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IMPROVED CROP PERFORMANCE AND RESIDUAL SOIL FERTILITY OF RICE (*Oryza sativa* L.) IN RESPONSE TO MYCORRHIZAL BIOFERTILIZER APPLICATION

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ABSTRACT

Sustainable food production is a global challenge in 21st century agriculture. Rice, the world's major cereal grain, depends heavily on chemical fertilisers, which can reduce soil fertility, create environmental constraints, and cause nutrient imbalances. The arbuscular mycorrhizal fungi (AMF) are good alternatives for sustainable rice cultivation. The AMF–based products offer several agronomic and environmental benefits, *viz*., higher yield, better nutrient uptake, and improved soil properties. Considering this, a field experiment was conducted during the *kharif* season of 2023 to evaluate the different doses of mycorrhizal biofertilizer, along with the recommended dose on yield, nutrient uptake, and residual soil fertility in the lower Indo–Gangetic Plain Zone of West Bengal, India. The trial was laid out in a Randomized Block Design (RBD) with 3 replications and 7 treatments. The treatments were – T_1 – 100% RDF, T_2 – 100% RDF + RhizoMyx @ 2.5 kg ha^{-1} at basal, T_3 – 100% RDF + RhizoMyx @ 5 kg ha^{-1} at basal, T_4 – 100% RDF + RhizoMyx @ 7.5 kg ha^{-1} at basal, T_5 – 100% RDF + RhizoMyx @ 10 kg ha^{-1}at basal, T_6 – 100% RDF + RhizoMyx @ 12.5 kg ha^{-1} at basal, T_7 – 100% RDF + RhizoMyx @ 15 kg ha^{-1} at basal. Plots treated with biofertilizer performed better in terms of yield, nutrient uptake, and soil properties, compared to control. T_5 (100% RDF + RhizoMyx @ 10 kg ha^{-1}at basal) recorded the highest grain yield, uptake, partial factor productivity, and soil nutrients.

Key words : Rice, Arbuscular mycorrhizal fungi, Biofertilizer, Residual soil fertility, Nutrient uptake.

Introduction

Rice is the most widely consumed food grain worldwide, especially in South and Southeast Asia (Bandumula, 2018), providing 21% of global per capita energy (Mishra *et al*., 2022). In the 2024–25 season, rice was cultivated on about 51.4 M ha across India, yielding 150.18 M t and achieving an average productivity of about 4.3–4.4 t ha^{-1} (Government of India, 2025). Rice is a huge nutrient–demanding crop (Rajendran *et al*., 2025), requiring very high amounts of chemical inputs to achieve high yield potential. But the excessive use of chemical fertilizers leads to soil fertility degradation, long–term yield declines and ecosystem productivity risks (Devi *et al*., 2025). Hence, it is a major challenge for agronomists to enhance food grain production to fulfil the global food demand without hampering ecosystem sustainability (Cakmakci *et al*., 2025).

Arbuscular mycorrhizal fungi (AMF) belong to the phylum *Glomeromycota*, forming symbiotic relationships with 75–80% of terrestrial plants (Clasen *et al*., 2018), except for Brassicaceae, Polygonaceae, Amaranthaceae, Caryophyllaceae and Chenopodiaceae (Kumar *et al*., 2018). AMF is one of the most important tools in sustainable crop production, performing several functions, including enhanced nutrient uptake, disease resistance, heavy metal contamination tolerance, improved soil

properties, and overall ecosystem health (Boyno *et al*., 2025; Vaishnav and Jansa, 2026). The interaction of rice and AMF is well known, making it a model plant for evaluating mycorrhizal inoculation in agriculture (Wang *et al*., 2021). The effect of AMF in upland rice conditions is well documented scientifically, whereas the lowland submerged ecosystem has received little attention. Although arbuscular mycorrhiza are aerobic, a few studies have reported the presence and effectiveness of some AMF species under aquatic conditions (Iqbal *et al*., 2021; Li *et al*., 2022). Recent experiments have found crop improvement with AMF inoculation under submerged conditions, but such studies are very limited in the lower Indo–Gangetic Plain Zone of West Bengal, India. Keeping this in view, the present experiment was carried out to evaluate the different doses of AMF biofertilizer on both crop performance and residual soil fertility. This study can provide a guideline for applying mycorrhizal biofertilizer in a submerged rice ecosystem.

Materials and Methods

Site of experiment and climatic conditions

The field experiment was conducted during the *kharif* (rainy) season of 2023 at C Block Incheck Farm, under Bidhan Chandra Krishi Viswavidyalaya (B.C.K.V.), Mohanpur, Nadia, West Bengal, India. The experimental site comes under the New Alluvial Zone (NAZ) of West Bengal, situated at 22°57' N latitude and 88°20' E longitude, with an elevation of 9.75 meters above mean sea level, characterized by lowland topography. The climatic conditions are experienced by hot summers, erratic rainfall, high humidity, and a brief, mild winter. Cropping is divided into three seasons: *pre kharif* (March–May; dry and warm), *kharif* (June–October; wet and warm) and *rabi* (November–February; dry and cool). Mean annual precipitation is about 1,396 mm, of which 70–80% arrives with the southwest monsoon, usually commencing in the second week of June. The textural property of the experimental soil was sandy clay loam with a near neutral pH of 7.04, medium organic carbon (0.51%), low available nitrogen (188.9 kg ha^{-1}), medium potassium (184.70 kg ha^{-1}) and high available phosphorus (39.35 kg ha^{-1}).

Experimental design and crop management

The trial was laid out in a Randomized Block Design (RBD) with 3 replications and 7 treatments, each plot measuring 5 m × 3 m. Rice was transplanted at 20 cm × 20 cm spacing at the seedling stage of 22 days. A full recommended dose of fertilizer (RDF) of 60 kg N, 30 kg P_2O_5 and 30 kg K_2O ha^{-1} was supplied as urea, single superphosphate (SSP), and muriate of potash (MOP), respectively. 1/3rd of the total N and the entire P_2O_5 and K_2O were applied basally; the remaining 2/3rd of N was top-dressed in two equal splits at tillering and panicle initiation. Mycorrhizal biofertilizer (RhizoMyx) was broadcast uniformly at the prescribed rates and incorporated into the upper 5–10 cm of the soil layer just before transplanting the seedlings. To favour AMF establishment and root colonization, plots were maintained near field capacity (no standing water) for the first 5–7 days after transplanting. Thereafter, irrigation was adjusted according to evapotranspiration and rainfall, maintaining a standing water depth of 5 ± 2 cm throughout the vegetative and reproductive phases until 10 days before physiological maturity.

The treatments were – T_1 – 100% RDF, T_2 – 100% RDF + RhizoMyx @ 2.5 kg ha^{-1} at basal, T_3 – 100% RDF + RhizoMyx @ 5 kg ha^{-1} at basal, T_4 – 100% RDF + RhizoMyx @ 7.5 kg ha^{-1} at basal, T_5 – 100% RDF + RhizoMyx @ 10 kg ha^{-1}at basal, T_6 – 100% RDF + RhizoMyx @ 12.5 kg ha^{-1} at basal, T_7 – 100% RDF + RhizoMyx @ 15 kg ha^{-1} at basal.

Characteristics of mycorrhizal biofertilizer

RhizoMyx ® is a commercial mycorrhizal biofertilizer, available in granular form, and supplies AMF propagules along with proprietary biostimulant constituents. This formulation promotes greater nutrient uptake and stimulates root proliferation, thereby improving root system development across cereals, pulses, and vegetables. By enhancing access to nutrients and water, it supports higher growth potential in treated crops. (Source: https://www.novonesis.com/en/biosolutions/animal-and-plant/plant/rhizomyx)

Recorded observations

To assess different parameters, five plants were randomly chosen from the net plot area of each experimental unit, excluding the border rows. These plants were tagged and used for taking measurements at the appropriate crop growth stages.

For grain and straw yield, crop plants from each net plot were harvested individually at physiological maturity, followed by threshing, cleaning and weighing to determine grain yield and converted to t ha^{-1}. Straw from each plot was collected post-threshing, sun-dried, and weighed to obtain straw yield (t ha^{-1}).

Partial factor productivity (PFP) for nitrogen (N), phosphorus (P), and potassium (K) was computed individually to assess grain yield obtained per unit of each nutrient applied through chemical fertilizer, using the following equation:

$$\text{PFP (kg grain yield kg}^{-1}\text{ nutrient applied)} = \frac{\text{Grain yield (kg ha}^{-1})}{\text{Nutrient applied through fertilizer (kg)}}$$

For residual soil fertility, soil samples were collected from each plot at 0–15 cm depth using an auger. Samples were air-dried, gently crushed, sieved through 2 mm, and analysed for residual available N, P, K and organic carbon using standard protocols.

Available nitrogen was determined by the alkaline potassium permanganate method (Subbiah and Asija, 1956), in which soil was treated with alkaline $KMnO_4$, the liberated ammonia was distilled into boric acid, and titrated with standard H_2SO_4; the results were expressed as kg ha^{-1}. Available phosphorus was estimated by the Olsen method (Olsen *et al*., 1954) using 0.5 M $NaHCO_3$ extraction at pH 8.5, with extractable P measured colourimetrically and reported as kg ha^{-1}. Available potassium was extracted with neutral 1 N ammonium acetate and quantified by flame photometry (Jackson, 1973), with results expressed as kg ha^{-1}. Soil organic carbon was assessed by the Walkley–Black wet-oxidation procedure (Walkley and Black, 1934), based on oxidation of organic carbon with potassium dichromate and H_2SO_4, followed by titration of the residual dichromate and reported as %.

Statistical analysis

The data were analysed statistically by Analysis of Variance (ANOVA) following established procedures (Cochran and Cox, 1967; Gomez and Gomez, 1984; Panse and Sukhatme, 1985). Treatment effects were evaluated using the error mean square and Fisher–Snedecor's F-test at the 0.05 probability level. Critical differences (CD) at the 5% significance level were determined with reference to Fisher and Yates tables. Duncan's Multiple Range Test (DMRT) at the 5% level of significance was analysed in Python (Virtanen *et al*., 2020) using appropriate statistical packages.

Results and Discussion

Grain and straw yield

Grain and straw yield were significantly influenced by the application of mycorrhizal biofertilizer RhizoMyx. Grain yield varied from 3.61 t ha^{-1} to 4.95 t ha^{-1} with a variation of 37.12% (Table 1). T_5 (100% RDF + RhizoMyx @ 10 kg ha^{-1} at basal) recorded the highest grain yield (4.95 t ha^{-1}) among all the treatments, which was statistically at par with T_4 (4.76 t ha^{-1}). A similar trend was also observed in straw yield. The increased yield was probably due to the production of higher amount of photosynthates that eventually led to higher grain production (Elita *et al*., 2023). The hyphal network

Table 1 : Effect of mycorrhizal biofertilizer on yield of rice.

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	% grain yield increase over T_1
T_1	3.61^{e}	4.70^{d}	—
T_2	4.3^{bcd}	5.43^{bc}	19.10
T_3	4.52^{abc}	5.56^{b}	25.12
T_4	4.76^{ab}	6.23^{a}	31.73
T_5	4.95^{a}	6.34^{a}	36.90
T_6	4.09^{cde}	5.33^{bcd}	13.19
T_7	3.8^{de}	4.85^{cd}	5.17
SEm (±)	0.18	0.22	—
CD (at 5% level)	0.54	0.66	—

produced by the AMF expanded the rhizosphere region, which resulted in greater uptake of essential nutrients (Huey *et al*., 2020; Franzoni *et al*., 2021). Previous research has demonstrated that AMF colonization can promote plant biomass accumulation, improve stomatal conductance and photosystem II activity and enhance nitrogen and phosphorus acquisition, while increasing IAA concentration and reducing ABA production in rice plants (Mitra *et al*., 2021). Furthermore, the combined application of AMF and NPK fertilization improved crop growth and yield, according to the observations of Raya-Hernández *et al*. (2020). Greater plant response by mycorrhizal inoculation under flooded conditions was reported earlier by Madhushan *et al*. (2023) and Martín-Cardoso *et al*. (2025). Under flooded lowland conditions, arbuscular mycorrhizal fungi (AMF) enhanced rice yield primarily by maintaining a functional mycorrhizal phosphorus (P) uptake pathway and associated physiological adjustments, even though flooding suppresses overall colonization (John and Ray, 2023). Periodic soil flooding reduces AMF root colonization and extraradical hyphal density, yet mycorrhizal P-pathway genes such as the fungal phosphate transporter *GintPT* and the rice mycorrhiza-inducible transporter *OsPT11* remain induced in colonized roots, indicating that the symbiotic P-uptake pathway stays active when colonization is depressed (Wang *et al*., 2021). Extraradical hyphae extend the effective absorption zone beyond the depleted rhizosphere, enabling access to P in soil volumes that roots and diffusion cannot easily reach, which is critical in flooded soils, where P mobility is limited and root systems are often shallow. AMF symbiosis further increases acid phosphatase activity in mycorrhizal roots and hyphae, promoting mineralization of organic P and phytate and raising soil P availability in lowland paddy

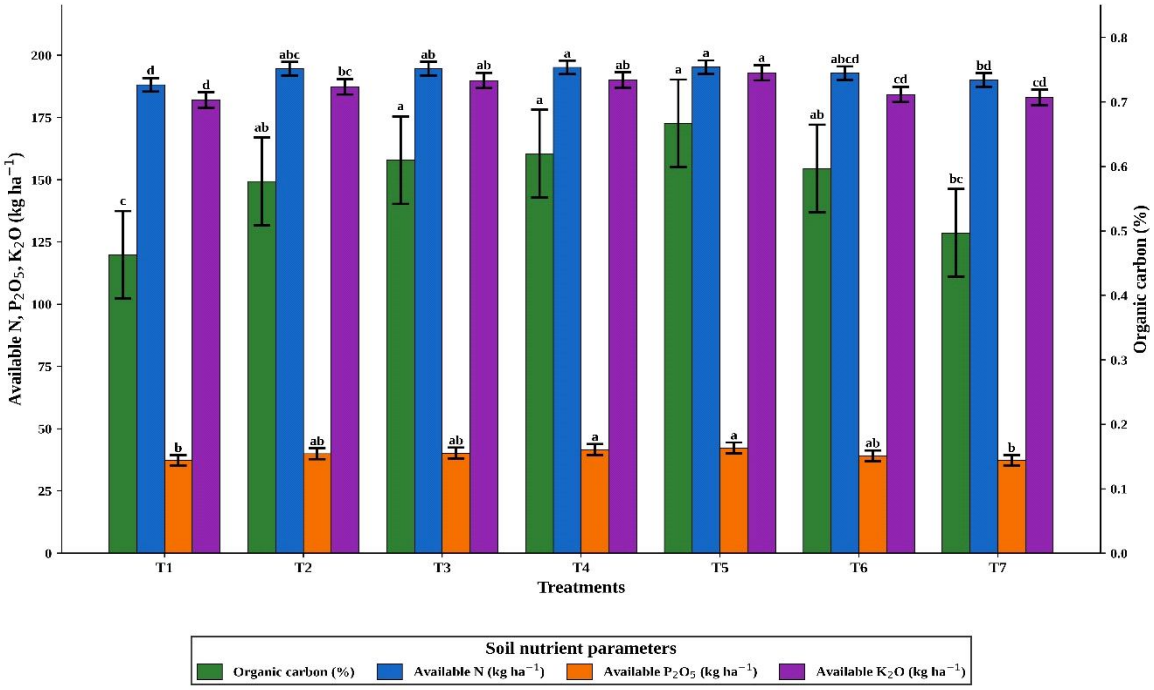


Fig. 1 : Effect of mycorrhizal biofertilizer on residual soil fertility of rice.

Table 2 : Effect of mycorrhizal biofertilizer on nutrient uptake and partial factor productivity of rice.

Treatments	Grain N uptake (kg ha^{-1})	Grain P uptake (kg ha^{-1})	Grain K uptake (kg ha^{-1})	PFP N (kg grain yield kg^{-1} nutrient applied)	PFP P (kg grain yield kg^{-1} nutrient applied)	PFP K(kg grain yield kg^{-1} nutrient applied)
T_1	52.85 ”	17.48 ”	18.00I”	60.22œ”	120.44œ”	120.44œ”
T_2	61.73H”	25.33œ”	22.39œ”	71.72G”	143.44G”	143.44G”
T_3	66.14œ”	26.28œ”	23.61œ”	75.28C”	150.56C”	150.56C”
T_4	71.37G”	28.07G”	25.46G”	79.33C”	158.67C”	158.67C”
T_5	76.40C”	31.36C”	29.08C”	82.44C”	164.89C”	164.89C”
T_6	60.67H”	23.94H”	22.46œ”	68.17G”	136.33G”	136.33G”
T_7	58.49I”	20.97I”	21.16H”	63.33G”	126.67G”	126.67G”
SEm(±)	0.44	0.59	0.63	2.95	5.89	5.89
CD (at 5% level)	1.34	1.81	1.94	9.09	18.17	18.17

Values with different letters are statistically significant.

(Wang *et al.*, 2023).

Nutrient uptake and partial factor productivity

Greater nutrient uptake is directly associated with greater yield. The higher-yielding plots resulted in higher nutrient uptake. The extraradical hyphal network greatly increased the soil volume explored and accesses root-inaccessible microsites, enabling enhanced acquisition of P, N and K (Li *et al.*, 2022), and other nutrients that are diffusion-limited under flooded conditions. AMF hyphae express high-affinity transporters for ammonium and phosphate and can absorb NH_4^+, NO_3^- and simple amino acids from organic patches (Xiao *et al.*, 2023), effectively substituting for root hairs and improving N capture in paddy soils. For P, AMF not only explore a larger soil volume but also secrete phosphatases and modify rhizosphere chemistry to mineralize organic P, thereby sustaining a functional mycorrhizal P-uptake pathway even when flooding depresses overall colonization. In rice, AMF inoculation has been shown to upregulate host nutrient transporters and increase nutrient concentrations, improving nutrient-use efficiency and supporting higher panicle numbers and grain filling (Han *et al.*, 2024), which

ultimately led to higher partial factor productivity of nutrients (Table 2). The higher nutrient uptake was observed in AMF-treated plots in our experiment and therefore likely reflects both improved hyphal foraging and enhanced physiological capacity for nutrient acquisition, particularly under the moderate-to-low fertilizer regimes typical of many lowland systems.

Residual soil fertility

Significant variation in residual soil nutrients was observed between the treatments (Fig. 1). The maximum value was observed in T_5, which was statistically at par with T_2. The glomalin-related soil proteins (GRSP) produced through extramatrical mycelia of the AMF contain a higher concentration of alkyl carbon and aromatic carbon, which contribute to their hydrophobic nature; the presence of aromatic structures resulted in higher resistance to the decomposition of organic matter, which led to a higher organic carbon pool in the soil (Zhang *et al*., 2017).

The AMF improved the soil biogeochemical cycles, which accelerated nutrient cycling and increased the essential nutrients by reducing nutrient loss (Fall *et al*., 2022). Furthermore, the formation of soil macro-aggregates resulted in improved soil physical characteristics, including better water infiltration and better retention of water and minerals, especially potassium (Parihar *et al*., 2020). The AMF fixed some of the N-fixing genes and stimulated the activity of nitrate reductase and organic acids, which resulted in greater N and P content (Gou *et al*., 2024; Jin *et al*., 2024).

The study found that *kharif* rice growth and yield declined beyond an optimal mycorrhizal biofertilizer dose, suggesting a shift from mutualism toward a less beneficial or potentially parasitic interaction at excessive inoculum levels. This pattern is consistent with a negative mycorrhizal growth response, where AMF colonize roots but suppress vegetative growth due to an unfavourable carbon-for-nutrient balance. Guigard *et al*. (2023) showed that certain rice–AMF combinations can reduce dry weight by up to 21% and height by 14–19% (*e.g*., in IR 64), attributing this to fungal carbon demand exceeding nutrient returns to the host. At higher doses, elevated soil P likely masked additional biofertilizer benefits on growth and yield traits (Zinati *et al*., 2025).

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