PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7788

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RESEARCH ARTICLE

Impact of integrated nutrient management on growth, productivity and soil biochemical property of kharif rice

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OPEN ACCESS

ARTICLE HISTORY
Received: 17 February 2025
Accepted: 11 March 2025
Available online
Version 1.0 : 18 March 2025

Check for updates

Additional information

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

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CITE THIS ARTICLE
Sagar P, Prasannajit M, Bijay KM, Narayan P, Araya Kumar BM. Impact of integrated nutrient management on growth, productivity and soil biochemical property of kharif rice. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.7788

Abstract

An experiment was conducted during kharif season of 2022 and 2023 to evaluate the performance of rice under integrated nutrient management using inorganic, organic and nano fertilizers. The experiment was designed as a Randomized Block Design (RBD) for rice during Kharif. The rice variety "Kalinga Dhan 1204" was sown in July with seven treatments: T_1- Control (No fertilizer), T_2- Full soil test based nitrogen recommendation (STBNR) through inorganic sources, T_3- Full STBNR through organic sources (FYM), T_4- Full STBNR through 50 % organic (FYM) + 50 % inorganic sources, T_5- Full STBNR through 25 % organic (FYM) + 75 % inorganic sources, T_6- 50 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage), T_7- 75% N through inorganic sources + 2 nano urea spray (Tillering & PI stage). Pooled data indicated application of Full STBNR through 25 % organic (FYM) + 75 % inorganic sources resulted in highest plant height (117.05 cm), leaf area index (LAI) (5.26), dry matter production per square meter (1085.50 g m^{-2}), number of tillers per square meter (393.17), panicle length (26.60 cm), panicle weight (2.96 g), number of filled grains per panicle (166.67), grain yield (6.64 t ha^{-1}), straw yield (7.45 t ha^{-1}) and harvest index (47.13 %).

Keywords

Kalinga Dhan 1204; nano urea; rice; yield

Introduction

India's agriculture heavily relies on rice-based cropping systems, which play a crucial role in ensuring food security, boosting incomes, enhancing livelihoods, generating employment and mitigating poverty. These systems support over half a billion farming families. Rice (*Oryza sativa* L.) serves as the main dietary staple for approximately two-thirds of the world's population. In 2023, India reached a record rice production of about 137.8 million metric tons. The rice cultivation area was around 47.8 million hectares, showcasing consistent agricultural practices over recent years. The average yield of rice stood at 4.3 tons per hectare, continuing a positive trend in productivity improvements over the last decade. This marked an increase from the 135.7 million metric tons produced in the previous year, indicating the effectiveness of enhanced farming techniques and resilience despite environmental challenges (1). *Kharif* agriculture is vital for food security, economic growth, rural employment and sustainable water use, relying on monsoon rains for high-yield crop production. Major kharif crops are rice, maize and cotton, whereas major fertilizers used are urea, di ammonium phosphate (DAP) and muriate of potash (MOP). In the state of Odisha rice is the predominant kharif crop.in the year 2023 out of total cultivated area of 6.18 million hectares, *kharif* rice area was 4.06 million hectares. In Odisha rice is mostly grown in low and medium lands. Major low land verities are CR Dhan 810, CR Dhan 510, Swarna and Lalat (150-165 days duration), while major medium land verities are CR Dhan 309, Pratikshya, Ajay and Khandagiri (130-145 days duration). For this experiment recently released medium land high yielding verity Kalinga Dhan 1204 was used. Application of only traditional N, P, K fertilizers resulted in increasing cost of cultivation, soil and atmosphere pollution, declining soil health and low nutrient use efficiency. Application of only N, P, K fertilizer without any organic manure resulted in declining response of crop to fertilizers gradually. Hence application of NPK fertilizers alone is insufficient to maintain soil productivity under continuous intensive cropping (2). Integrated Nutrient Management (INM) using organic manure and nano fertilizers is crucial for sustaining crop production and productivity while maintaining soil health in these conditions. Fertilizers have become increasingly vital for enhancing food production and quality, especially with the development of high-yielding and fertilizer-responsive cultivars. While researchers have focused on improving rice production, there have been limited studies on the application of nanomaterials in agriculture (3, 4). Nanomaterials are units that range in size from 1 to 100 nm in at least one dimension (5). Nano fertilizers represent the next advancement in nanotechnology for achieving more sustainable agriculture. For instance, compared to over 1 mm of traditional urea prill, nano urea contains 55000 nitrogen particles (6). Nano urea reduces the need for conventional urea by half or more while enhancing crop production, soil health and the nutritional quality of the yield without compromising soil productivity. Additionally, nano urea is less expensive than conventional urea, reducing input costs for farmers and increasing their profits. The addition of organic manures enhances soil's physical and biological properties, soil fertility and crop yields (7). However, organic manures cannot fully replace chemical fertilizers due to their lower nutrient content. Determining the optimal substitution level of chemical fertilizers with organic nutrients is essential to maintain yields. The long-term nutrient release from organic sources can also fulfil the nutrient needs of the succeeding crop, potentially reducing the need for additional fertilizers. Application of biofertilizer helps to convert the nutrients into available form and resulting in better uptake and utilisation of nutrients. Previously some experiments had been conducted by integrating organic manure with N, P, K fertilizers but research on nano fertilizers in integrated nutrient management was very much limited. Hence considering all the factors, the study was conducted on kharif rice to evaluates impact of integrated nutrient management including inorganic, organic and nano fertilizers to improve, productivity and profitability of rice without hampering soil health.

Materials and Methods

The field experiment was conducted at Agronomy Main Research Farm, Central Research Station, Odisha University of Agriculture and Technology, Bhubaneswar during the Kharif season of 2022 and 2023. The latitude and the longitude of the research station was $20^0$15'53.7"N and $85^0$52'45.78"E respectively, with an altitude of 25.9 m above the mean sea level. The study aimed to evaluate the performance of rice under integrated nutrient management using inorganic, organic and nano fertilizers.

The experiment was designed as a Randomized Block Design (RBD) for rice during Kharif. The rice variety "Kalinga Dhan 1204" was sown in July with seven treatments: T_1- Control (No fertilizer), T_2- Full soil test based nitrogen recommendation (STBNR) through inorganic sources, T_3- Full STBNR through organic sources (FYM), T_4- Full STBNR through 50 % organic (FYM) + 50 % inorganic sources, T_5- Full STBNR through 25 % organic (FYM) + 75 % inorganic sources, T_6- 50 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage), T_7- 75 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage).

Data on yield parameters were collected at harvest from five randomly selected plants in each plot and averaged to obtain replicated data. Plant height, leaf area index (LAI) at 90 days after transplanting (90 DAT), Soil and Plant Analytical Development (SPAD) value at 60 days after transplanting (60 DAT) and dry matter production were the growth attributes measured. Number of tillers per square meter, number of grains per panicles, grain yield, straw yield and harvest index were all gathered as yield characteristics of rice.

Plant height

Ten plants were selected from each plot randomly and their height was measured. The average height was taken as the plant height for that treatment.

Leaf area index (LAI)

Five plants were randomly selected from every plot at 90 days after transplanting (DAT) and leaf area was measured using leaf area meter. The leaf area was determined by calculating the average leaf area per plant. This average leaf area was then divided by the ground area or spacing of the plant to find LAI.

$$\text{Leaf area index} = \frac{\text{Total area of leaf surface per plant}}{\text{Ground area occupied by the plant}}$$

Soil and Plant Analytical Development (SPAD) and green seeker value

Ten hills were randomly selected from each plot and SPAD and green seeker readings were recorded from the lower, middle and upper leaves of each plant using a SPAD meter at 60 days after transplanting (DAT)

Dry matter production per square meter

Five hills were randomly selected from each treatment. The leaves, stems and roots were separated and oven-dried for 24 hrs at 60 ± 5 °C. The dry weight of all parts, except the roots, was summed and average then converted into grams per square meter (g m^{-2}) by multiplying it with population per square meter.

Number of tillers per square meter

Five hills were taken randomly from each treatment and tillers of each hill counted at harvest. The mean numbers of tiller $hill^{-1}$ were calculated and multiplied by number of plants per square meter for that treatment.

Number of grains per panicle

Ten panicles were taken each plot and the number of grains was then counted. The average number of grains per panicle for each treatment was then calculated.

Grain yield and straw yield- Grain yield and straw yield were taken separately for each treatment after threshing and expressed in tons per hectare (t ha^{-1}).

Harvest index (%)

Harvest Index was calculated by using the following formulae;

$$\text{Harvest index} = \frac{\text{Grain yield}}{\text{Grain yield + Straw yield}} \times 100$$

Soil microbial (Bacteria, actinomycetes, fungus population

Specific culture media were prepared for microbial isolation, including nutrient agar for bacteria, actinomycete isolation agar for actinomycetes and potato dextrose agar for fungi. The total counts of soil bacteria, actinomycetes and fungi were determined using the serial dilution and plate count method. These microbial populations were calculated per gram of dry soil using the formula:

$$\text{Total population per gram of oven dry soil} = \frac{\text{Number of colonies x Dilution factor}}{\text{Dry weight of one gram moist soil}}$$

Soil organic carbon content

Soil organic carbon content was determined using a standard protocol (8).

Results and Discussion

Effect of integrated nutrient management on growth attributes of rice: Among different treatments, full STBNR (25 % organic (FYM) + 75 % inorganic) produced the highest plant height (115.43 cm and 118.67 cm) during both 2022 and 2023 and it was at par with full STBNR (50 % organic (FYM) + 50 % inorganic) (108.33 cm and 114.33 cm) at harvest. Similarly lowest plant height at harvest was recorded with control (No fertilizer) (96.50 cm and 96.33 cm) during both the years, as shown in Table 1. Highest mean plant height was obtained with full STBNR (25 % organic (FYM) + 75 % inorganic) (117.05 cm) whereas lowest mean plant height (97.58 cm) was obtained with control (No fertilizer) as shown in Table 1. As the plants matured, their height increased dramatically compared to the control group.

Nitrogen contributes to an increase in chlorophyll content at all growth stages, as it is an essential component that likely enhances photosynthesis and, consequently, plant height. The significant increase in plant height may be attributed to the enhanced availability and consistent release of nutrients provided by organic sources such as FYM (farmyard manure). These nutrient sources may support plant recovery and growth, particularly towards the reproductive stage. Adequate supply of plant nutrients positively affects plant height (9). The observed maximum plant height could be linked to the application of combination of inorganic fertilizer and FYM, which may have boosted the plant's metabolic and physiological activities, enabling greater nutrient assimilation and growth. Additionally, integrated nutrient management practices might have increased nutrient availability, thereby facilitating the conversion of carbohydrates into proteins and enhancing meristematic cellular activities such as cell division and elongation. This cellular activity is expressed in measurable growth attributes, such as increased plant height, which ultimately leads to greater dry matter accumulation. Similar outcomes were previously reported (10).

Similarly plant height at harvest obtained with 75 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage) (103.67 cm and 105.67 cm) was found to be at par with 50 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage) (101.53 cm and 101.67 cm) and full STBNR through inorganic sources (102.67 cm and 104.67 cm) during both years (2022 and 2023). The effectiveness of nano urea may be attributed to the slow and controlled release of nutrients from nano-nitrogen, which regulates plant development and enhances nutrient uptake. Nano fertilizers improve nutrient absorption, transportation and utilization. Similar findings have already reported (11).

The leaf area index (LAI) was kept on increasing up to 90 days after transplanting, then it was reduced. Among different treatments, highest leaf area index (LAI) at 90 DAT (5.22 and 5.29) was obtained with full STBNR through 25 % organic (FYM) + 75 % inorganic sources in both years (2022 and 2023) followed by full STBNR through 50 % organic (FYM) + 50 % inorganic sources (5.02 and 5.09). Lowest leaf area index (LAI) (3.43 and 3.53) was recorded with control (No fertilizer). Leaf area index (LAI) at 90 DAT obtained with 75 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage) (4.73 and 4.82) was found to be at par with full STBNR through inorganic sources (4.67 and 4.59). Higher mean leaf area index was obtained with full STBNR through 25 % organic (FYM) + 75 % inorganic sources (5.26) whereas lowest mean leaf area index (3.48) was recorded with control (No fertilizer) as shown in Table 1.

Among different treatments, full STBNR (25 % organic (FYM) + 75 % inorganic) resulted in highest Soil and Plant Analytical Development (SPAD) reading (39.43, 40.00 and 39.72) (during 2022, 2023 as well as pooled) and green seeker reading (0.63, 0.64 and 0.63) at 60 DAT (during 2022, 2023 as well as pooled). Similarly lowest SPAD reading (32.70, 33.10 and 32.90) and green seeker reading (0.51, 0.51 and 0.51) at 60 DAT was recorded with control (No fertilizer) during both the years as well as mean as shown in Table 2.

Leaf area development plays a crucial role in determining a crop's response to added nitrogen. Increased leaf area facilitates greater light interception, contributing to

Table 1. Effect of integrated nutrient management on plant height and leaf area index of rice

Particular	Plant height (cm)			Leaf area index (90 days after transplanting)		
Integrated nutrient management	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T1-Control (No fertilizer)	96.50	96.33	96.42	3.43	3.53	3.48
T2-Full STBNR through inorganic sources	102.67	104.67	103.67	4.67	4.59	4.63
T3-Full STBNR through organic sources (FYM)	99.97	99.33	99.65	4.00	3.96	3.98
T4-Full STBNR (50% organic (FYM) + 50% inorganic)	108.33	114.33	111.33	5.02	5.09	5.06
T5-Full STBNR (25% organic (FYM) + 75% inorganic)	115.43	118.67	117.05	5.22	5.29	5.26
T6-50% N inorganic sources + 2 nano urea spray	101.53	101.67	101.60	4.46	4.50	4.48
T7-75% N inorganic sources + 2 nano urea spray	103.67	105.67	104.67	4.73	4.82	4.78
SEm±	3.49	3.39	2.24	0.21	0.23	0.14
CD (P= 0.05)	10.75	10.44	6.53	0.65	0.71	0.41

Values indicate mean of 3 replications; Pooled data indicate average of 2022,2023

SEm = Standard error of mean, CD = Critical difference

higher dry matter production. Additionally, the combined use of organic manure and chemical fertilizers promotes chlorophyll and carbohydrate production, potentially leading to increased photosynthesis, leaf expansion and an increased leaf area index. These findings align with the previous observations (12, 13). Similarly, use of nano urea increases chlorophyll formation and the rate of photosynthesis, leading to overall plant growth and the development of a greater number of leaves. Use of nano urea increases nutrient use efficiency, nutrient uptake leading to better plant growth and higher leaf area index (14, 15).

The treatment full STBNR through 25 % organic (FYM) + 75 % inorganic sources resulted in the highest dry matter production per square meter at harvest (1068.33 g m^{-2} and 1102.66 g m^{-2}) during both the years (2022 and 2023) and it was at par with full STBNR through 50% organic (FYM) + 50 % inorganic sources (1009.33 g m^{-2}cm and 1028.56 g m^{-2}), whereas lowest dry matter production per square meter at harvest (497 g m^{-2} and 512.98 g m^{-2}) was recorded with control (No fertilizer). Similarly dry matter production per square meter at harvest obtained with 75 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage) (890.67 g m^{-2} and 921.18 g m^{-2}) was found to be at par with full STBNR through inorganic sources (898.00 g $m^{-2}$and 908.96 g m^{-2}). Higher mean dry matter production per square meter at harvest was obtained with full STBNR through 25 % organic (FYM) + 75 % inorganic sources (1085.50 g m^{-2}) whereas lowest mean dry matter production per square meter at harvest (504.99 g m^{-2}) was recorded with control (No fertilizer) as shown in Table 2.

The combined use of inorganic fertilizers and organic manure ensures balanced nutrient availability, improving soil structure, nutrient uptake and microbial activity, leading to favourable soil conditions. This supports increased vegetative growth and dry matter production through enhanced leaf and stem dry weight. Nitrogen contributes to higher photosynthetic activity, light interception, tiller production and leaf area development, boosting overall dry matter accumulation. These findings align with previous research (16). Similarly larger surface area and smaller particle size of the nano urea, which allows it to penetrate the plant more effectively and improve nutrient use efficiency, leading to increased dry matter production.

***Effect of integrated nutrient management on yield attributes and yield of rice*:** Highest number of tillers per square meter at harvest obtained with full STBNR (25 % organic (FYM) + 75 % inorganic) (382 and 404.33) during both years (2022 and 2023) and it was at par with full STBNR through 50 % organic (FYM) + 50 % inorganic sources (347.33 and 359.33). Lowest number of tillers per square meter (282.33 and 297.00) was recorded with control (No fertilizer). Highest number of tillers per square meter (pooled) at harvest obtained with full STBNR (25 % organic (FYM) + 75 % inorganic) (393.17) whereas lowest number of tillers (pooled) per square meter (289.67) was recorded with control (No fertilizer).

This could be attributed to the enhanced nutrient availability provided by FYM and inorganic fertilizer, as well as the microbial stimulation and gradual nitrogen mineralization from FYM. These findings align with those reported in similar

Table 2. Effect of integrated nutrient management on SPAD reading, green seeker reading and dry weight per square meter of rice

Particular	SPAD (60 days after transplanting)			Green seeker (60 days after transplanting)			Dry weight per square meter (g m^{-2})		
Integrated nutrient management	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T1-Control (No fertilizer)	32.70	33.10	32.90	0.51	0.51	0.51	497.00	512.98	504.99
T2-Full STBNR through inorganic sources	37.97	38.47	38.22	0.57	0.57	0.57	898.00	908.96	903.48
T3-Full STBNR through organic sources (FYM)	33.60	34.03	33.82	0.54	0.54	0.54	751.67	765.18	758.42
T4-Full STBNR (50% organic (FYM) + 50% inorganic)	38.67	39.53	39.10	0.61	0.62	0.61	1009.33	1028.56	1018.95
T5-Full STBNR (25% organic (FYM) + 75% inorganic)	39.43	40.00	39.72	0.63	0.64	0.63	1068.33	1102.66	1085.50
T6-50% N inorganic sources + 2 nano urea spray	37.53	37.57	37.55	0.54	0.54	0.54	764.67	778.18	771.42
T7-75% N inorganic sources + 2 nano urea spray	38.13	38.60	38.37	0.58	0.61	0.59	890.67	921.18	905.92
SEm±	1.08	1.42	0.80	0.02	0.02	0.01	34.00	36.60	22.43
CD (P= 0.05)	3.32	4.37	2.33	0.05	0.06	0.05	104.75	112.77	65.47

Values indicate mean of 3 replications; Pooled data indicate average of 2022,2023

* SEm = Standard error of mean, CD = Critical difference

studies (17, 18). Additionally, the combination of inorganic fertilizers with organic manure and promoted the growth and development of rice tillers, resulting in an increased number of tillers per hill (19).

Number of tillers per square meter at harvest obtained with 75 % N through inorganic sources + 2 nano urea spray (Tillering & PI stage) (329.33, 345.67 and 337.50) was found to be at per with full STBNR through inorganic sources (324.67, 336.33 and 330.50), as shown in Table 3.

The effectiveness of nano urea is due to the reduced particle size, which enhances the specific surface area and the number of particles of the fertilizer per unit area. This increase in surface area allows for more interactions with the fertilizer, leading to improved penetration and nutrient uptake. It resulted in better leaf expansion, better photosynthesis and ultimately resulting in a higher number of tillers per square meter (20).

In comparison to other treatments panicle length (26.20 cm, 27 cm and 26.60 cm), panicle weight (2.87 g, 3.04 g and 2.96 g) and number of filled grains per panicle (159, 169.33 and 166.67) was higher in full STBNR (25 % organic (FYM) + 75 % inorganic) in both years (2022 and 2023) as well as mean. This effect might be attributed to the enhancement in enzymatic activity, which leads to the formation and transportation of photosynthates. This, in turn, may result in an increase in the panicle length, panicle weight and number of grains per panicle (19), as shown in Table 3.

The use of integrated nutrient management practices has a significant impact on grain (Fig. 1). Highest grain yield (6.54 t ha^{-1}, 6.73 t ha^{-1} and 6.64 t ha^{-1}) was recorded with full STBNR (25% organic (FYM) + 75 % inorganic) during both years (2022 and 2023) as well as pooled followed by full STBNR through 50 % organic (FYM) + 50 % inorganic sources (6.12 t ha^{-1}, 6.26 t ha^{-1} and 6.19 t ha^{-1}). Lowest grain yield (2.94 t ha^{-1}, 2.98 t ha^{-1} and 2.96 t ha^{-1}) was recorded with control (No fertilizer). Similarly grain yield obtained with treatment 75 % N inorganic sources + 2 nano urea spray (5.49 t ha^{-1}, 5.68 t ha^{-1} and 5.59 t ha^{-1}) was also found to be at par with grain yield obtained with full STBNR through inorganic sources (5.42 t ha^{-1}, 5.55 t ha^{-1} and 5.49 t ha^{-1}) during both the years and mean.

Among different treatments highest straw yield was recorded with full STBNR (25 % organic (FYM) + 75 % inorganic) (7.34 t ha^{-1} ,7.55 t ha^{-1} and 7.45 t ha^{-1}) during both the years (2022 and 2023) as well as mean, followed by full

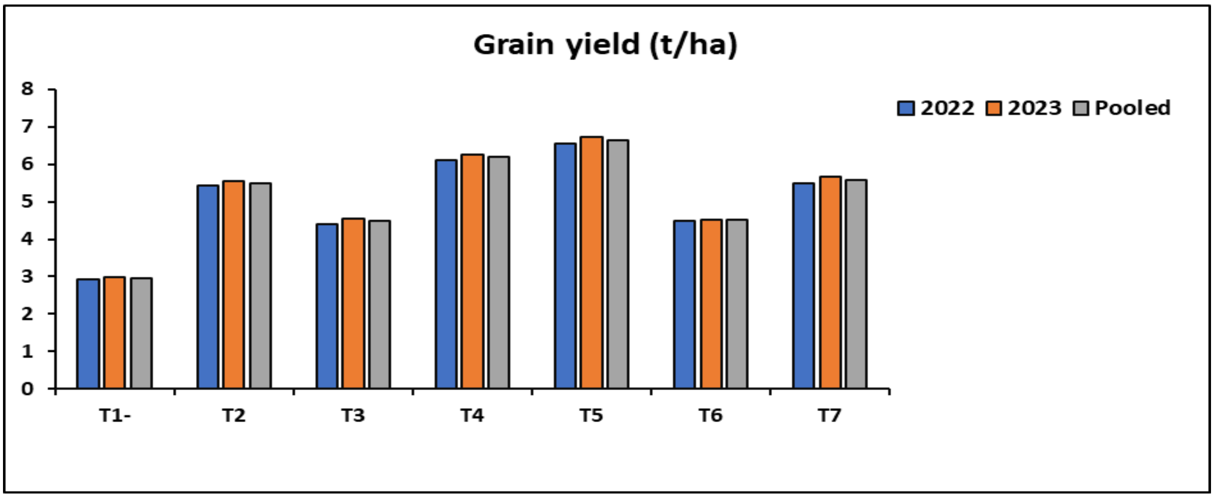

Fig. 1. Effect of integrated nutrient management on grain yield of rice (T1-Control (No fertilizer); T2-Full STBNR through inorganic sources; T3-Full STBNR through organic sources (FYM); T4-Full STBNR (50 % organic (FYM) + 50 % inorganic); T5-Full STBNR (25 % organic (FYM) + 75 % inorganic); T6-50 % N inorganic sources + 2 nano urea spray; T7-75 % N inorganic sources + 2 nano urea spray).

Table 3. Effect of integrated nutrient management on number of tillers per square meter, panicle length, number of filled grains per panicle and panicle weight of rice

Particular	**Number of tillers m^{-2}**			**Panicle length (cm)**			**Number of filled grains $panicle^{-1}$**			**Panicle weight (g)**		
Integrated nutrient management	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T1-Control (No fertilizer)	282.33	297.00	289.67	19.33	19.73	19.53	123.67	130.67	127.17	1.76	1.85	1.81
T2-Full STBNR through inorganic sources	324.67	336.33	330.50	23.17	23.10	23.13	142.67	151.00	146.83	2.46	2.49	2.47
T3-Full STBNR through organic sources (FYM)	301.00	309.67	305.33	22.27	20.20	21.23	135.67	142.33	139.00	1.94	2.04	1.99
T4-Full STBNR (50% organic (FYM) + 50% inorganic)	347.33	359.33	353.33	24.20	24.47	24.33	153.33	161.00	157.17	2.72	2.83	2.78
T5-Full STBNR (25% organic (FYM) + 75% inorganic)	382.00	404.33	393.17	26.20	27.00	26.60	159.00	174.33	166.67	2.87	3.04	2.96
T6-50% N inorganic sources + 2 nano urea spray	307.67	316.33	312.00	22.57	22.00	22.28	137.67	149.67	143.67	2.33	2.40	2.37
T7-75% N inorganic sources + 2 nano urea spray	329.33	345.67	337.50	23.30	23.30	23.30	144.67	152.67	148.67	2.52	2.52	2.52
SEm±	16.63	18.91	11.31	0.92	1.13	0.68	6.41	7.23	4.38	0.08	0.07	0.03
CD (P= 0.05)	51.22	58.27	33.02	2.83	3.48	2.00	19.74	22.27	12.78	0.23	0.22	0.09

Values indicate mean of 3 replications; Pooled data indicate average of 2022,2023

* SEm = Standard error of mean, CD = Critical difference

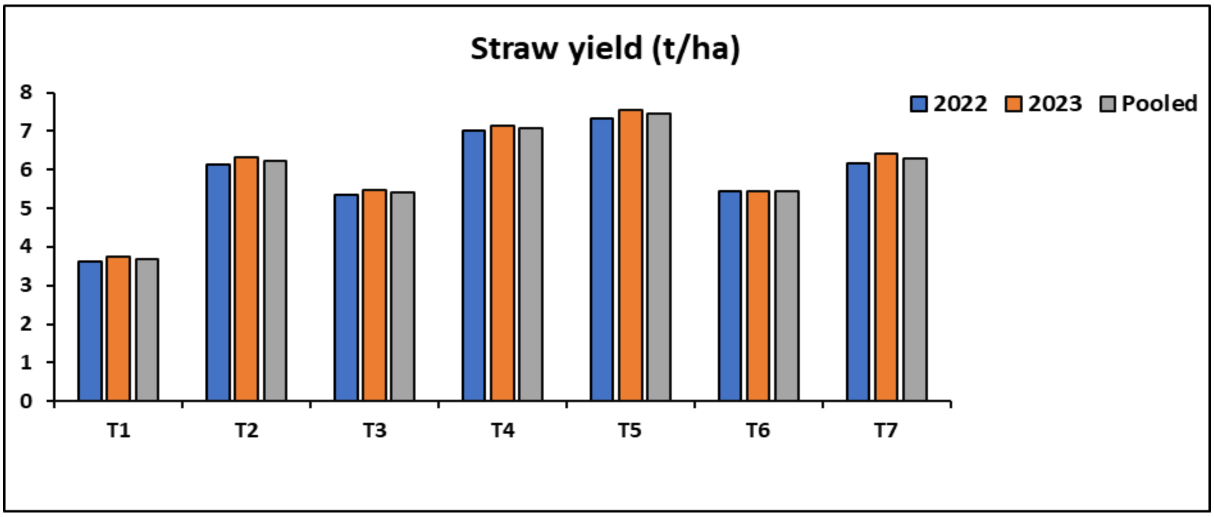

Fig. 2. Effect of integrated nutrient management on straw yield of rice (T1-Control (No fertilizer); T2-Full STBNR through inorganic sources; T3-Full STBNR through organic sources (FYM); T4-Full STBNR (50 % organic (FYM) + 50 % inorganic); T5-Full STBNR (25 % organic (FYM) + 75 % inorganic); T6-50 % N inorganic sources + 2 nano urea spray; T7-75 % N inorganic sources + 2 nano urea spray).

STBNR (50 % organic (FYM) + 50 % inorganic) (7 t ha^{-1}, 7.14 t ha^{-1}and 7.07 t ha^{-1}), as depicted in Fig. 2. Lowest straw yield (3.63 t ha^{-1}, 3.75 t ha^{-1} ha and 3.69 t ha^{-1}) was recorded with control (No fertilizer). The ideal blend of traditional fertilizers and FYM resulted in maximum straw production. Similarly straw yield obtained with treatment 75 % N inorganic sources + 2 nano urea spray (6.18 t ha^{-1}, 6.41 t ha^{-1} and 6.29 t ha^{-1}) was also found to be at par with straw yield obtained with full STBNR through inorganic sources (6.14 t ha^{-1} and 6.32 t ha^{-1} and 6.23 t ha^{-1}) during both the years as well as pooled.

Among different treatments, highest harvest index was recorded with the application of full STBNR (25 % organic (FYM) + 75 % inorganic) (47.16 % and 47.11 %) which was statistically at par with 75 % N inorganic sources + 2 nano urea spray (47.05 % and 46.99 %), full STBNR through inorganic sources (46.87 % and 46.75 %) and full STBNR (50 % organic (FYM) + 50 % inorganic) (46.66 % and 46.71 %) during both the years of study. However, control (No fertilizer) resulted in the lowest harvest index (44.86 % and 44.34 %). Highest mean harvest index was recorded with the application of full STBNR (25 % organic (FYM) + 75 % inorganic) (47.13 %) whereas control (No fertilizer) resulted in lowest mean harvest index (44.60 %), as depicted in Fig. 3.

Organic fertilizers (FYM) are highly effective in enhancing crop yields due to their rich nutrient content and low C/N ratio, which allows for faster mineralization compared to other organic materials. This gradual nutrient release supports higher nutrient availability and uptake, leading to better accumulation and translocation of photosynthates, ultimately resulting in increased grain yield. Combining NPK with FYM further improves grain yield by enhancing soil fertility and nutrient supply gradually throughout the season, which leads to better leaf expansion and better photosynthesis as well as efficient translocation of photosynthates to the grain. Increased straw yield with integrated nutrient management (INM) treatments is linked to higher leaf area expansion, better photosynthesis which leads to a greater number of tillers. This resulted in better dry matter production and improved growth attributes. A higher harvest index indicates more economic yield which was mainly due to proper nutrient availability during reproductive, panicle initiation and grain filling stages as well as efficient translocation of photosynthates to the grains. These outcomes are consistent with the previous research findings (19-21), who observed significant positive effects of combining organic and chemical fertilizers on rice straw and biological yields.

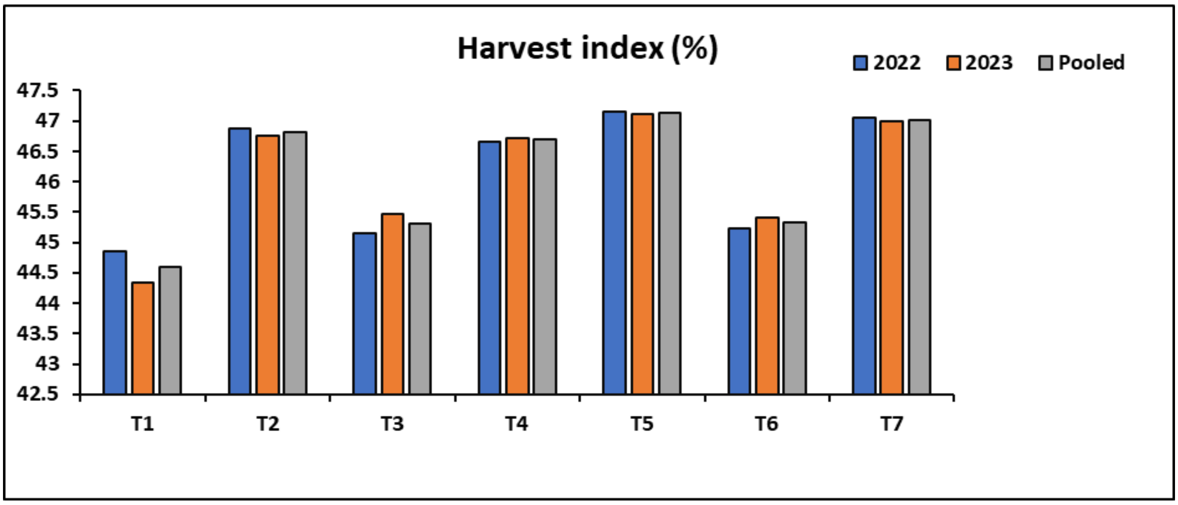

Fig. 3. Effect of integrated nutrient management on harvest index of rice (T1-Control (No fertilizer); T2-Full STBNR through inorganic sources; T3-Full STBNR through organic sources (FYM); T4-Full STBNR (50 % organic (FYM) + 50 % inorganic); T5-Full STBNR (25 % organic (FYM) + 75 % inorganic); T6-50 % N inorganic sources + 2 nano urea spray; T7-75 % N inorganic sources + 2 nano urea spray).

Similarly, combined application of conventional fertilizer as a basal dose and the split application of nano urea sprayed on the plant surface leads to the storage of residual nitrogen in plant cells, which is released slowly, thereby preventing biotic and abiotic stress and resulting in higher grain yield. The application of nano urea boosts yields by promoting the growth of plant parts and enhancing metabolic processes such as photosynthesis. This leads to the accumulation and translocation of more photosynthates to the economic parts of the plant. Similar findings have been reported (22-24). Controlled release of nutrients, which meets the plant's nutrient demands, regulates growth and enhances target activity, leading to increased biological production of the crop. The rapid uptake and efficient translocation of nano fertilizers by the plant likely contributed to improved photosynthesis rates and increased dry matter formation, leading to higher straw production when applied as a foliar spray. Similar results were also reported (25).

***Effect of integrated nutrient management on soil biochemical properties*:** The chemical properties of the soil after two years of cropping (Table 4) showed a slight increase in pH and organic carbon content compared to the initial values except organic carbon content of control plot which was found lower than initial. Application of FYM alone or in combination with inorganic fertilizers resulted in higher soil organic carbon content after harvest as compared to other treatments and similar trend was also observed in soil p^H.

After two years of cropping, the population of bacteria and actinomycetes increased, while the fungal population declined compared to the initial levels (Table 4). Organic management in rice promoted microbial colony formation more effectively than INM and inorganic practices (bacteria 11.77 ×10^6, actinomycetes 8.44 ×10^6 and fungi 8.20 ×10^4 cfu/g soil). This could be attributed to the superior influence of organic inputs on microbial populations and their activities compared to their combined use with inorganic inputs (26).

Correlation studies: Correlation analysis depicted that; correlation coefficient values between grain yield with most of the growth and yield attributes was more than 0.9 which indicates grain yield has a strong positive correlation with green seeker reading, SPAD reading, dry weight per square meter, , leaf area index, number of filled grain per panicle, panicle length and panicle weight as shown in Fig. 4. Correlation coefficient value between grain yield and plant height was less than 0.9 which indicates less strong correlation compared to other treatments. Panicle length has a strongly positive correlation with number of filled grain per panicle. Similarly, R^2 value between grain yield and green seeker reading (Fig. 5), SPAD reading (Fig. 6), dry weight per square meter (Fig. 7), plant height (Fig. 8), leaf area index (Fig. 9), number of filled grain per panicle (Fig. 10), panicle length (Fig. 11) and panicle weight (Fig. 12) were found to be 0.9461, 0.8909, 0.997, 0.8076, 0.9451, 0.9402, 0.924 and 0.9129 respectively.

	Grain yield	*Panicle weight*	*Panicle length*	*Number of filled grain*	*Leaf area index*	*Plant height*	*Dry weight*	*SPAD reading*	*Green seeker*
Grain yield	1.00000								
Panicle weight	0.95547	1.00000							
Panicle length	0.96127	0.97604	1.00000						
Number of filled grain	0.96962	0.97527	0.99431	1.00000					
Leaf area index	0.97215	0.99086	0.96538	0.96983	1.00000				
Plant height	0.89867	0.93495	0.96193	0.96400	0.89751	1.00000			
Dry weight	0.99850	0.95607	0.96236	0.97335	0.97371	0.89786	1.00000		
SPAD reading	0.94387	0.99135	0.96293	0.96153	0.98695	0.91967	0.94062	1.00000	
Green seeker reading	0.97267	0.95241	0.96346	0.97054	0.94889	0.95303	0.96500	0.95451	1.00000

Fig. 4. Correlation plot between grain yield, green seeker reading, SPAD reading, dry weight per square meter, plant height, leaf area index, number of filled grain per panicle, panicle length and panicle weight.

Table 4. Effect of integrated nutrient management on soil organic carbon, pH, bacteria, actinomycetes and fungal population in soil

Particular / **Integrated nutrient management**	**Organic carbon (%)**	**pH**	**Bacteria (x 10^6 cfu /g soil)**	**Actinomycetes (x 10^6 cfu /g soil)**	**Fungi (x 10^4 cfu /g soil)**
T1-Control (No fertilizer)	0.51	5.11	8.77	6.77	4.99
T2-Full STBNR through inorganic sources	0.57	5.32	8.11	5.89	5.66
T3-Full STBNR through organic sources (FYM)	0.64	5.57	11.77	8.44	8.20
T4-Full STBNR (50% organic (FYM) + 50% inorganic)	0.61	5.53	11.00	7.78	7.77
T5-Full STBNR (25% organic (FYM) + 75% inorganic)	0.60	5.37	9.07	7.66	6.22
T6-50% N inorganic sources + 2 nano urea spray	0.56	5.21	8.55	6.64	5.55
T7-75% N inorganic sources + 2 nano urea spray	0.56	5.26	7.66	6.11	5.64
SEm±	0.04	0.04	0.46	0.29	0.30
CD (P= 0.05)	NS	0.13	1.41	0.89	0.93
Initial	0.55	5.04	6.31	7.15	9.34

*cfu = Colony forming unit, SEm = Standard error of mean, CD = Critical difference

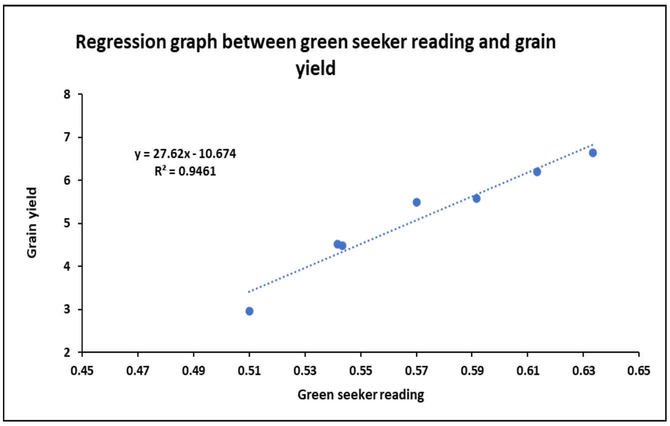

Fig. 5. Regression graph between green seeker reading and grain yield.

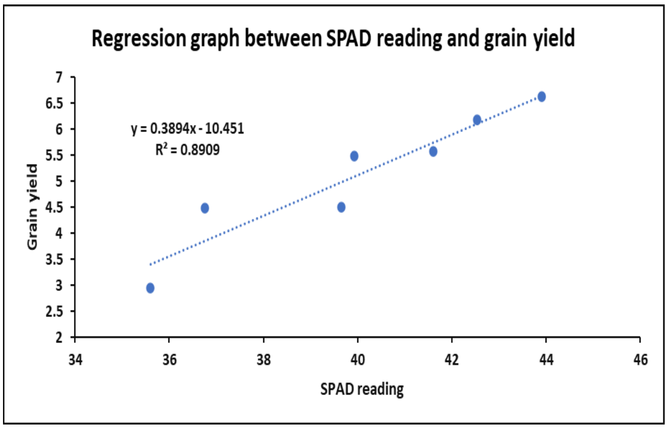

Fig. 6. Regression graph between SPAD reading and grain yield.

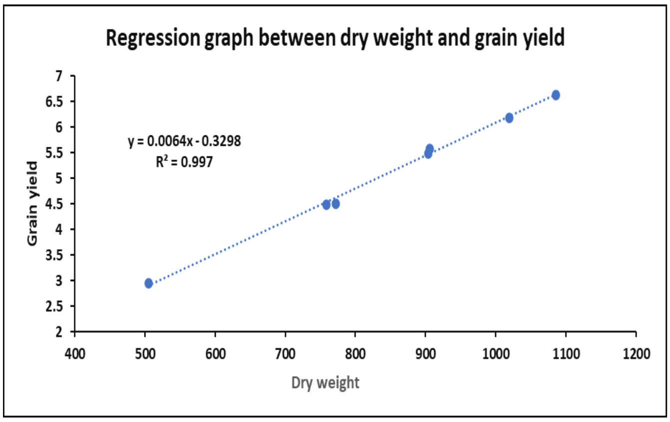

Fig. 7. Regression graph between dry weight per square meter and grain yield.

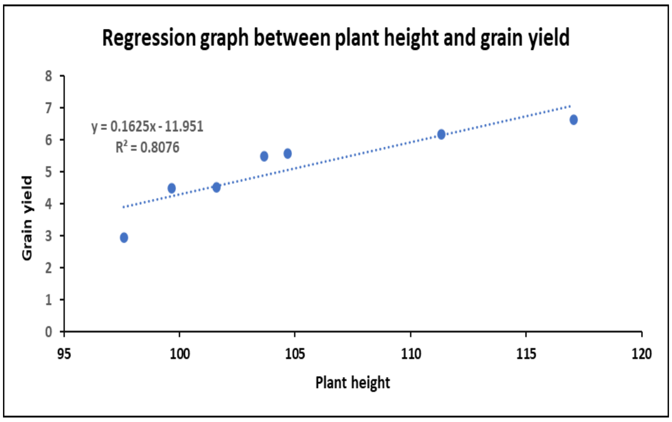

Fig. 8. Regression graph between plant height and grain yield.

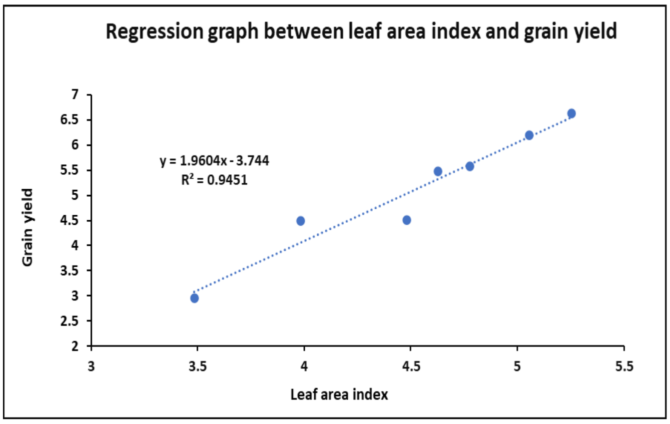

Fig. 9. Regression graph between leaf area index and grain yield.

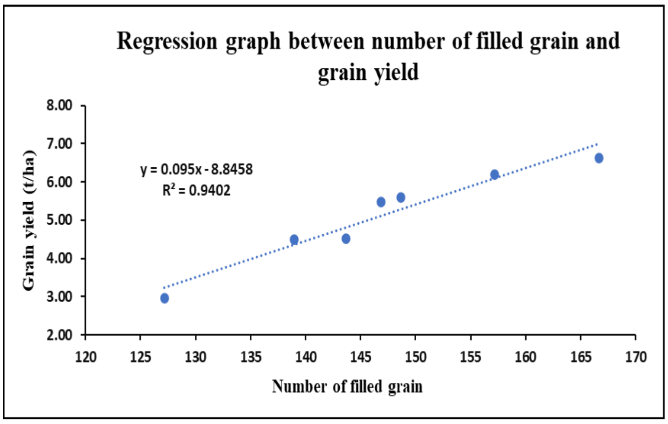

Fig. 10. Regression graph between number of filled grain per panicle and grain yield.

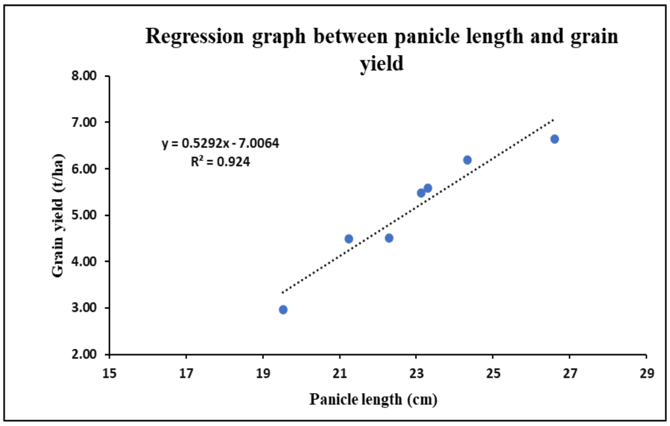

Fig. 11. Regression graph between panicle length and grain yield.

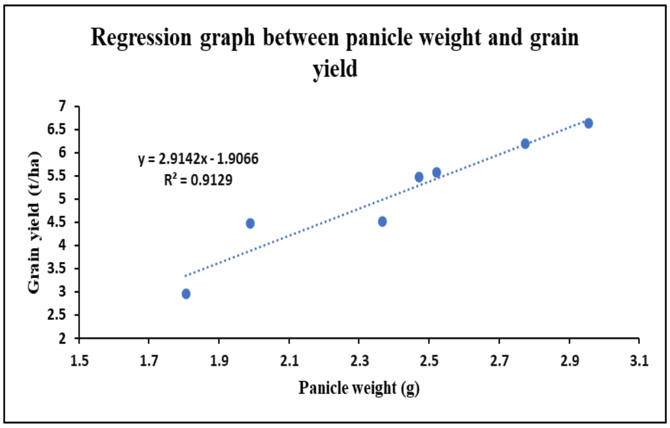

Fig. 12. Regression graph between panicle weight and grain yield.

Conclusion

Based on findings of the experiment conducted for two consecutive years, it can be concluded that application of full STBNR (25 % organic (FYM) + 75 % inorganic) is the best practice to achieve higher productivity in rice as well as to maintain ideal soil health. Similarly combined application of 75 % N through inorganic sources with 2 nano urea spray can be used to reduce urea requirement to produce same amount of rice yield.

Acknowledgements

The authors sincerely thank the Vice-Chancellor, OUAT, Bhubaneswar, for his invaluable support and for providing the essential facilities during the research period. Their assistance has contributed significantly to the success of this study.

Authors' contributions

All the authors contributed to the above work, starting from designing the experiment, collecting data, assisting with statistical analysis, interpretation of results, and manuscript preparation. Conceptualization of research was done by SP and PJM. Designing of the experiments was carried out by SP, PJM and BKM. Experimental materials were contributed by SP, NP and AKBM. Field/lab experiments and data collection were executed by SP, PJM, BKM, NP and AKBM. Analysis of data and technical guidance supported by SP and PJM. The original draft of the manuscript was prepared by SP and PJM; modified and coordinated by SP, PJM, BKM, NP and AKBM. All the 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

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