):1–15.
Available:https://doi.org/doi.org/10.3390/agronomy12061277

47. Dan LIU, Huibo ZHAO, Zi WANG, Jing XU, Yiting LIU, Jiajia WANG, Minmin CHEN, Xiong LIU, Zhihai ZH, Jiangsu CEN, Li ZHU, Jiang HU. Deyong REN. Leaf Morphology Genes SRL1 and RENL1 Co-Regulate Cellulose Synthesis and Affect Rice Drought Tolerance. Rice Science. 2024;31(1):103–117.
Available:https://doi.org/10.1016/j.rsci.2023.10.001

48. Zhang L, Shi N, Fan J, Wang F, George TS, Feng G. Arbuscular mycorrhizal fungi stimulate organic phosphate mobilization associated with changing bacterial community structure under fi eld conditions. Environmental Microbiology. 2018;20(7):2639–2651.
Available:https://doi.org/10.1111/1462-2920.14289

49. Park Y, Ryu C. Understanding Plant Social Networking System : Avoiding Deleterious Microbiota but Calling Beneficials. International Journal of Molecular Sciences. 2021;22(3319):1–20.
Available:https://doi.org/doi.org/10.3390/ijms22073319

50. Wen X, Wu L, Luo N, Hui C, Hung M, Li H. Geoderma Arbuscular mycorrhizal fungi and the associated bacterial community in fl uence the uptake of cadmium in rice. Geoderma. 2019;337:749–757.
Available:https://doi.org/10.1016/j.geoderma.2018.10.029

51. Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, Subramanian S, Smith DL. Plant Growth-Promoting Rhizobacteria : Context , Mechanisms of Action , and Roadmap to Commercialization of Biostimulants for Sustainable Agriculture. Frontiers in Plant Science. 2018;9(1473):1–17.
Available:https://doi.org/10.3389/fpls.2018.01473

52. Dongwei DI, Mingkun MA, Xiaoyang ZH, Yufang LU, Ronzucker HJK, Weiming SHI. Potential Secretory Transporters and Biosynthetic Precursors of Biological Nitrification Inhibitor 1 , 9-Decanediol in Rice as Revealed by Transcriptome and Metabolome Analyses. Rice Science. 2024;31(1):87–102.
Available:https://doi.org/10.1016/j.rsci.2023.09.002

53. Matsushima C, Shenton M, Kitahara A, Wasaki J, Oikawa A. Cheng W. Multiple analysis of root exudates and microbiome in rice (*Oryza sativa*) under low P conditions. Archives of Microbiology. 2021;203(9):5599–5611.
Available:https://doi.org/10.1007/s00203-021-02539-5

54. Gan S, Xin S, Zini W, Xiaocan X, Xin X, Yanping T, Xinqiong L, Xianyin T, Chuntai W, Yonghua Q. Alternative Splicing of OsCYL4 Controls Drought Resistance via Regulating Water Loss and Reactive Oxygen Species-

Scavenging in Rice. Rice Science. 2024;31(1):1–5. Available:https://doi.org/10.1016/j.rsci.2023.08.003

55. Chandrasekaran M, Kim K, Krishnamoorthy R, Hu S, Oh S, Sa T. Mycorrhizal Symbiotic Efficiency on C 3 and C 4 Plants under Salinity Stress – A Meta-Analysis. Frontiers in Microbiology. 2016;7:1–13. Available:https://doi.org/10.3389/fmicb.2016.01246

56. Ningning GAO, Shuifeng YE, Yu ZH, Liguo ZHOU, Xiaosong MA, Hanxi YU. ScienceDirect A β-Carotene Ketolase Gene NfcrtO from Subaerial Cyanobacteria Confers Drought Tolerance in Rice. Rice Science. 2024;31(1):62–76. Available:https://doi.org/10.1016/j.rsci.2023.10.002

Peer-review history:
The peer review history for this paper can be accessed here:
https://prh.ikprress.org/review-history/12282