PLANT SCIENCE TODAY
Vol 13(sp5): 01–11
https://doi.org/10.14719/pst.14995

eISSN 2348-1900

RESEARCH ARTICLE

Integrated nutrient management and system of rice intensification to optimise black rice production for growth, chlorophyll, soil health, quality and yield

Nilabja Banerjee[1, 2*], Ashok Sambhaji Dambale[2], Prasann Kumar[2], Sayan Das[2], Makey Sri Chakra Naga Vardhan[2*], Rajneesh Bhardwaj[3], Ashwani Kumar Tyagi[4], Atin Kumar[5], Patatri Mali[6], Sayon Banerjee[6]

[1]Department of Agriculture, Srinath University, Jamshedpur 831 013, Jharkhand, India
[2]Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144 411, Punjab, India
[3]School of Agriculture, Graphic Era Hill University, Dehradun 248 002, Uttarakhand, India
[4]Department of Genetics and Plant Breeding, IIMT University, Ganga Nagar, Meerut 250 001, Uttar Pradesh, India
[5]School of Agriculture, Uttaranchal University, Dehradun 248 007, Uttarakhand, India
[6]School of Agricultural Science, Sona Devi University, Ghatsila 832 303, Jharkhand, India

*Correspondence email - nilabjabanerjee007@gmail.com; mscnvardhana@gmail.com

Received: 14 April 2026; Accepted: 17 July 2026; Available online: Version 1.0: 22 September 2026

Cite this article: Nilabja B, Ashok SD, Prasann K, Sayan D, Makey SCNV, Rajneesh B, Ashwani KT, Atin K, Patatri M, Sayon B. Integrated nutrient management and system of rice intensification to optimise black rice production for growth, chlorophyll, soil health, quality and yield. Plant Science Today. 2026;13(sp5):01–11. https://doi.org/10.14719/pst.14995

Abstract

The influence of integrated nutrient management (INM) on the growth characteristics, soil nutrient status, grain quality metrics and overall productivity of black rice cultivated under the system of rice intensification (SRI) was evaluated through a field experiment. This research was conducted during the 2024 kharif season on sandy loam soil at the Lovely Professional University's Agriculture Research Farm in Phagwara, Punjab within the Indian subtropical zone. The optimal treatment combination, encompassing the full recommended dose of fertilisers (RDF), 15 t ha^{-1} farmyard manure, 3.5 kg ha^{-1} *Azospirillum* culture and 40 kg ha^{-1} zinc sulphate mono-hydrate ($ZnSO_4 \cdot H_2O$), yielded the highest growth and yield parameters. Physiologically, this INM strategy demonstrated the best expression of crop growth rate (CGR) and absolute growth rate (AGR), also enhanced photosynthetic pigment content, including chlorophyll a, chlorophyll b and total chlorophyll. Concurrently, grain biochemical quality was maximised, notably the levels of protein and total soluble sugars and milling performance improved significantly across recovery rates. Furthermore, this balanced nutrient regimen resulted in the highest measurable grain, straw and total biological yields, simultaneously improving soil health indicators, such as organic carbon and available macronutrients. Consequently, this study validates the use of combined chemical and organic inputs (FYM, *Azospirillum* and $ZnSO_4 \cdot H_2O$) as a highly recommended and sustainable management strategy for enhancing black rice production under the SRI method in subtropical climates.

Keywords: black rice; chlorophyll; grain quality; integrated nutrient management; soil health; system of rice intensification; yield

Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops globally as it continues to be the main source of energy in human nutrition, accounting for dietary calories of over half of the world's population, especially Asia (1, 2). Rice production is the main source of livelihood for the rural population in India and also plays a significant role in the food security of the country. Yet, the over-reliance on chemical fertilisers, reduction of nutrient-use efficiency and the degradation of soils over time have become significant challenges to rice production sustainability (3). In such context, there is a need for nutrient management strategies that are both ecologically sustainable and productive in order to maintain soil health.

Black rice emerges as a promising specialty rice for science and commerce because of its exceptional nutritional value and rich nutritional content of bioactive compounds like anthocyanin, phenolics and antioxidants, making it useful for functional and therapeutic purpose (3). Although black rice has several nutritional advantages, it generally has lower productivity and is more susceptible to nutrient imbalance than the regular varieties, so it is essential to properly manage nutrients in order to boost productivity and grain quality.

Integrated nutrient management (INM) is a new agronomic strategy which is a combination of inorganic nutrient and other nutrient sources such as organic amendments, micronutrients and beneficial microbial inoculants to optimise nutrient synchronisation, nutrient-use efficiency and soil biological function while reducing environmental impacts. At the same time, the system of rice intensification (SRI) has been proven as a resource-efficient method of rice cultivation that promotes tillering, root development, photosynthetic efficiency and water productivity through the use of younger seedling transplantation, wider spacing, alternate wetting and drying irrigation and mechanical weeding (4).

Despite the findings on beneficial impact of INM and SRI in the conventional rice cultivation systems, the combined effects on the physiology, chlorophyll biosynthesis, grain quality, soil nutrient dynamics and performance of black rice under subtropical agro-ecosystems are still limited. Hence, the present study was carried out to study the interactive effect of SRI with INM system for the optimization of growth, chlorophyll dynamics, grain quality, soil health and productivity of black rice crop in subtropical region (5).

Materials and Methods

Experimental site

The field investigation was conducted during the *kharif* season of 2024 at the Agronomy Research Farm of Lovely Professional University, Phagwara, Punjab, India (31°15' N latitude, 75°42' E longitude; 234 m above mean sea level). The experimental site possessed a sandy loam soil comprising 63.94 % sand, 18.68 % silt and 17.38 % clay and was alkaline in reaction (pH 8.45) with medium electrical conductivity (0.42 dS m^{-1}) and low organic carbon content (0.40 %). Based on the fertility rating, the soil was low in available nitrogen (232.18 kg ha^{-1}), high in available phosphorus (25.90 kg ha^{-1}) and medium in available potassium (117.67 kg ha^{-1}). During the crop growth period (July–November), the mean maximum temperature fluctuated between 31.0 °C and 35.8 °C, while the minimum temperature ranged from 15.3–27.3 °C. The total rainfall received during the season was 537.6 mm. Relative humidity varied from 89.3–91.8 % in the morning and from 67.5–48.6 % during evening hours. The bright sunshine duration during the experimental period ranged between 4.9 and 9.4 hr per day (Table 1).

Experimental details

The experiment was conducted under randomised block design (RBD) with 3 replications and 9 treatments were based on INM, viz. T_1= absolute control; T_2= 100 % RDF (recommended dose of filter), T_3= 75 % RDF; T_4= 75 % RDF + 3.5 kg ha^{-1} *Azospirillum* + 30 kg ha^{-1} $ZnSO_4.H_2O$ (Zinc sulphate monohydrate); T_5= 100 % RDF+ 3.5 kg ha^{-1} *Azospirillum* + 40 kg ha^{-1} $ZnSO_4.H_2O$; T_6= 75 % RDF + 12 t farmyard manure (FYM) ha^{-1}+ 30 kg ha^{-1} $ZnSO_4.H_2O$; T_7= 100% RDF + 15 t FYM ha^{-1}+ 40 kg ha^{-1} $ZnSO_4.H_2O$; T_8= 75 % RDF + 12 t FYM ha^{-1}+ 3.5 kg ha^{-1} *Azospirillum* + 30 kg ha^{-1} $ZnSO_4.H_2O$; T_9= 100 % RDF + 15t FYM ha^{-1}+ 3.5 kg ha^{-1} *Azospirillum* + 40 kg ha^{-1} $ZnSO_4.H_2O$. The treatment combinations were designed with the principles of integrated nutrient management system, which is the inorganic fertiliser, organic manure, micronutrients and biofertilizers to enhance the efficiency of nutrient use and soil health (6). Zinc sulphate monohydrate containing 33 % elemental zinc (Zn) was applied as a soil amendment according to the respective treatment combinations during final land preparation. The addition of Zn to rice has been documented to enhance growth, yield, uptake and enrichment of rice in submerged rice ecosystems (7). Farmyard manure was added prior to transplanting to improve the soil organic carbon content and microbial activity and *Azospirillum* was used as a biofertiliser to provide biological nitrogen fixation and root stimulation (8). The area of the plots was 432 m^2, 16 m^2 per plot. The black rice variety, AAU-TTB-Dhan 41 (Labanya) was sown in the middle of July using the seed rate of 3 kg ha^{-1} in SRI method and while transplanting, a spacing of 25 cm × 25 cm was maintained (9). The seedlings (14 days old) are treated with *Azospirillum* at the rate of 3.5 kg ha^{-1} and the dose of 100 % RDF is 100:30:30 (N: P_2O_5: K_2O) through urea, single super phosphate and muriate of potash. The crop was harvested at physiological maturity (~130–135 (DAT) days after transplanting) when about 95 % of the grains were golden yellow and harvested by hand at low height with a sickle (Fig. 1).



Fig. 1. Measuring of plant height every 30 days interval.

Crop management

Seedlings (14 days old) were uprooted on 26 June, 2024 and subjected to root dip treatment with *Azospirillum* (where required by the treatment plan) before manual transplanting. *Azospirillum* root inoculation has been reported to promote early crop vigour, nutrient uptake, biological nitrogen fixation and root proliferation in rice cultivation system (9). Farm yard manure applied at the time of field preparation, half of the nitrogen (as urea) (10) along with the full recommended dose of phosphorus (P) supplied as single superphosphate (SSP) and potassium (K), supplied as muriate of potash (MOP) was incorporated as basal at 10 DAT to ensure early crop establishment. The remaining nitrogen was applied at 30–35 DAT during the active tillering phase to enhance tiller proliferation and final yield formation, high amounts of nitrogen applied in the period of active tillering are found to have a significant effect on the synthesis of chlorophyll (Fig. 2), the photosynthetic activity and the formation of productive tillers of the rice plants (11). Additionally, $ZnSO_4{\cdot}H_2O$ was applied at 15 DAT to support micronutrient balance and metabolic activity. Gap filling was carried out 10 DAT wherever needed. In the early growth stages, weed intensity remained low due to stagnant water. Later, weed growth was primarily observed along the border areas. Two manual weedings were performed as per the weed intensity in the field.

Table 1. The monthly meteorological data observed during the crop growth period, 2024

Date	Maximum temp (°C)	Minimum temp (°C)	Relative humidity % (Morn.)	Relative humidity % (Even.)	Bright sunshine hour (hr)	Total rainfall (mm)
July	35.8	27.3	89.3	67.5	4.9	146.9
August	34.0	26.7	93.4	74.0	5.6	210.9
September	34.3	25.0	94.3	68.7	7.1	150.6
October	33.7	17.8	93.5	51.7	9.2	19.8
November	31.0	15.3	91.8	48.6	9.4	9.4

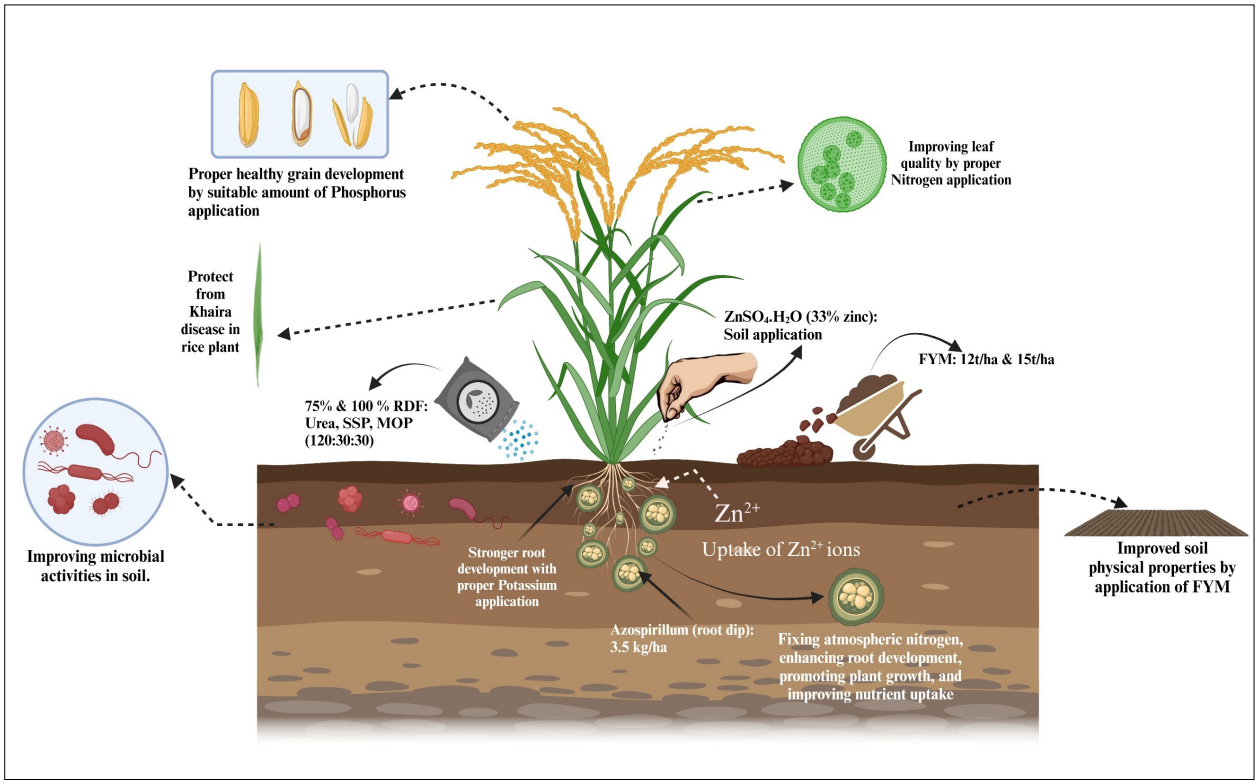


Fig. 2. Black rice (*Oryza sativa* L.) optimisation conceptual framework, which incorporates system of rice intensification (SRI) and integrated nutrient management (INM) contained 4 different nutrients' combination, showing the synergistic interaction between physiological vigour, chlorophyll biosynthesis, grain quality and soil health (T_9).

Observation recorded

All observations were recorded from 5 randomly selected plants per plot and pooled the data. Functional growth parameters were computed following standard biometric formulae (12). Altogether 5 plants were randomly harvested in each plot, pooled into one plant composite per replications for laboratory analyses. This composite sample was used for chlorophyll, crude protein and total soluble sugar analyses. To ensure analytical precision, each biochemical assay was repeated three times (technical replicates) (n = 3) and the mean of these was used for statistical analysis. The crop growth rate (CGR) for dry matter accumulation was assessed during 30–60, 60–90 and 90–120 DAT intervals, where CGR (g $m^{-2}day^{1}$) = (W_2 - W_1) / (t_2-t_1). The absolute growth rate (AGR) for plant height and dry matter was quantified at 0–30, 30–60, 60–90 and 90–120 DAT using AGR height (cm $plant^{-1}$ day^{-1}) = (H_2 - H_1) / (t_2 - t_1) and AGR dry matter (g $plant^{-1}$ day^{-1}) = (W_2 - W_1) / (t_2 - t_1) respectively. Growth analysis indices as CGR and AGR are extensively used to assess the efficiency of dry matter accumulation and productivity of the crop under various agronomic practices (13).

Chlorophyll *a*, chlorophyll *b* and total chlorophyll were measured at 30 day intervals (30, 60, 90 and 120 DAT) using the acetone extraction technique and calculated from absorbance readings as per standard chlorophyll estimation formulae (14, 15):

Chl *a* (mg g^{-1} FW) = (12.7(A663) - 2.69(A645)) × V/ (1000 × W)

Chl *b* (mg g^{-1} FW) = (22.9(A645) - 4.68(A663)) × V/ (1000 × W)

Total chlorophyll (mg g^{-1} FW) = (20.2(A645) + 8.02(A663)) × V/ (1000 × W),

Where FW = fresh weight, V = final volume (mL), W = leaf fresh weight (g) and A = absorbance at the respective wavelengths.

Crude protein was estimated by multiplying total grain nitrogen with a factor of 6.25 (16). Total soluble sugars were measured following the Anthrone reagent assay, where ethanol extracts of 100 mg powdered grain were prepared, concentrated, reconstituted and allowed to react with Anthrone reagent. Absorbance was read at 620 nm and results were expressed as mg g^{1}.

Brown rice recovery was calculated as the percentage of de-husked rice obtained from total paddy, The brown rice was processed using a standard milling/polishing machine and the weight of the milled rice was then recorded, from the milled rice, 3/4th and whole kernels were separated to determine head rice recovery. The full and broken grains were sorted and their respective weights were recorded.

Brown rice recovery (%) = (Weight of dehusked rice / Weight of paddy sample) × 100.

Milled rice recovery (%) = (Weight of polished rice / Weight of sample) × 100.

Head rice recovery (%) = (Weight of whole kernels / Weight of sample) × 100.

The quality indicators of the rice milling process such as brown rice recovery and head rice recovery are used in a wide-ranging context as indicators of grain quality and market value (17).

Soil organic carbon was analysed using Walkley and Black's wet oxidation method. Available N was determined by Kjeldahl digestion, P by Olsen's method (18) using spectrophotometric reading and K was measured after extraction with neutral normal ammonium acetate using a flame photometer. All nutrient values are expressed in kg ha^{-1}.

Grain weight and straw yield from each net plot (excluding border area) were recorded and converted into quintal per hectare basis. Harvest index (%) was computed as (grain yield / total biological yield) × 100 (19).

Irrigation management

Irrigation was provided according to the principles of the SRI using an alternate wetting and drying approach. A shallow water layer of about 2–3 cm was maintained during the 1st 7–10 days after transplanting to support proper seedling establishment (20). After this period, irrigation was applied at regular intervals, allowing the soil surface to dry until fine hairline cracks appeared before the next irrigation. Sufficient soil moisture was maintained during important growth stages such as active tillering , panicle initiation, flowering and grain filling to avoid moisture stress (21). A temporary shallow standing water layer during the early crop growth stage also helped in reducing weed infestation.

Statistical analysis

The quantitative data generated from the experiment were subjected to rigorous analysis employing standard procedures appropriate for the RBD. The primary analytical framework used was the analysis of variance (ANOVA), which was applied to evaluate the effect of the INM treatments on all recorded parameters (including growth, yield components, quality attributes and post-harvest soil nutrient status). To identify specific, significant differences among the 9 treatment means following a positive F-test result, a post-hoc comparison was performed using the critical difference (CD) method. Statistical significance was established at a probability level of 5 % ($p \leq 0.05$). Exceptions were noted for derived parameters like the CGR and AGR, where treatment effects were interpreted solely through the direct comparison of mean values.

Results and Discussion

Chlorophyll content

Integrated nutrient management brought about a substantial improvement in the physiological performance of black rice cultivated under the SRI. All measured physiological attributes-chlorophyll concentration (Fig. 3), CGR, AGR for plant height and AGR for dry matter responded positively to nutrient-enriched treatments. Among all treatments, T_9 consistently demonstrated the highest values, while the control (T_1) recorded the lowest. These findings are in accordance with recent studies reporting that INM significantly enhances growth and nutrient assimilation in coloured and specialty rice varieties (22). The increased chlorophyll content in MA led to an improvement in nitrogen availability under integrated nutrient management, which also involved Zn-mediated stimulation of chlorophyll biosynthetic enzymes, thereby increasing the photosynthetic capacity and crop growth (23). Similarly, the higher growth rate and absolute growth rate recorded under the nutrient enriched treatments might relate to improved production of assimilates and dry matter partitioning under balanced nutrient supply (21).

Crop growth rate for dry matter

Crop growth rate exhibited pronounced treatment effects, with T_9 maintaining significantly higher growth rates throughout vegetative and early reproductive phases. Crop growth rate (Fig. 4) values of 33.12 g m^{-2} day^{-1} (60–90 DAT) and 37.94 g m^{-2} day^{-1} (90–120 DAT) were nearly five-fold higher than those of the control. This enhancement corresponds well with higher chlorophyll accumulation, which strengthens photosynthetic activity and biomass conversion efficiency under INM. Similar improvements in chlorophyll content (Fig. 4) and physiological vigour under integrated nutrient strategies have been reported in recent rice experiments. The higher physiological vigour and biomass gained by INM in the present study is consistent with the recent INM results in rice growing system that showed significant improvement in crop growth rate, leaf area (Fig. 4), dry matter accumulation and productivity under sustainable rice management practices (24). Similar responses have been documented where the improvement of better root growth and enhanced photosynthetic under alternate wetting and drying irrigation systems (21)

Absolute growth rate for plant height and dry matter

The maximum AGR of the plant height and dry matter was observed under treatment T_9(Fig. 5), which was 1.417 cm $plant^{-1}$ day^{-1} and 1.305 g $plant^{-1}$ day^{-1} within the 30–60 DAT period (Fig. 5). Such physiological excellence can be explained by the combination of balanced supply of nutrients, hormonal stimulation by *Azospirillum* and Zn-aided enzyme activity, which combined to enhance cell

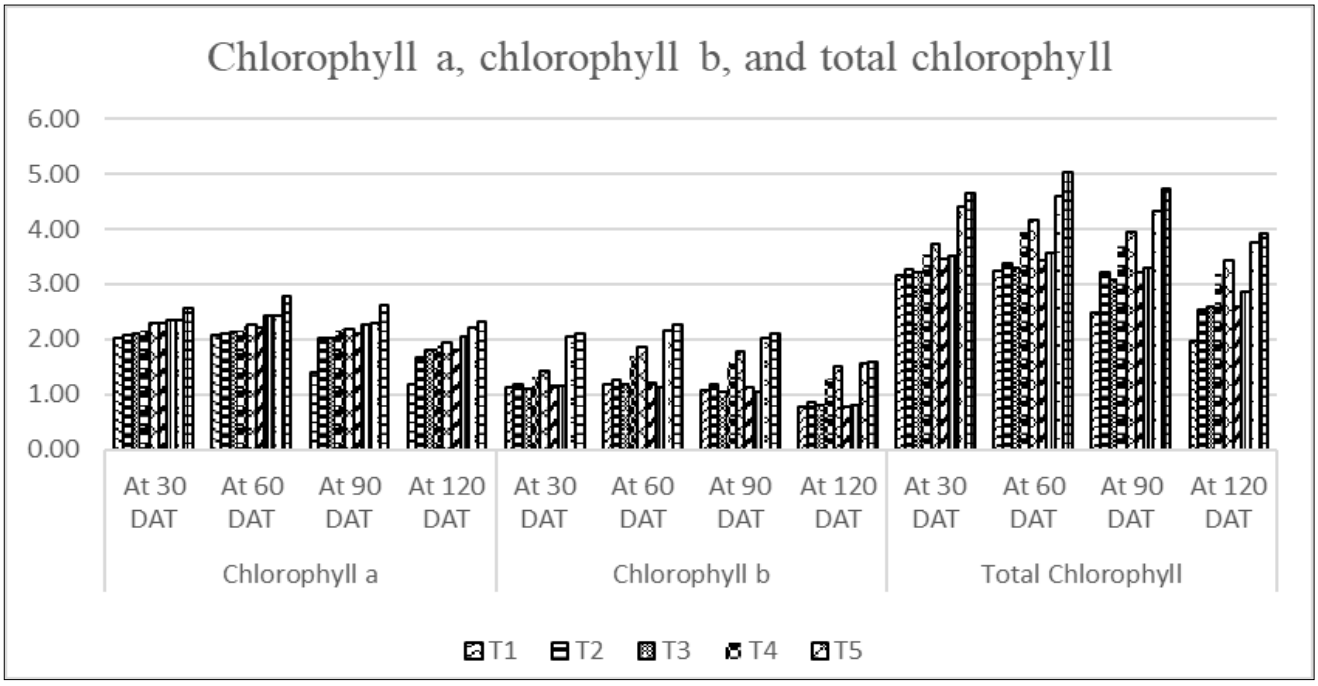


Fig. 3. Chlorophyll pigment dynamics under the integrated nutrient management in black rice.

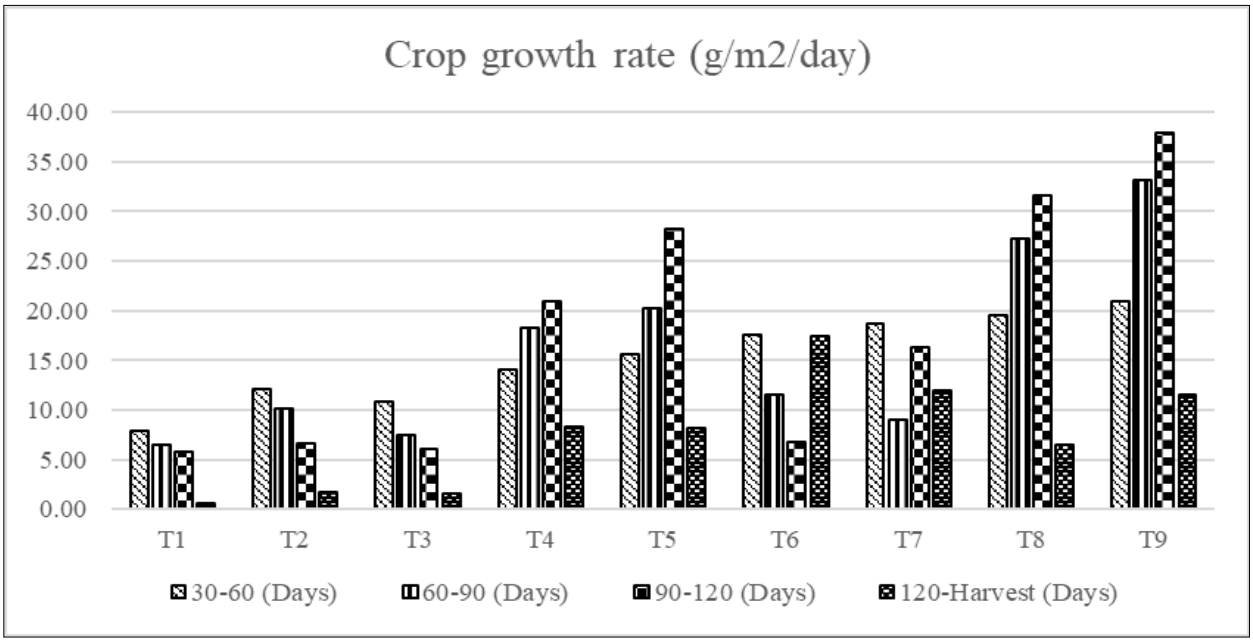
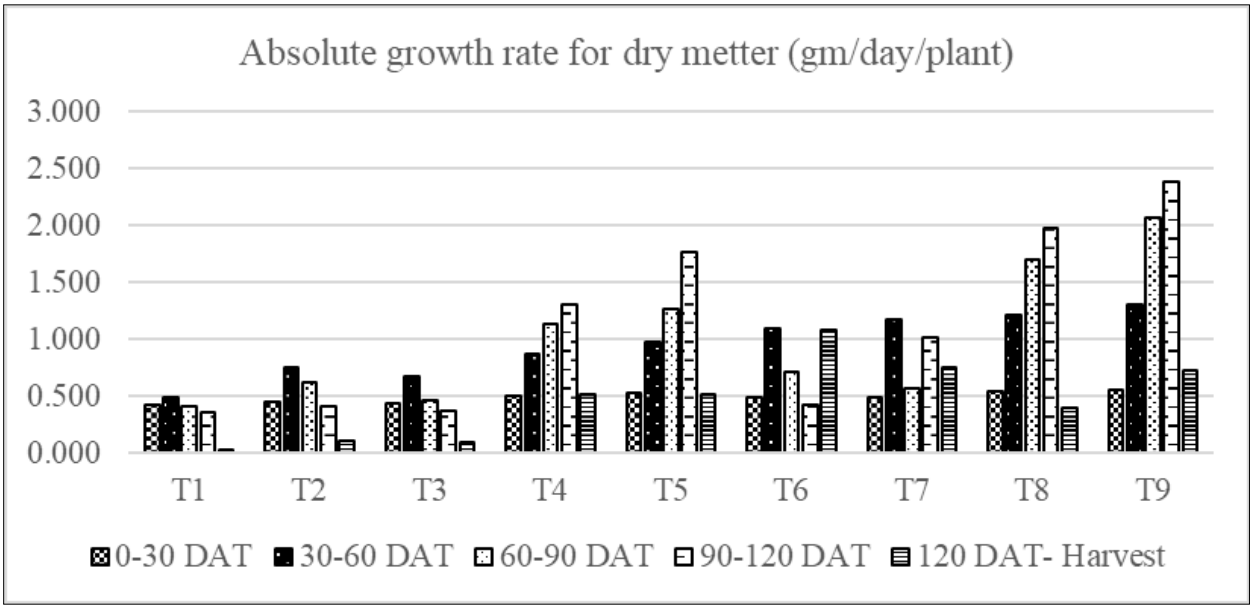


Fig. 4. Effect of different integrated nutrient management practices on crop growth rate (CGR) for dry matter (g $m^{-2}day^{-1}$).



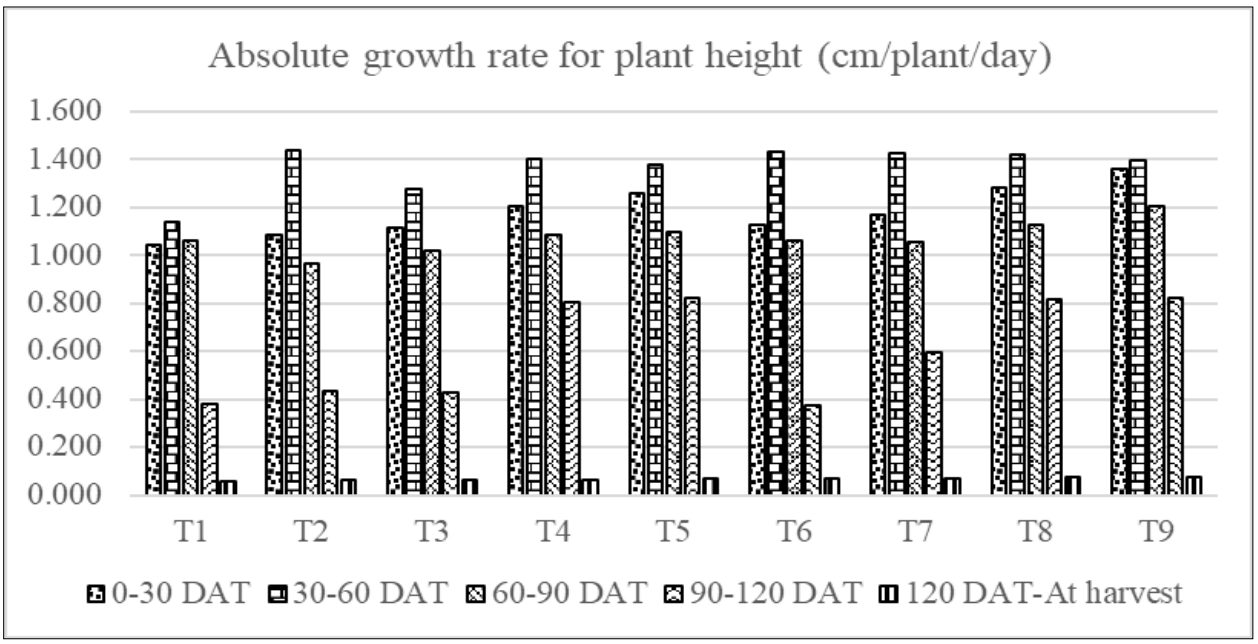


Fig. 5. Effect of different integrated nutrient management practices on absolute growth rate for plant height (g $m^{-2}day^{-1}$) and dry matter (g $m^{-2}day^{-1}$).

elongation and chloroplast stability (1). The results are consistent with the recent studies, INM enhances nutrient absorption, microbial activity and carbon uptake. Treatment T_9 demonstrated the effectiveness of integrated organic and inorganic nutrient inputs in improving rice physiology through enhanced assimilate production and greater biomass accumulation throughout the crop growth period.

Protein content (%)

Protein concentration (Fig. 6) in black rice grains varied significantly across INM treatments. The highest protein content (8.23 %) was recorded under T_9, whereas T_1 registered the minimum value (6.44 %). The improvement under T_9 appears to be driven by the combined availability of quickly accessible nitrogen from urea, sustained release of organic nitrogen from FYM and enhanced biological nitrogen fixation by *Azospirillum* (25). These components likely optimized nitrogen assimilation pathways, thereby improving protein biosynthesis during grain development. Integrating organic and inorganic nitrogen sources increases nitrogen assimilation and enhances grain protein synthesis by improving amino acid metabolism and N remobilisation during grain filling.

Total soluble sugars (mg g^{-1})

Integrated nutritional management also significantly influenced the accumulation of total soluble sugars (Fig. 5). The maximum soluble sugar content (Fig. 6) (4.89 mg g^{-1}) was observed in T_9, which differed significantly from other treatments. Enhanced sugar synthesis in this treatment can be attributed to improved nutrient availability that stimulated vegetative Vigour, enzymatic activities and photosynthetic efficiency (26). The balanced nutrient supply from urea, SSP and MOP supported the primary nutrient needs, while FYM enhanced microbial activity and soil structure. *Azospirillum* further contributed to nitrogen fixation and phytohormone production, whereas $ZnSO_4 \cdot H_2O$ likely facilitated key enzyme functions involved in carbohydrate metabolism. In contrast, nutrient-deficient conditions in T_1 limited sugar biosynthesis due to suboptimal enzymatic activity and restricted assimilate translocation. Integrated nutrient management enhances photosynthetic efficiency and boosts sugar biosynthesis pathways through improved SPS activity, chlorophyll stability and efficient source-sink functioning in cereals.

Brown, milled and head rice recovery (%)

Although statistical data did not indicate significant differences in the recovery of brown rice, results demonstrated that brown rice recovery increased, but T_9 provided the highest % of recovery (74.31) than the control (61.14). Milled rice (71.91) and head rice recovery (44.36) were found to be significantly improved under T_9 due to the effects of better grain density and structural integrity. This high performance is attributed to equal nutrient distribution, enhanced root activity and microbial stimulation by FYM and *Azospirillum* which in combination lead to grain hardness and less breakage. Moreover, Zn supplementation aids in the enzyme functions that are required to form starch-protein matrix. Such nutrient-balanced environments guarantee structurally sound grains and increased milling returns, which supports the role of integrated management in enhancing kernel stability and commercial recovery. In rice, integrated nutrient management has also shown to improve the grain quality and milling recovery, driven by improved assimilate partitioning and grain filling (27).

Soil organic carbon (%)

Soil organic carbon (SOC) exhibited a clear positive response to the INM treatments. Across the experimental treatments SOC values ranged from 0.38–0.52 %, with the maximum recorded under T_9 (100 % RDF + 15t FYM ha^{-1} + 3.5kg ha^{-1} *Azospirillum* + 40 kg ha^{-1} $ZnSO_4 \cdot H_2O$). Conversely, the minimum SOC level was observed in the control (T_1), which did not receive any nutrient amendments. The increase in SOC under nutrient-supplemented treatments can be attributed to the combined effects of FYM incorporation, which contributes substantial organic matter and enhanced root biomass driven by better nutrient supply. Treatments containing *Azospirillum* further supported SOC buildup, likely through stimulated microbial activity and biological nitrogen fixation, which together enhance root proliferation and soil organic matter return. In contrast to the control, where a slight decline in SOC was noted after harvest, all INM treatments either preserved or increased soil carbon reserves. This trend underscores the effectiveness of balanced organic-inorganic nutrient inputs in improving soil carbon stabilization and long-term soil fertility (28). The increase in soil organic carbon under integrated nutrient management may be attributed to the combined effect of FYM addition, enhanced root biomass and stimulated microbial activity, whereas the decline in the control plot reflects depletion of native carbon reserves without organic replenishment.

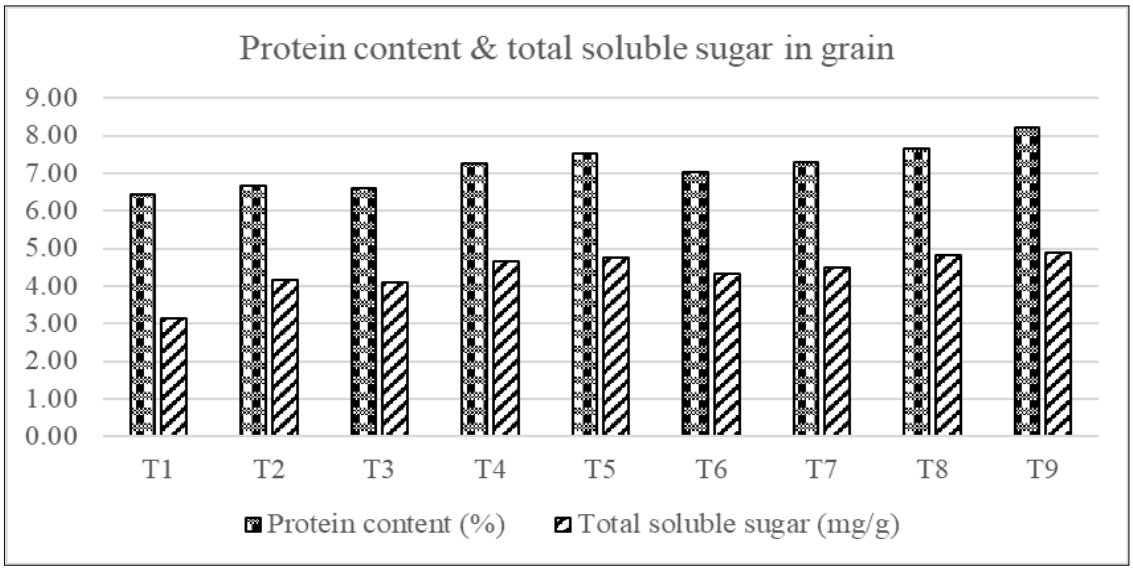


Fig. 6. Changes in grain protein and soluble sugar levels of black rice across integrated nutrient treatments.

Available nitrogen, phosphorus, pottassium content in soil after harvest

The INM practices exerted a significant influence on the post-harvest soil nutrient status (Fig. 7) in terms of available nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). Across the treatments, available N ranged from 224.77–277.10 kg ha^{-1}, available P_2O_5 from 22.27–40.89 kg ha^{-1} and available K_2O from 138.92–163.51 kg ha^{-1}, reflecting substantial improvements in soil fertility under combined nutrient sources. The maximum available N (277.10 kg ha^{-1}), P_2O_5 (40.89 kg ha^{-1}) and K_2O (163.51 kg ha^{-1}) were consistently recorded under the T_9 This treatment remained statistically at par with T_8 (75% RDF + 12 t ha^{-1} FYM + 3.5 kg ha^{-1} *Azospirillum* + 30 kg ha^{-1} $ZnSO_4 \cdot H_2O$) for available N and P_2O_5, indicating the effectiveness of integrated use of organic manures, biofertilisers and micronutrients in enhancing post-harvest nutrient pools (Fig. 7). Conversely, the lowest values of available N (224.77 kg ha^{-1}), P_2O_5 (22.27 kg ha^{-1}) and K_2O (138.92 kg ha^{-1}) were reported under T_1, the absolute control. This confirms that omission of nutrient inputs markedly reduces soil nutrient availability after crop harvest (28).

Grain yield, straw yield and biological yield

The application of the INM practices significantly enhanced the yield of the black rice with treatment T9 (Fig. 8) that achieved the highest yields in all the yield parameters. Grain yield ranged from 14.30 q ha^{-1} in the control (T_1) to a peak of 36.22 q ha^{-1} in T_9 a 153 % increase followed by T_8 (32.88 q ha^{-1}) and T_5 (29.49 q ha^{-1}) (Fig. 8). Straw yield followed a similar trajectory, increasing from 27.28 q ha^{-1} (T_1) –64.74 q ha^{-1} (T_9), with T_8 and T_5 recording 61.59 q ha^{-1} and 50.66 q ha^{-1} respectively. As a result, the biological yield was greatly optimized in T_9 (100.96 q ha^{-1}), then T_8 (94.47 q ha^{-1}) and T_5 (80.15 q ha^{-1}) as opposed to the lowest of 41.58 q ha^{-1} in the control. These results underscore the fact that the most appropriate and effective method of maximizing yield in the SRI is the combination inorganic fertiliser, FYM, Azospirillum and Zn in T_9 (Fig. 6) because it enhances nutrient availability, crop vigour and assimilate partitioning (29).

The better growth and yield recorded under treatment T_9 (Fig. 2) could be linked to the combined effect of inorganic fertilisers, farmyard manure, *Azospirillum* and Zn, which together created a more favourable nutrient environment for crop growth. The

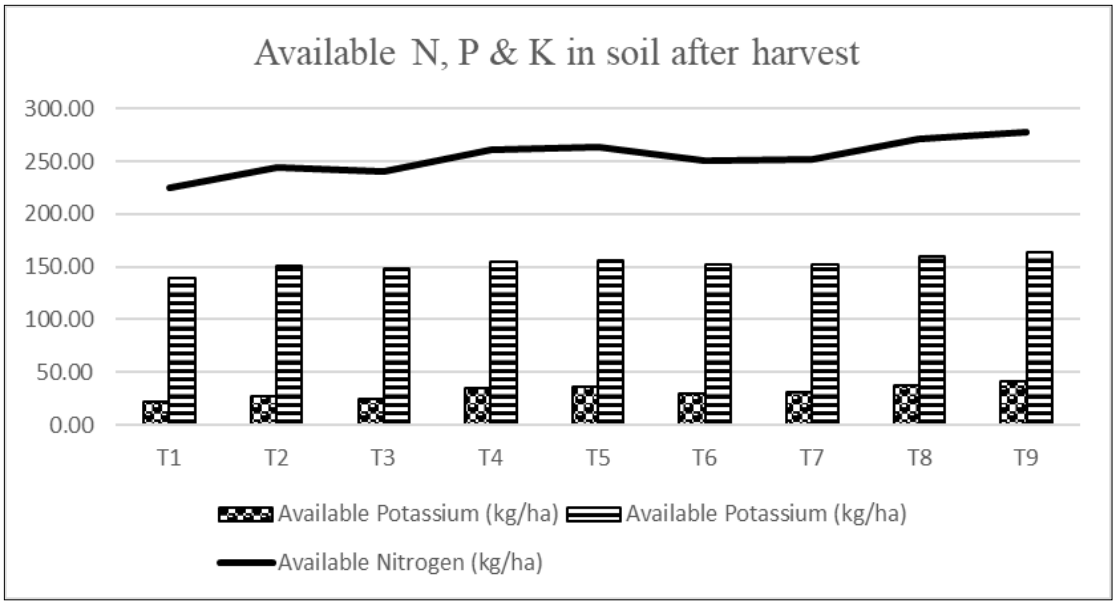


Fig. 7. Treatment-wise variation in post-harvest soil available nitrogen, phosphorus and potassium.

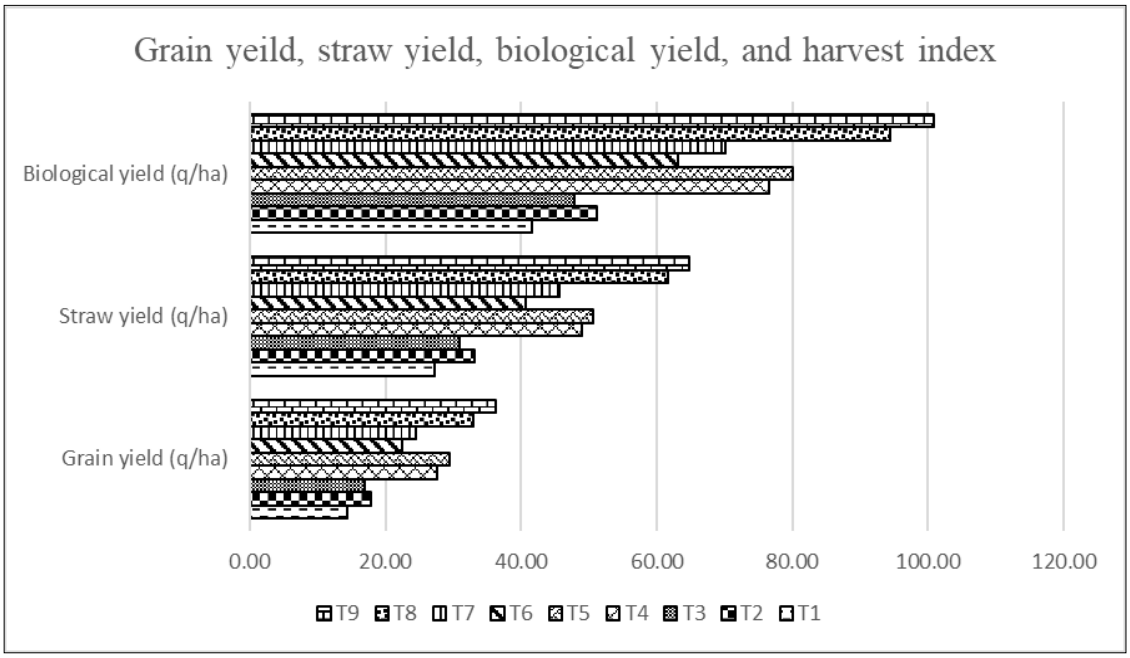


Fig. 8. Yield performance of black rice under different integrated nutrient management practices.

balanced supply of nutrients likely promoted stronger root development, improved chlorophyll formation and enhanced photosynthetic activity throughout the growing period. The addition of farmyard manure may have improved soil structure, moisture retention and microbial activity, thereby supporting better nutrient uptake. At the same time, *Azospirillum* might have contributed through biological nitrogen fixation and the production of plant growth-promoting substances. Zn, being an essential micronutrient, probably played an important role in activating several enzymatic processes and carbohydrate metabolism, which ultimately supported greater biomass production and improved grain development.

Chlorophyll dynamics

The application of INM has had a considerable increase in chlorophyll concentration (Fig. 9) in black rice and treatment T_9 had the highest chlorophyll concentration at all times (Fig. 3). This increased photosynthesis is boosted by chlorophyll *a* and this was the major pigment that was used to absorb light during the crop cycle. The combination of nitrogen supply for biosynthesis, farmyard manure to enhance soil retention and *Azospirillum* to increase root uptake has made INM successful. In addition, Zn supplementation (Fig. 2) was critical in stabilising these pigments using the enzyme activation. Chlorophyll levels decreased during the later stages of growth, but integrated treatments were effective to delay senescence, retain high levels of pigment and extend photosynthetic activity to enhance overall crop performance. The higher chlorophyll concentration and delayed senescence under INM can be explained by the synergistic effect of the combined application of organic and inorganic nutrient sources, which increase the NUE, increase the organic carbon pool and increase overall productivity of rice (30).

Physiological basis

The better CGR (Fig. 6) and AGR (Fig. 7) achieved with INM, which is treatment T_9 was a result of sustained, synergistic provision of nutrients that supports continuous accumulation of biomass. The instant effect of the inorganic fertilisers, in conjunction with the slow-releasing nutrients and enhanced soil structure as a result of the FYM provides a perfect root-zone medium to grow (31). This has been supported by *Azospirillum* which promotes root growth and fixation of N and Zn which promotes enzymatic reactions necessary to photosynthetic metabolism (32). These treatments thus ensure a high photosynthetic activity at both the vegetative and reproductive stages and the maximum growth rates are recorded at the 30–90 DAT (Fig. 3). Although AGR is expected to decrease after 90 DAT when the vegetative growth of the plant is replaced by grain filling (Fig. 7), the balanced use of organic, inorganic and biological growth factors guarantees a much greater overall productivity, in comparison with the conventional practices. In a similar pattern, AGR for dry matter accumulation progressively increased from the initial growth stages and reached its peak during 90–120 DAT, coinciding with maximum photosynthetic efficiency and biomass formation. The superior dry matter accumulation under T_9 can be linked to balanced nutrient supply, improved soil physical properties due to FYM incorporation, enhanced nitrogen availability through biological fixation by *Azospirillum* and Zn-driven activation of metabolic enzymes (30). The decline in AGR during the final growth phase (120 DAT to harvest) reflects reduced vegetative activity and the onset of senescence associated with grain development and maturation (Fig. 7).



Fig. 9. Lab experiment on chlorophyll estimation of rice leaf.

Protein and nitrogen assimilation

A marked increase in protein content under T_9 indicates enhanced nitrogen assimilation efficiency in the plants. The simultaneous supply of readily available nitrogen (urea), slow-releasing organic nitrogen (FYM) and biologically fixed nitrogen (*Azospirillum*) likely ensured a continuous nitrogen supply throughout the growing stages. This sustained nitrogen availability may have supported amino acid biosynthesis and protein deposition in grains (33). The lower protein levels observed in the control treatment confirm that nitrogen constraints directly limit protein accumulation.

Soluble sugars and carbohydrate metabolism

The substantial rise in total soluble sugar content under T_9 suggests improved source-sink coordination in response to optimal nutrient availability. farmyard manure-mediated improvements in soil structure and microbial activity likely enhanced root functioning and nutrient acquisition, while Zn involvement in enzyme activation may have facilitated efficient carbohydrate metabolism. These factors collectively contributed to greater sugar accumulation during grain filling (34). Conversely, the reduced soluble sugar content in T_1 indicates impaired photosynthate production and limited enzymatic activity under nutrient-deficit conditions.

Milling quality and grain structural integrity

The improvements in brown rice recovery, milled rice recovery and head rice recovery under T_9 highlight the link between nutrient management and grain structural robustness. Adequate macro- and micronutrient supply supports grain hardness, endosperm strength and hull separation efficiency, all of which are essential for improved milling yield (35). Farm yard manure likely enhanced cell wall strength, while Zn played an important role in maintaining membrane stability and starch-protein interactions, leading to reduced grain breakage during milling. In contrast, weaker grain structure in the control treatments resulted in lower milling efficiency.

Synergistic role of integrated nutrient inputs

The uniform trend across biochemical (protein, sugars) and physical (milling) traits indicates a strong synergistic effect of combining organic inputs with chemical fertilisers and biofertilisers. Organic matter enhances microbial populations and nutrient buffering, while *Azospirillum* improves nitrogen availability and phytohormone production. Zinc supplementation further activates key enzymatic systems and supports grain development. Such synergies create a sustained nutrient supply that optimises physiological, biochemical and structural processes during grain formation.

Implications for black rice cultivation

Improving the nutritional and processing quality of black rice is particularly important due to its reputation as a high-value functional food. The findings of this study suggest that INM not only enhances yield-related traits but also significantly improves grain quality attributes that determine market value and consumer acceptance (36). Adoption of INM strategies could therefore promote both productivity and profitability for farmers cultivating specialty rice varieties.

Overall interpretation

Collectively, the results demonstrate that INM provides a holistic pathway to improving grain nutritional quality, biochemical profile and milling efficiency in black rice. The consistent advantage of the T_9 treatment confirms that diversified nutrient sources create conditions that optimise grain filling, structural integrity and metabolite accumulation. These findings reinforce the growing consensus that sustainable nutrient management practices are indispensable for achieving high-quality rice production under subtropical agroecosystems (37).

Soil organic carbon

Integrated nutritional management (especially in treatment T_9) has been shown to improve SOC through the use of organic amendments alongside the addition of microbial inputs to maintain soil health. The addition of FYM provides a source of stable organic matter and improves soil structure, but *Azospirillum* improves microbial activity and nutrient cycling, which promotes the production of microbially-produced carbon. Moreover, equal fertilisation improves the biomass of roots, adding to the carbon inputs by rhizodeposition and root turnover. On the other hand, SOC in control plots is reduced due to the unremitting decomposition due to the non-replacement of external carbon (38). It can therefore be concluded that the use of manures, biofertilisers and inorganic sources, which are part of INM strategies, enhances carbon sequestration, soil aggregation and long-term soil fertility of intensive rice-based systems.

Yield representation

The grain, straw and biological yields of black rice are highly increased INM (Fig. 8), where treatment T_9 proposes the best results. Such increase in yield is due to increased availability of nitrogen at the vital stages of growth resulting in enhanced tillering, panicle formation and grain filling (39). Although organic fertilisers such as FYM help in improving the soil structure and water retention, biofertilisers help in root growth and Zn stimulates the metabolic enzymes to translocate carbohydrates (Fig. 2). Collectively, these elements help maintain nutrient availability, alleviate plant stress and enhance physiological efficiency, leading to increased biomass growth and enhanced assimilate partitioning to the grain. Finally, the use of INM strategies will guarantee increased productivity and the long-term fertility of soil in contrast to single chemical fertilisation or low-input systems.

Conclusion

Under subtropical conditions, the present study showed that use of the integrated nutrient management (INM) under the system of rice intensification (SRI) had a significant effect on the physiological performances, the quality of the black rice, the fertility of the soil and the productivity of black rice. T_9 always produced better growth, chlorophyll content, biomass accumulation, grain yield, protein content and post-harvest soil nutrient status among the different treatments. Additionally, the soil health and sustainability were improved by the integrated application of organic, inorganic and biological nutrients, which also increased the availability of soil organic carbon and nutrients. The results indicate that INM-based nutrient management strategies can be an effective and sustainable nutrient management strategy for optimising black rice variety, AAU-TTB-Dhan 41 (Labanya) production in SRI system. Future studies are needed to validate the practices of INM at multiple locations, to assess the soil health over a longer period of time, to evaluate nutrient-use efficiency and to determine the economic viability of INM in various agro-climatic regions.

Acknowledgements

The author is highly thankful to Lovely Professional University, Phagwara, Punjab for providing the necessary facilities to carry out the research on optimising Black Rice (*Oryza sativa* L.) Production: Integrating Nutrient Management and System of Rice Intensification for Improved Physiology, Chlorophyll Content, Quality, Soil and Yield.

Authors' contributions

NB and ASD have selected the research topic for research and prepared the framework of the research paper. NB, SD and MSCNV collected all the field data, analysed it and NB, PM, SB completed the paper writing. The final editing and proofreading were carried out by NB, ASD, AK, RB, PK and AKT. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Fukagawa NK, Ziska LH. Rice: importance for global nutrition. J Nutr Sci Vitaminol (Tokyo). 2019;65(Suppl): S2–3. https://doi.org/10.3177/jnsv.65.S2
2. Muthayya S, Sugimoto JD, Montgomery S, Maberly GF. An overview of global rice production, supply, trade and consumption. Ann N Y Acad Sci. 2014;1324(1):7–14. https://doi.org/10.1111/nyas.12540
3. Sen S, Chakraborty R, Kalita P. Rice-not just a staple food: a comprehensive review on its phytochemicals and therapeutic potential. Trends Food Sci Technol. 2020;97:265–85. https://doi.org/10.1016/j.tifs.2020.01.022
4. Uphoff N, Kassam A, Harwood R. SRI as a methodology for raising crop and water productivity: productive adaptations in rice agronomy and irrigation water management. Paddy Water Environ. 2010;9(1):3–11. https://doi.org/10.1007/s10333-010-0224-4
5. Midya A, Saren BK, Dey JK, Maitra S, Praharaj S, Gaikwad DJ, et al. Crop establishment methods and integrated nutrient management improve: Part I. Crop performance, water productivity and profitability of rice (*Oryza sativa* L.) in the Lower Indo-Gangetic Plain, India. Agronomy. 2021;11(9):1860. https://doi.org/10.3390/agronomy11091860
6. Haque MM, Biswas JC, Islam MR, Islam A, Kabir MS. Effect of long-term chemical and organic fertilization on rice productivity, nutrient use-efficiency and balance under a rice-fallow-rice system. J Plant Nutr. 2019;42(20):2901–14. https://doi.org/10.1080/01904167.2019.1659338
7. Prathap S, Thiyageshwari S, Krishnamoorthy R, Prabhaharan J, Vimalan B, Gopal NO, et al. Role of zinc solubilizing bacteria in enhancing growth and nutrient accumulation in rice plants (*Oryza sativa*) grown on zinc (Zn) deficient submerged soil. J Soil Sci Plant Nutr. 2022;22(3):971–84. https://doi.org/10.1007/s42729-021-00706-7
8. Mattos MLT, Valgas RA, Martins JFS. Evaluation of the agronomic efficiency of *Azospirillum brasilense* strains Ab-V5 and Ab-V6 in flood-irrigated rice. Agronomy. 2022;12(12):3047. https://doi.org/10.3390/agronomy12123047
9. Fukami J, Cerezini P, Hungria M. *Azospirillum*: benefits that go far beyond biological nitrogen fixation. AMB Express. 2018;8:73. https://doi.org/10.1186/s13568-018-0608-1
10. Fageria NK, Baligar VC. Enhancing nitrogen use efficiency in crop plants. Adv Agron. 2005;88:97–185. https://doi.org/10.1016/S0065-2113(05)88004-6
11. Peng S, Buresh RJ, Huang J, Zhong X, Zou Y, Yang J, et al. Improving nitrogen fertilization in rice by site-specific N management: a review. Agron Sustain Dev. 2010;30(3):649–56. https://doi.org/10.1051/agro/2010002
12. Hunt R. Basic growth analysis: plant growth analysis for beginners. London: Unwin Hyman; 1990. https://doi.org/10.1007/978-94-010-9117-6
13. Beadle CL. Growth analysis. In: Hall DO, Bolhàr-Nordenkampf HR, Leegood RC, Long SP, editors. Photosynthesis and production in a changing environment: a field and laboratory manual. London: Chapman & Hall; 1993. p. 36–46.
14. Arnon DI. Copper enzymes in isolated chloroplasts: polyphenoloxidase in Beta vulgaris. Plant Physiol. 1949;24(1):1–15. https://doi.org/10.1104/pp.24.1.1
15. Lichtenthaler HK. Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. Methods Enzymol. 1987;148:350–82. https://doi.org/10.1016/0076-6879(87)48036-1
16. Piper CS. Soil and plant analysis: a laboratory manual of methods for the examination of soils and the determination of the inorganic constituents of plants. Asian ed. Bombay: Hans Publishers; 1966.
17. Custodio MC, Cuevas RP, Ynion J, Laborte AG, Velasco ML, Demont M. Rice quality: how is it defined by consumers, industry, food scientists and geneticists? Trends Food Sci Technol. 2019;92:122–37. https://doi.org/10.1016/j.tifs.2019.07.039
18. Olsen SR, Cole CV, Watanabe FS, Dean LA. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington (DC): US Department of Agriculture; 1954. USDA Circular 939. p. 1–19.
19. Donald CM, Hamblin J. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Adv Agron. 1976;28:361–405. https://doi.org/10.1016/S0065-2113(08)60559-3
20. Thakur AK, Mandal KG, Mohanty RK, Ambast SK. Rice root growth, photosynthesis, yield and water productivity improvements through modifying cultivation practices and water management. Agric Water Manag. 2018;206:67–77. https://doi.org/10.1016/j.agwat.2018.04.027
21. Carrijo DR, Lundy ME, Linquist BA. Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. Field Crops Res. 2017;203:173–80. https://doi.org/10.1016/j.fcr.2016.12.002
22. Mangaraj S, Paikaray RK, Maitra S, Pradhan SR, Garnayak LM, Satapathy M, et al. Integrated nutrient management improves the growth and yield of rice and greengram in a rice-greengram cropping system under the coastal plain agro-climatic condition. Plants. 2022;11(1):142. https://doi.org/10.3390/plants11010142
23. Wang Y, Farooq MR, Guo Y, Sun H, Rao P, Peng Z, et al. Zinc biofortification of selective colored rice cultivars: improvement of zinc uptake, agronomic traits and nutritional value. Agriculture. 2024;14(10):1835. https://doi.org/10.3390/agriculture14101835
24. Udhaya A, Sengodan R, Govindan SK, Veerasamy R, Ponnusamy J, Swaminathan M. Effect of integrated nutrient management practices on nutrient uptake, yield and quality of improved black kavuni rice variety (CO57). Plant Sci Today. 2024;11(4):4840.
25. Bhattacharyya PN, Jha DK. Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol. 2012;28(4):1327–50. https://doi.org/10.1007/s11274-011-0979-9
26. Cassán F, Coniglio A, López G, Molina R, Nievas S, de Carlan CLN, et al. Everything you must know about *Azospirillum* and its impact on agriculture and beyond. Biol Fertil Soils. 2020;56(4):461–79. https://doi.org/10.1007/s00374-020-01463-y
27. Custodio MC, Cuevas RP, Ynion J, Laborte AG, Velasco ML, Demont M. Rice quality: how is it defined by consumers, industry, food

scientists and geneticists? Trends Food Sci Technol. 2019;92:122–37. https://doi.org/10.1016/j.tifs.2019.07.039

28. Majumder B, Mandal B, Bandyopadhyay PK, Gangopadhyay A, Mani PK, Kundu AL, et al. Organic amendments influence soil organic carbon pools and rice-wheat productivity. Soil Sci Soc Am J. 2008;72(3):775–85. https://doi.org/10.2136/sssaj2006.0378

29. Zayed BA, Salem AKM, El Sharkawy HM. Effect of different micronutrient treatments on rice (*Oryza sativa* L.) growth and yield under saline soil conditions. World Appl Sci J. 2011;13(11):2385–92.

30. Pan G, Zhou P, Li Z, Smith P, Li L, Qiu D, et al. Combined inorganic/organic fertilization enhances N efficiency and increases rice productivity through organic carbon accumulation in a rice paddy from the Tai Lake region, China. Agric Ecosyst Environ. 2009;131(3-4):274–80. https://doi.org/10.1016/j.agee.2009.01.020

31. Satyanarayana V, Prasad PVV, Murthy VRK, Boote KJ. Influence of integrated use of farmyard manure and inorganic fertilizers on yield and yield components of irrigated lowland rice. J Plant Nutr. 2002;25(10):2081–90. https://doi.org/10.1081/PLN-120014062

32. Ruíz-Sánchez M, Armada E, Muñoz Y, García de Salamone IE, Aroca R, Ruíz-Lozano JM, et al. *Azospirillum* and arbuscular mycorrhizal colonization enhance rice growth and physiological traits under well-watered and drought conditions. J Plant Physiol. 2011;168(10):1031–7. https://doi.org/10.1016/j.jplph.2010.12.019

33. Kunwar UB, Manzoor N, Wen J, Pandit NR. Integrating agronomic and molecular advancements to enhance nitrogen use efficiency (NUE) and promote sustainable rice production. Nitrogen. 2025;6(2):34. https://doi.org/10.3390/nitrogen6020034

34. Bhardwaj AK, Malik K, Chejara S, Rajwar D, Narjary B, Chandra P. Integration of organics in nutrient management for rice-wheat system improves nitrogen use efficiency via favorable soil biological and electrochemical responses. Front Plant Sci. 2023;13:1075011. https://doi.org/10.3389/fpls.2022.1075011

35. Islam SMM, Gaihre YK, Islam MN, Jahan A, Sarkar MAR, Singh U, et al. Effects of integrated nutrient management and urea deep placement on rice yield, nitrogen use efficiency, farm profits and greenhouse gas emissions in saline soils of Bangladesh. Sci Total Environ. 2024;909:168660. https://doi.org/10.1016/j.scitotenv.2023.168660

36. Kakar K, Xuan TD, Noori Z, Aryan S, Gulab G. Effects of organic and inorganic fertilizer application on growth, yield and grain quality of rice. Agriculture. 2020;10(11):544. https://doi.org/10.3390/agriculture10110544

37. Paramesh V, Kumar P, Bhagat T, Nath AJ, Manohara KK, Das B, et al. Integrated nutrient management enhances yield, improves soil quality and conserves energy under the lowland rice-rice cropping system. Agronomy. 2023;13(6):1557. https://doi.org/10.3390/agronomy13061557

38. Zhao Y, Wang M, Hu S, Zhang X, Ouyang Z, Zhang G, et al. Economics - and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. Proc Natl Acad Sci U S A. 2018;115(16):4045–50. https://doi.org/10.1073/pnas.1700292114

39. Xu M, Li D, Li J, Qin D, Yamagishi K, Hosen Y. Effects of organic manure application with chemical fertilizers on nutrient absorption and yield of rice in Hunan of southern China. Agric Sci China. 2008;7(10):1245–52. https://doi.org/10.1016/S1671-2927(08)60171-6

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (https://creativecommons.org/licenses/by/4.0/)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.