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Effect of integrating organic and inorganic sources of nutrients on growth, root morphology, yield parameters and yield of improved black kavuni rice variety (CO 57)

A Udhaya[1], S Radhamani[1*], G Senthil Kumar[1], V Ravichandhran[2], P Janaki[3] & S Manonmani[4]

[1] Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2] Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3] Nammazhvar Organic Farming, Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4] Department of Rice, CPBG, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: subhamythili@yahoo.co.in

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Abstract

The growing demand for high-quality rice and rice products is motivating farmers to cultivate traditional rice varieties. To meet this demand, rice production must increase significantly, which requires effective nutrient management practices. Therefore, this study was conducted to assess the impact of integrated nutrient management practices on the growth, root morphology, yield parameters and overall yield of improved black Kavuni rice during the *Early Kar* season (April - August 2023) and *Late Samba* season (September - January, 2023-24). The experiment followed a Randomized Block Design (RBD) with 12 treatments and 3 replications. Based on nitrogen (N) equivalence, appropriate amounts of inorganic fertilizers, farmyard manure (FYM), vermicompost (VC) and poultry manure (PM) were applied. Data on plant growth, root morphology, yield parameters and yield were recorded and analysed using LSD at a 5 % significance level. The results indicated that the treatment involving 50 % of the recommended nitrogen dose (RDN) from inorganic fertilizer, 50 % from vermicompost and foliar sprays of 0.5 % $ZnSO_4$ and 1 % $FeSO_4$ at the tillering, panicle initiation (PI) and flowering stages (T_{11}) produced significantly better growth, root morphology and yield parameters. This treatment was statistically on par with the treatment involving 50 % RDN from inorganic fertilizer, 50 % from vermicompost and foliar sprays of 0.5 % $ZnSO_4$ and 1 % $FeSO_4$ at the tillering and panicle initiation stages (T_8).

Keywords

improved kavuni; growth; root morphology; yield

Introduction

Rice (*Oryza sativa* L.) holds a prominent position among the food crops cultivated worldwide and remains the most important staple food globally. It provides major source of calories for 40 % of world's population (1). India ranks as the second-largest rice producer, following China. In India, rice is cultivated over an area of 46.3 million ha, with a production of 129.5 million tons and an average productivity of 2798 kg/ha (2). In recent times, there has been an increasing demand for quality rice and rice products, encouraging farmers to cultivate traditional rice varieties known for their stable yields, even under adverse environmental and soil conditions.

Traditional rice varieties are known for their numerous health benefits. Black Kavuni, a low-fat, pigmented, glutinous rice variety, is especially valued for its high anthocyanin content in the bran layer (3). Its potent antioxidant activity provides a range of health benefits, including anti-inflammatory, anti-cancer, immune-modulating and anti-allergic properties, earning it the reputation of being a "superfood." Black Kavuni is a season-bound variety, with its optimal growing season from September to January and it is photosensitive (4). In contrast, the improved Kavuni rice variety, CO 57, released by Tamil Nadu Agricultural University in 2023, is suitable for year-round cultivation, as it is photo-insensitive. CO 57 produces 55.74 % higher yields compared to traditional Black Kavuni. This variety is also nutritionally superior, offering high fiber and protein content with lower carbohydrates. Its lower glycemic index helps prevent sudden spikes in blood sugar levels and the presence of flavonoids contributes to its anticancer properties (5).

Nitrogen is a vital nutrient for rice growth and development. It plays a key role in enabling improved cereal varieties to reach their full productive potential. Nitrogen is essential for the synthesis of amino acids, chlorophyll and nucleotides (6). The timing of nitrogen availability is crucial for rice, as it directly affects yield components such as the number of tillers, productive tillers, grains per panicle and 1000-grain weight (7). To achieve sustainable agricultural production, it is important to develop an effective fertilization strategy that enhances both agricultural productivity and environmental quality. This involves the balanced use of both chemical and organic fertilizers (8).

Inorganic fertilizers are widely used for cultivating high-yielding crop varieties, but their excessive use has led to significant nutrient depletion in soils. Inefficient use of chemical fertilizers has contributed to the deterioration of soil quality (9). Improper nutrient management has resulted in imbalances, with some nutrients being in excess while others are deficient. According to a study, the indiscriminate use of chemical fertilizers without incorporating organic manures can lead to several problems, such as environmental pollution, health risks, disruption of natural ecosystems, destruction of biological communities essential for crop production, depletion of soil organic carbon and mineral nutrients, contamination of groundwater, altered soil pH, soil crusting, compaction, reduced water-holding capacity and soil acidification or alkalization (10).

The application of organic manures offers numerous advantages due to their balanced nutrient supply. According to a report, the balanced use of nutrients from sources like farmyard manure (FYM), poultry manure (PM), vermicompost (VC) and inorganic fertilizers is essential for maintaining soil fertility and achieving maximum crop yields (11). It was noted that organic manures enhance the soil's physicochemical and biological properties, as they are rich in beneficial microflora, enzymes and growth hormones (12). Organic nutrients also improve soil biological activity, promote biological nitrogen fixation and increase plant nutrient availability. However, the use of organic manures alone may not meet the crop's nutrient demands during critical growth stages when nutrient requirements are highest (13, 14). Vermicompost (VC), an organic fertilizer, is particularly valuable due to its high nutrient content, as well as its ability to improve soil aeration, porosity and water-holding capacity. In addition to managing organic waste, VC acts as an effective plant growth regulator. Its microbial activity enhances the availability of essential macronutrients like nitrogen, phosphorus and potassium, as well as micronutrients (15). This contributes to better root development, allowing plants to absorb nutrients more efficiently, ultimately resulting in improved growth and higher yields (16).

Micronutrient deficiencies are considered one of the primary factors contributing to the decline in rice productivity (17). Among these, zinc (Zn) and iron (Fe) deficiencies are widespread in India, significantly impacting crop growth and yield. Both Fe and Zn can become immobilized in the soil, particularly in soils with high pH and clay content. Fe tends to adsorb onto clay particles, while Zn can become fixed in the soil, rendering it unavailable to plants. As a result, foliar application of micronutrients is often used to quickly restore the plant's nutritional balance. Applying Zn and Fe through foliar sprays can enhance chlorophyll production, improve nitrogen metabolism and increase pollen viability and flowering in plants (18). According to one report, foliar spraying of these micronutrients is an effective, low-cost (19) and sustainable method for increasing Zn and Fe levels in the edible parts of staple crops. Furthermore, it was also reported that foliar application of Zn and Fe boosts rice grain production (20).

To maintain soil fertility and ensure sustainable agricultural production, the adoption of Integrated Nutrient Management (INM) practices is a viable solution. The combination of inorganic fertilizers and organic manures not only enhances soil health but also improves nutrient use efficiency, while sustaining crop productivity (21). Reports are on the use of organic manures alongside chemical fertilizers can reduce nitrogen losses and increase its availability throughout the crop's growth period (22). With this in mind, the present study was designed to assess the impact of INM practices on the growth, yield attributes and yield of the improved traditional rice variety, black kavuni.

Materials and Methods

Experimental site

The field experiment was conducted during *Early kar* (April - August, 2023) and *Late samba* (September - January, 2023-24) at the Wetland Farm, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore. The location is situated at 11°01'06" N latitude, 76°58'21" E longitude and at an altitude of 426.7 m above MSL. The experimental field’s soil was clay loam in texture with a pH range of 8.12 to 8.0 and EC of 0.47 and 0.45 dsm^{-1}. The soil nutrient status was characterized by low available $KMnO_4$- nitrogen (215 and 226 kg ha^{-1} respectively) (23), medium Olsen available phosphorus (20.8 and 21.9 kg ha^{-1} respectively) (24) and high available NH_4O Ac- potassium (569 and 585 kg ha^{-1} respectively) (25).

Experimental design and treatments

The experimental design comprised twelve treatments arranged in Randomized Block Design (RBD) with 3 replications. The details of the treatments are presented in Table 1. Prior to application, the N content of various organic manures was analyzed to determine the appropriate quantities for use. The nitrogen content of FYM, PM and VC were found to be 0.43, 2.92 and 2.26 % respectively.

Crop management

The rice variety CO 57 (Improved black Kavuni), which has a duration of 130-135 days and an average yield of 4.6 t ha^{-1}, medium grain black rice, was used in this experiment. Paddy seeds were directly sown in a nursery bed under a thin film of water. After 30 days, the rice seedlings were transplanted to the main field, which was prepared under puddled soil conditions. A spacing of 25 × 25 cm was adopted. The recommended N dose of 150 kg ha^{-1} was applied as per the treatment schedule. N and K were applied at basal, tillering, panicle initiation and heading stages, while P was applied in full as a basal application. Organic manures were also applied at the basal stage according to the treatment schedule. Prior to application, the N content in the different organic manures was analyzed.

Assessment of growth parameters

Plant height was measured from the base of the plant to the tip of the longest leaf. The number of tillers per plant was manually counted from 5 randomly selected rice plants in each treatment. The plants were carefully uprooted from the field, oven-dried at 70 ˚C for 48 h and weighed to determine their dry weight. The leaf area of the plants was measured using a LI-COR 3000 leaf area meter (26).

Assessment of root morphology by using WinRHIZO software

Root samples were collected from the experimental field using a spade, ensuring careful removal to avoid damaging the roots. The samples were then thoroughly washed with distilled water to eliminate soil, dust and debris. After washing, the root samples were placed in a tray filled with water, arranged without overlapping. This tray was then positioned in a dual scan optical scanner connected to the system. The WinRHIZO optical scanner (version 5.0) software was utilized to analyse the root samples and images were captured at a resolution of 400 dpi with a colour scale. The scanned root images of rice were assessed for various growth and developmental parameters, including Total Root Length (TRL), Surface Area (SA), Root Volume (RV) and Number of Tips (NT).

Yield parameters and yield

The number of productive tillers per m^2 was counted from each net plot. For each tagged plant, the total number of filled grains per panicle was recorded. To determine the 1000-grain weight (g), the grains were counted and weighed. Grain yield was calculated following the harvesting of the crop.

Statistical analysis

The data collected on various parameters were analysed using R software version 4.2.0 (R Studio 2022.02.3+492) in accordance with the Randomized Block Design. The analysis was conducted to determine significance difference at the 5 % level among 12 treatment means.

Results

Growth parameters

During *Early kar* and *Late samba* seasons, the highest plant height, total number of tillers m^{-2}, Leaf Area Index (LAI) (Table 2) and dry matter production (DMP) (Fig. 1) were observed with the application of 50 % RDN through inorganic fertilizer, 50 % RDN through VC, foliar spray of 0.5 % $ZnSO_4$ and 1 % $FeSO_4$ at the tillering, PI and Flowering stage (T_{11}). This treatment was comparable to the combination of 50 % RDN through inorganic fertilizer, 50 % RDN through VC, foliar spray of 0.5 % $ZnSO_4$, 1 % $FeSO_4$ at tillering and PI stage (T_8). The lowest growth parameters were recorded in the control group (T_1).

Root morphology

The adoption of different nutrient management practices significantly influenced the root morphology of rice at 30 DAT (Table 3). During the *Early kar* and *Late samba* seasons, total root length (TRL), surface area (SA), root volume (RV), and the number of tips (NT) were significantly enhanced by INM practices, specially the combination of inorganic fertilizers, VC, and foliar application of nutrients (0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering, PI and Flowering stage) (T_{11}). This treatment was comparable to T_8. The lowest values for root morphology were recorded in the control plot (T_1).

Table 1. Treatment details.

		Treatments
T_1	-	Control (Without fertilizer)
T_2	-	100 % RDN* through inorganic fertilizer
T_3	-	50 % RDN through inorganic fertilizer + 50 % RDN through FYM
T_4	-	50 % RDN through inorganic fertilizer + 50 % RDN through PM
T_5	-	50 % RDN through inorganic fertilizer + 50 % RDN through VC
T_6	-	50 % RDN through inorganic fertilizer + 25 % RDN through PM + 25 % RDN through VC
T_7	-	T_4 + Foliar application of 0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering and PI* stage
T_8	-	T_5 + Foliar application of 0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering and PI stage
T_9	-	T_6 + Foliar application of 0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering and PI stage
T_{10}	-	T_4 + Foliar application of 0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering, PI and Flowering stage
T_{11}	-	T_5 + Foliar application of 0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering, PI and Flowering stage
T_{12}	-	T_6 + Foliar application of 0.5 % $ZnSO_4$ + 1 % $FeSO_4$ at Tillering, PI and Flowering stage

Table 2. Effect of INM on growth parameters of improved black kavuni rice during *Early kar* and *Late samba* seasons.

Treatments	*Early kar* (2023)			*Late samba* (2023-24)		
	Plant height (cm)	Total number of tillers m^{-2}	LAI	Plant height (cm)	Total number of tillers m^{-2}	LAI
T_1	77.0^{h}	245^{g}	4.00^{f}	77.30^{e}	269^{g}	4.02^{f}
T_2	93.7^{cdef}	312^{ef}	4.77^{cde}	95.20^{bcd}	378^{cd}	4.85^{cde}
T_3	85.3^{g}	281^{f}	4.49^{e}	88.90^{d}	315^{f}	4.51^{e}
T_4	95.2^{cdef}	339de	4.90^{bcde}	97.80^{bc}	385^{bc}	5.00^{bcd}
T_5	99.7^{bc}	389^{bc}	5.31^{b}	100.90^{b}	411^{b}	5.42^{b}
T_6	88.3^{fg}	290^{f}	4.57^{de}	90.00^{d}	327^{ef}	4.58^{de}
T_7	97.7^{cde}	368^{cd}	4.99^{bcd}	98.10^{bc}	390^{bc}	5.16^{bc}
T_8	106.6^{ab}	416^{ab}	5.80^{a}	108.60^{a}	440^{a}	5.91^{a}
T_9	90.2^{efg}	294^{f}	4.60^{de}	92.00^{cd}	349^{e}	4.63^{de}
T_{10}	98.2^{cd}	372^{cd}	5.07^{bc}	99.30^{bc}	399^{bc}	5.21^{bc}
T_{11}	107.8^{a}	423^{a}	5.86^{a}	109.20^{a}	447^{a}	5.94^{a}
T_{12}	91.0^{defg}	297^{f}	4.61^{cde}	92.50^{cd}	354de	4.68^{de}
SEd	3.7	16	0.22	3.6	13	0.23
CD (P=0.05)	7.6	33	0.46	7.4	28	0.47

Same alphabets are on par with each other

Table 3. Effect of INM on root morphological traits of improved black kavuni rice during *Early kar* and *Late samba* seasons.

Treatments	Root morphological traits* (30 DAT)							
	Early kar (2023)				*Late samba* (2023-24)			
	TRL (cm)	SA (cm^2)	RV (cm^3)	NT	TRL (cm)	SA (cm^2)	RV (cm^3)	NT
T_1	262^{e}	289^{e}	0.60^{f}	2686^{e}	283^{d}	291^{f}	0.63^{f}	2702^{e}
T_2	351^{c}	381^{bc}	0.95^{c}	3839^{bc}	358^{c}	385^{bcde}	1.10^{cd}	3898^{bc}
T_3	314^{d}	343^{d}	0.76^{e}	3382^{d}	328^{c}	358^{e}	0.94^{e}	3492^{d}
T_4	388^{b}	394^{bc}	1.00^{bc}	4100^{b}	394^{b}	400^{bcd}	1.19^{bc}	4166^{b}
T_5	430^{a}	431^{a}	1.10^{a}	4468^{a}	442^{a}	443^{a}	1.35^{a}	4524^{a}
T_6	319^{cd}	365^{cd}	0.80^{de}	3558^{cd}	332^{c}	371de	0.97^{e}	3585^{cd}
T_7	391^{b}	395^{bc}	1.02^{b}	4109^{b}	400^{b}	406^{bc}	1.21^{b}	4170^{b}
T_8	437^{a}	433^{a}	1.13^{a}	4472^{a}	449^{a}	448^{a}	1.37^{a}	4548^{a}
T_9	323^{cd}	368^{bcd}	0.84^{d}	3566^{cd}	336^{c}	374de	1.00^{de}	3590^{cd}
T_{10}	394^{b}	398^{b}	1.03^{b}	4116^{b}	409^{b}	410^{b}	1.24^{b}	4174^{b}
T_{11}	442^{a}	436^{a}	1.14^{a}	4476^{a}	454^{a}	451^{a}	1.40^{a}	4569^{a}
T_{12}	327^{cd}	372^{bcd}	0.86^{d}	3570^{cd}	339^{c}	377^{cde}	1.02^{de}	3599^{cd}
SEd	17	15	0.03	162	15	15	0.05	164
CD (P=0.05)	35	31	0.07	336	31	31	0.10	341

Same alphabets are on par with each other

* TRL - Total Root length (cm); SA - Surface Area (cm2); RV - Root volume (cm3); NT- Number of Tips

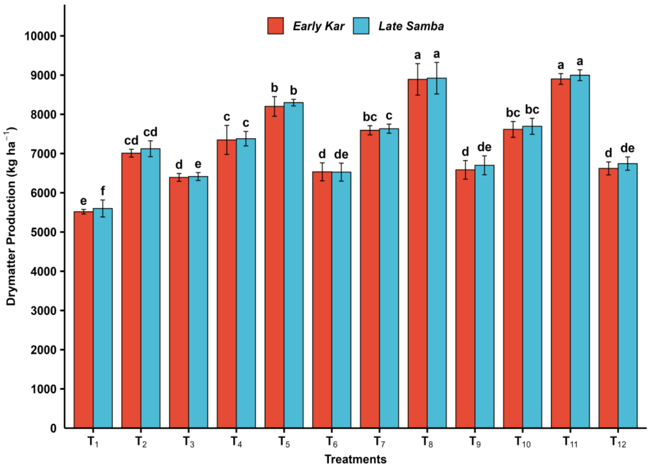

Fig. 1. Effect of INM on DMP (kg ha^{-1}) of improved black kavuni rice during *Early kar* and *Late samba* seasons. Error bar with same alphabets is on par.

Grain yield

The yield parameters (Table 4) and grain yield (Fig. 2) were significantly influenced by various nutrient management practices. During the *Early kar* and *Late samba* seasons, the application of 50 % RDN through inorganic fertilizer combined with 50 % RDN through VC and a foliar spray of 0.5 % $ZnSO_4$ and 1 % $FeSO_4$ at the tillering, PI and Flowering stage (T_{11}) resulted in higher grain yield of 3972 and 4114 kg ha^{-1} for the *Eary kar* and *Late samba* seasons, respectively. The yield was comparable to that of the treatment involving 50 % RDN through inorganic fertilizer and 50 % RDN through VC, along with foliar spray of 0.5 % $ZnSO_4$ and 1 % $FeSO_4$ at the tillering and PI stage (T_8). Conversely, the control treatment without nutrient application (T_1) recorded significantly lower yield parameters and grain yield.

Correlation analysis

Correlation analysis was conducted to assess the relationship between root morphology and yield (Fig. 3). The results indicated that total root length (0.97 and 0.94), surface area (0.98 and 0.99), root volume (0.98 and 0.98), and number of tips (0.99 and 0.98) of the improved traditional rice were positively correlated with grain yield during *Early kar* and *Late samba* seasons respectively.

Table 4. Effect of INM on yield parameters of improved black kavuni rice during *Early kar* and *Late samba* seasons.

Treatments	*Early kar* (2023)			*Late samba* (2023-24)		
	No. of productive tillers m^{-2}	No. of filled grains $panicle^{-1}$	1000 grain weigh (g.)	No. of productive tillers m^{-2}	No. of filled grains $panicle^{-1}$	1000 grain weight (g.)
T_1	148^{f}	96^{g}	20.50	173^{f}	101^{f}	20.87
T_2	224^{d}	125^{de}	21.32	246^{d}	130^{d}	21.39
T_3	194^{e}	109^{f}	20.89	219^{e}	117^{e}	20.98
T_4	246^{c}	131^{d}	21.40	268^{c}	142^{c}	21.49
T_5	282^{b}	161^{b}	21.60	306^{b}	165^{b}	21.87
T_6	201^{e}	113^{f}	20.95	224^{e}	119^{de}	21.11
T_7	258^{c}	144^{c}	21.42	281^{c}	148^{c}	21.51
T_8	301^{a}	174^{a}	21.89	330^{a}	180^{a}	22.00
T_9	207^{de}	115^{ef}	21.20	232^{de}	123^{de}	21.33
T_{10}	261^{c}	148^{c}	21.47	284^{c}	151^{c}	21.55
T_{11}	309^{a}	176^{a}	22.00	335^{a}	185^{a}	22.09
T_{12}	211^{de}	119^{ef}	21.25	237de	126^{de}	21.36
SEd	9	5	1.06	10	6	1.07
CD (P=0.05)	18	10	NS	20	11	NS

Same alphabets are on par with each other

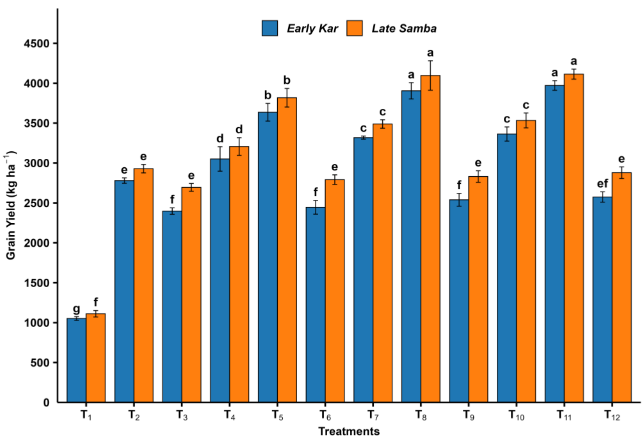

Fig.2. Effect of integrated nutrient management on grain yield (kg ha^{-1}) improved black kavuni rice during *Early kar* and *Late samba* seasons. Error bar with same alphabets is on par.

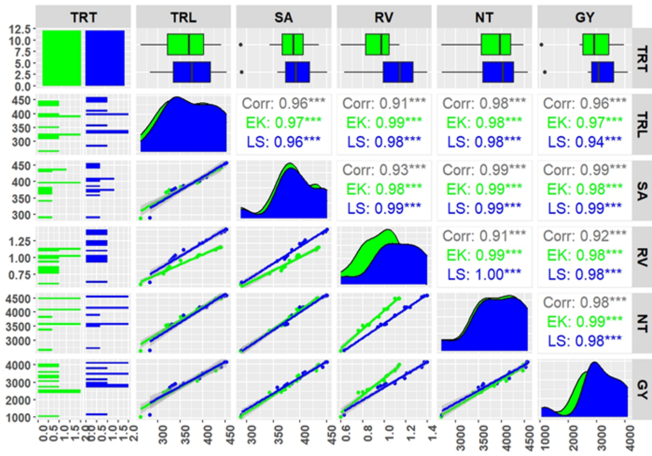

Fig. 3. Effect of integrated nutrient management on correlation analysis of root morphological traits and yield of improved black kavuni rice during *Early kar* and *Late samba* seasons (TRT- Treatments; TRL - Total Root length (cm); SA - Surface Area (cm^2); RV - Root volume (cm^3); NT- Number of Tips; GY- Grain yield (kg ha^{-1}); EA- *Early kar*; LS- *Late samba*).

Discussion

Plant height (cm)

The highest plant height may be attributed to the combined application of organic and inorganic nutrients, which significantly increases the available N content in the soil. The addition of organic sources likely enhanced nitrogen availability due to the mineralization of nitrogen from organic manures. This increases nitrogen availability and uptake by plants, subsequently boosted metabolic activity, leading to the formation of meristematic tissues, improved cell division and elongation, ultimately resulting in increased plant height. These findings align with the observations of (27). According to a study, foliar fertilization with Fe and Zn significantly impacts plant growth parameters (28). This effect may be due to the direct entry of nutrients into metabolic sites, as both Zn and Fe play crucial roles in plant growth-related metabolic activities. The influence of Zn and Fe on auxin metabolism may have contributed to the significant improvements in growth traits during critical crop growth stages. These results are consistent with the findings of (29). The shortest plant height was recorded in the control treatment (T_1), which did not receive any fertilizer application.

Total number of tillers m^{-2}

Tillering results from the proliferation of auxiliary buds, which is closely linked to the nutritional conditions of the culm. During its early growth phase, a tiller draws nutrients and carbohydrates from the culm and this process is enhanced by the application of nitrogen (30). The use of organic manures in conjunction with inorganic fertilizers increases nitrogen availability, resulting in a healthier soil system and greater root activity. This observation is consistent with the findings of (31). The increased root growth, proliferation and nutrient translocation and uptake lead to a higher number of tillers (32). According to one report, tillering is a crucial characteristic for cereal crops like rice, as it is essential for producing an adequate number of panicles (33). Effective tillering, which ensures good panicle formation, is necessary to achieve higher crop yields. The control treatment (T_1) recorded a lower number of tillers per square meter in both seasons.

Leaf Area Index (LAI)

The addition of nitrogen promotes the production of more leaves and increases leaf area. This effect can be attributed to the adequate supply of nutrients, which enhances both the quantity and size of leaves, thereby improving the crop's ability to absorb nutrients through enhanced root development and greater carbohydrate transfer from the source to the growing grains (34). The Leaf Area Index (LAI) is a crucial plant growth indicator that measures how effectively crops can absorb solar energy for biomass production, the extent of transpiration and how crop management techniques influence crop development (35).

Dry matter production (kg ha^{-1})

The highest dry matter yield can be attributed to increased nitrogen availability, which boosts the production of photo assimilates through the leaves. These photo assimilates are essential for plant growth during the vegetative stage and are subsequently distributed to the reproductive organs. Micronutrients play a critical role in crop growth, photosynthesis, respiration and various biochemical and physiological processes, contributing to enhanced biomass (36). When plants receive an adequate supply of major nutrients, they produce more leaves, leading to improved photosynthesis. This, in turn, enhances root and shoot growth, ultimately increasing dry matter production at all stages of observation (37). The dry matter yield is largely dependent on the mineral nitrogen status throughout the growing stage; thus, the rice crop produces a substantial amount of dry matter yield through the mineralization of organic nitrogen forms. The improved agronomic efficiency of both organic and inorganic nitrogen sources is reflected in the increased dry matter yield of the paddy crop (38). Higher accumulation of dry matter prior to heading and its greater translocation into the developing grains during the filling stage result in increased grain yield (39).

Root morphology

Roots are essential components of plant organs, playing a crucial role in water and nutrients uptake, the production of plant hormones and the anchoring of plants, as well as facilitating interactions with soil microbes. It is believed that roots and shoots interact reciprocally in terms of growth and activity. A high photosynthetic rate of shoots provides the roots with adequate photosynthates, ensuring strong root activity. Conversely, active roots enhance productivity by supplying shoots with sufficient nutrients to support high photosynthetic rate (40). Improved root characteristics result from increased enzymatic activity and the movement of certain degraded root materials near the rhizosphere, facilitated by the combined application of inorganic nutrients and organic manures. This approach enhances microbial populations and creates a synergistic effect on yield (41) (Fig. 4). According to one study, a vigorous root system leads to higher grain yields and improved plant N absorption (42). The maximum size and surface area of the absorbent roots determine greater nutrient absorption, contributing to plant health and increased productivity.

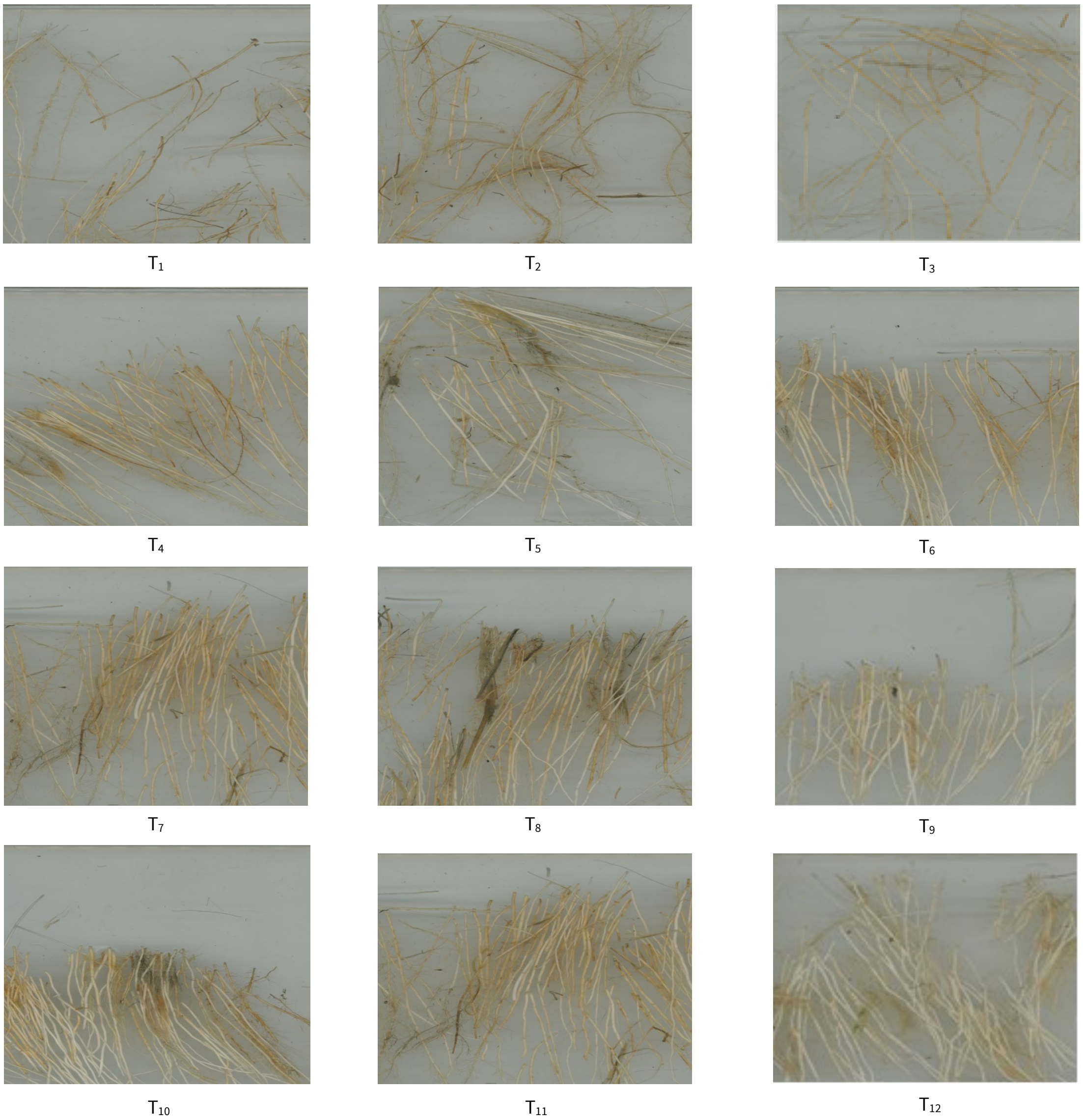

Fig. 4. Comparative photographs of root morphology in all the treatments.

Grain yield

The highest yield can be attributed to the combined application of organic and inorganic nutrient sources, which likely provided essential nutrients and acted as catalysts for the effective utilization of these nutrients, thereby increasing grain yield. Additionally, the basal application of vermicompost (VC) may have facilitated a gradual release of nutrients, aligning with the crop's growth requirements (43). This continuous supply of nutrients in balanced quantities throughout all growth stages allows rice plants to assimilate sufficient photosynthetic products. The resulting increase in dry matter and source capacity may lead to the production of more panicles, each with more fertile grains, as well as higher test weights and grain yields (44). According to studies (45-47), zinc (Zn) and iron (Fe) are essential for several enzymes that regulate plant metabolism. They play critical roles in auxin synthesis, carbohydrate conversion and sugar regulation within plants. The application of Zn and Fe is vital for promoting growth hormones and supporting the reproductive processes necessary for grain formation. By simultaneously applying organic and inorganic nutrient sources, plant nutrient storage in the soil is preserved, which not only enhances growth but also increases the translocation of resources from source to sink. Additionally, foliar sprays of Zn and Fe help to overcome yield barriers, resulting in higher overall yields.

Correlation analysis

The root system of rice is crucial for its ability to absorb nutrients and water, interact with soil microorganisms, and regulate hormonal balances, all of which are essential for yield parameters that ultimately enhance overall yield (48). Total root length, surface area and the number of root tips are essential for the uptake of nutrients and water, contributing to increase grain yield. Root volume reflects the overall biomass and storage capacity of the root system. An increased root volume allows more extensive storage of nutrients and water, promoting sustained growth and development, which leads to higher yields (49) (Fig. 3).

Conclusion

From this field experiment, it can be concluded that the application of 50 % RDN through inorganic fertilizer, combined with 50 % RDN through VC and foliar sprays of 0.5 % $ZnSO_4$ and 1 % $FeSO_4$ at the tillering, PI and Flowering stage, was most effective in enhancing plant growth, root characteristics, yield parameters and overall yield in the improved traditional black kavuni rice. Traditional rice varieties represent a rich genetic diversity that is essential for food security and adaptation to changing environmental conditions. INM supports the sustainable cultivation of these traditional varieties, helping to conserve their genetic traits and ensure their viability for future agricultural systems.

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Authors' contributions

UA wrote the first draft of the paper; RS conceptualized, reviewed and edited the research paper holistically. SG, RV, JP and MS reviewed the paper and shared their inputs for upscaling.

Compliance with ethical standards

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

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