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Improved agro-techniques for sustainable aerobic rice production in Northern dry zone of Karnataka

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Abstract
At the Agronomy Field Unit, ZARS, GKVK, Bengaluru, during the *kharif* 2021–22 and 2022–23, a field experiment titled "Improved Agro-techniques for sustainable Aerobic rice production in Northern dry zone of Karnataka" was carried out. The experiment was set up using a split-split plot design, with five nitrogen management strategies (N_1-Nutrient expert, N_2-Site specific nutrient management (SSNM), N_3-Green seeker, N_4-Nano urea, and N_5-RDN) as sub-sub plot treatments, mulching (M_0-without mulching and M_1-with mulching) as sub plot and two main plot treatments (S_1-Raised bed and S_2-Flat bed). Throughout the crop's life, drip irrigation was used to supply irrigation. The experiment is triple-replicated with twenty treatment combinations. The results of pooled data revealed raised bed recorded higher leaf area index (19.18 and 93.11 cm at 30 and 90 DAS, respectively), grain yield (5831 kg ha^{-1}) and straw yield (7181 kg ha^{-1}) over flat bed. With polythene mulching treatment outperformed over without mulching by recoding higher leaf area index (19.81 and 95.78 cm at 30 and 90 DAS, respectively), grain yield (5999 kg ha^{-1}) and straw yield (7364 kg ha^{-1}). Among nitrogen management practices, following Nutrient Expert advice recorded higher leaf area index (3316 cm^2 at 90 DAS), grain yield (6235 kg ha^{-1}) and straw yield (7620 kg ha^{-1}) over other practices. On par results were recorded in treatment with SSNM which recorded leaf area index (3224 cm^2 at 90 DAS), grain yield (6014 kg ha^{-1}) and straw yield (7461 kg ha^{-1}). Sustainable aerobic rice cultivation with raised beds, polythene mulching, and nitrogen control can be a promising way to address the challenges of modern agriculture, promoting both environmental and economic sustainability.

Keywords: Green seeker, nutrient expert, polythene mulching, aerobic rice

Introduction
Rice (*Oryza sativa*) holds a crucial position globally, with two-thirds of the world's population depending on it. In 2004, the United Nations designated it the 'International Year of Rice' to recognize its significance in combating poverty and malnutrition, as it provides around 700 calories per day to three billion people, primarily in developing nations. Asia, led by India as the second-largest producer and consumer, contributes to 90 percent of global paddy production and consumption. In India, rice cultivation spans 464 lakh ha, yielding 129.47 m t with an average productivity of 2798 kg ha^{-1}. Karnataka, a significant contributor, covers 13.97 lakh ha, producing 43.18 lakh t with a productivity of 3089 kg ha^{-1}.

Projected global population growth to 8.1 billion by 2025 necessitates a 2-3 percent annual increase in rice production to maintain self-sufficiency, all within existing land and water resources. Traditional flooded rice cultivation, which retains continuous standing water except at maturity, consumes a significant 30-45 percent of the world's fresh water resources. However, in today's water-scarce context, even water-saving methods like saturated soil cultivation, system of rice intensification (SRI) and alternate wetting and drying systems still demand substantial water use. The aerobic rice system offers promise as a water-saving approach, cultivating rice in non-flooded, aerobic soil with supplementary irrigation, reducing seepage, percolation, and evaporation. Precise water management and suitable genotypes could enhance yield and water efficiency, particularly under drip irrigation.

The use of raised beds in rice cultivation, as a modification to land configuration, presents a promising avenue for water conservation. This method, notably observed in Punjab, has showcased its potential to significantly reduce water consumption. In this region, the adoption of raised beds has led to a remarkable 50 percent decrease in the amount of irrigation water required, along with a reduced dependence on labor. Furthermore, this innovative approach has proven effective in minimizing the challenges posed by pests and diseases in rice crops, as evidenced by research conducted by Ockerby and Fukai in 2001 [15]. In essence, the implementation of raised beds represents a valuable strategy for conserving water resources, enhancing agricultural sustainability, and addressing agricultural challenges in rice production.

Mulching is a promising technique for safeguarding soil integrity, primarily in its role of preventing the loss of soil moisture due to evaporation. The application of mulch creates a protective barrier, shielding soil particles from direct exposure to raindrops, which not only reduces erosion but also curtails runoff and moisture loss. Furthermore, mulch serves as a vital regulator, moderating the speed of water flow over the soil, effectively minimizing the runoff losses and the subsequent soil erosion that can occur. It also plays a pivotal role in maintaining the optimal soil temperature, thereby fostering favorable conditions for healthy plant growth. Mulch serves as a natural weed inhibitor, preventing weed proliferation, and additionally aids in the preservation of essential nutrients within the soil. In the context of aerobic rice cultivation, the alternating wet and dry soil conditions may trigger processes like nitrification and denitrification, potentially leading to nitrogen loss in the form of N_2 and N_2O. Even with higher nitrogen applications in aerobic rice, there may be limitations on grain filling due to a lower contribution of post-anthesis assimilates, as documented by Zhang *et al*. in 2009 [20]. Furthermore, since aerobic rice is not transplanted, its roots predominantly occupy the shallow surface soil, which can result in relatively lower nitrogen uptake. Effectively managing fertilizers, particularly nitrogen, remains a significant challenge for researchers and farmers. There's a need for a monitoring technique that can assess nutrient dynamics, availability, and their alignment with crop requirements, determining the timing, quantity, and location of fertilizer application. This technique should be quick, cost-effective, and support real-time decision-making.

Recent tools like Nutrient Expert software and optical sensors like Green Seeker offer site-specific and demand-driven nitrogen management for cereal crops. These tools systematically collect location-specific data crucial for generating personalized recommendations, considering nutrient supply from both natural sources and external fertilizers.

Nutrient Expert, designed for rice growers, applies Site-Specific Nutrient Management principles. It offers field-specific fertilizer recommendations with a focus on yield improvement and agronomic efficiency, considering regional factors. This enables advisors to provide customized fertilizer guidance to farmers based on their unique farming conditions. The aim is to enhance water and nitrogen use efficiency while sustaining crop productivity, particularly in the context of aerobic rice cultivation under surface drip irrigation, various sowing methods, mulching, and precision nitrogen management technologies.

Materials and Methods

A field experiment was carried out during *Kharif* 2021-22 and 2022-23 at the Agronomy Field Unit, ZARS, GKVK, Bengaluru. The site is situated in the Agro-climatic Zone V: Eastern Dry Zone of Karnataka at 13° 05' North latitude and 77° 34' East longitude with an altitude of 924 m above mean sea level. The experiment consisted of twenty treatment combinations replicated three times, assigning two methods of sowing as main plot treatment (S_1 - Raised bed and S_2 - Flat bed) with two sub plots of polythene mulching (M_0 - Without mulching and M_1 - With mulching) and five sub-sub plot of nitrogen management (N_1 -Nutrient Expert, N_2 - Site Specific Nutrient Management (SSNM), N_3 – Green Seeker, N_4 - Nano urea and N_5 - RDN) was laid out in a split-split plot design. General view of the experimental plot is presented in the Plate 1.

The mulching material used for the experiment was a black polythene plastic sheet of 25 microns with 50 percent coverage each which was covered during the crop as per treatments. Seed priming was done by soaking KRH-4 seeds in clean water for six hours and tying them in the gunny bag for three hours. The primed seeds were again treated with *Azospirullum* @ 4 g kg^{-1} of seeds. The KRH-4 seeds were sown on 16th August 2021 and 20th August 2022 and seeds were sown manually by following the seed rate of 5 kg ha^{-1} with a spacing of 25 cm × 25 cm. Irrigation was providing through drip lines laid between two crop rows. The drip lines were laid under the mulch in the treatments receiving polyethene mulch. The irrigation was scheduled at three days intervals up to harvest through a drip system. Nutrients were applied as per the treatments in the form of urea, single super phosphate and murate of potash to supply nitrogen, phosphorus, and potassium, respectively as per the treatments and FYM of 10 t ha^{-1} was common for all the treatments. N_1-Nutrient Expert is a software developed by IPNI and CIMMYT, Mexico, for optimizing nutrient management in rice. N_2-SSNM, Nutrients required to achieve target yield (8 t ha^{-1}) were calculated by using the formulae given by Biradar and Aladakatti (2007) [1] and Jnanesha (2012) [8].

$$NR = \text{Uptake per quintal} \times T$$

Where,
NR = Nutrient required to achieve target yield in kg ha^{-1}
Uptake = Nutrient uptake by the crop per tonne grain yield in the respective crop and location
T = Target yield (ha^{-1})

N3- GreenSeeker is an optical sensor that emits, and measures reflected light at two different wavelengths. NDVI values range from 0 to 1. If NDVI values are below 0.3, apply 25 kg ha^{-1} nitrogen. If values are between 0.3 and 0.5, apply 20 kg ha^{-1} nitrogen. If it is not in the range, no nitrogen is applied, and values are more than 0.6, there is no need to apply additional nitrogen. N_4-Treatment receiving nano urea spray, 50 percent of nitrogen and 100 percent of recommended P and K were applied as basal dose. At 15, 30, 45 and 60 DAS nano urea spray was taken up @ 4 ml l^{-1} of water. N_5-RDN the 50 percent of nitrogen and total amount of phosphorus and potassium were applied at sowing time and the remaining 50 percent of nitrogen was applied as top dressing at 30 and 60 DAS in two equal splits. Timely weeding, plant protection and intercultivation operations were carried out.

Biometric observations on growth parameters were recorded randomly on selected five plants at 30, 60, 90 DAS and at harvest in the net plot. Data related to yield was recorded at the time of harvest of the crop. The data recorded on various parameters were subjected to Fisher's method of analysis of variance and interpretation of the data was made as given by Gomez and Gomez (1984) [4]. The level of significance used in the 'F' and 't' test was P = 0.05. Whenever the F-test was significant for comparison amongst the treatments, an appropriate value of critical differences (CD) was worked out. Otherwise, against CD values abbreviation 'NS' (Non-significant) is indicated.

Results and Discussion

Tiller production

The data on the number of tillers plant^{-1} were significantly influenced at later stages of aerobic rice (Table 1 and 2). Pooled data of number of tillers plant^{-1} showed that at 30 DAS there was no significant difference among flat bed, raised bed, mulching, without mulching and different precision nitrogen management. However, numerically higher number of tillers were recorded in raised bed (5.61), treatment receiving polythene mulch (5.75) and SSNM (5.70). There was a discernible difference in the number of tillers plant^{-1} among different treatments in the current field investigation. Aerobic rice grown on raised bed recorded significantly higher number of tillers plant^{-1} of 57.99 at 90 DAS over flat bed. The raised bed condition provided superior aeration and soil conditions for increased tiller production, resulting in a higher number of tillers reported (Mirza *et al*., 2009) [13]. Treatment with polythene mulch recorded significantly higher number of tillers plant^{-1} at 90 DAS (60.42) outperformed over flat bed. The reason for such outcome is the polythene mulching improved soil moisture and nutrient conditions, activating soil nutrients (Kader *et al*., 2017 and Zhu *et al*., 2019) [9, 21] promoting nutrient uptake and utilization and crop growth and development (Jia *et al*., 2018) [7]. Among various nitrogen management practices, application of nitrogen according to the recommendation of Nutrient Expert recoded significantly higher number of tillers plant^{-1} at all the stages. At 90 DAS, N_1 recorded higher number of tillers plant^{-1} of 61.13 which was on par with SSNM (58.99) as presented in Fig.1. GreenSeeker guide nitrogen management was found to be next best treatment (56.33). Rice tillering is an important agronomic feature for grain yield. Having more tillers to hold and support the leaves would increase dry matter production, leading to more grain produced. The emergence and growth of rice tillers are strongly impacted by elements including nitrogen supply, solar radiation, and temperature (Murata and Matsushima, 1975) [14]. One of a variety's most crucial traits is its ability to till, which depends on the generation of dry matter and its accumulation in the main stem during the early stages of growth (Honda and Okazima, 1969) [5]. Since, late tillers are small, mature slowly, and do not bear grain, the longer tillering time in a cultivar is unfavourable. Instead, primary and secondary tillers contribute more to grain yield. Interaction effect of different methods of sowing, mulching and precision nitrogen management were non-significant on number of tillers plant^{-1} at all the growth stages of aerobic rice.

Leaf area Index (LAI)

Aerobic rice plants grown on raised bed recorded significantly higher LAI at 90 DAS (5.09) over the flat bed. At 30 DAS (0.11), no significant difference was recorded in LAI of aerobic rice (Table 3 and 4). Raised beds allows easy penetration of roots by offering less resistance. This will encourage the plant to increase its foraging area, more uptake of nutrients and there by boost overall growth of the plant. Polythene mulching when compared to without mulching recorded significantly higher LAI (0.11 and 4.11 at 30 and 90 DAS, respectively). Nitrogen management through Nutrient Expert recorded significantly higher LAI at 30 DAS (1.17) and 90 DAS (5.30). The treatment with SSNM approach recorded on par results with the best treatment (1.13 and 5.16 at 30 and 90 DAS, respectively). Green seeker guided nitrogen management recorded next best whereas, foliar application of nano urea and RDN recorded least LAI. The higher basal application (50%) in the recommended plots may have supported initial higher growth and contributed to the similar LAI between recommended practices and other treatments (N_1 and N_2) plots initially, but as the growing season progressed, the blanket application was unable to keep up with the crop demand. In contrast, Nutrient Expert and SSNM the application of nutrient was more balanced, and there was a greater congruence between nutrient supply and crop demand. Additionally, the enhanced N application in the N_1 boosted plant height and tiller count, which in turn raised LAI.

Interaction effect of methods of sowing, mulching and precision nitrogen management were non-significant on leaf area index at all the growth stages of aerobic rice.

Days to 50 percent flowering

The pooled data revealed that there was no significant difference in methods of sowing but was significantly influenced by polythene mulching which recorded longer days (100.46) for 50 percent flowering. Plastic mulching improved soil environment which increased nutrient availability, conserves soil moisture altogether encouraged overall growth and delayed flowering. Foliar application of nano urea specially during the panicle initiation period gives plants increased vigour, encouraging early flowering (Midde *et al*., 2022) [12]. Hence, within 93.98 days (Table 5) 50 percent flowering were started over other nitrogen management practices.

Interaction effect of methods of sowing, mulching and precision nitrogen management were non-significant on days to 50 percent flowering of aerobic rice.

Grain and Straw yield

Grain yield and straw yield measured after harvest in both the years (2021 and 2022) varied significantly by methods of sowing, mulching and precision nitrogen management and is presented in the Table 6 and 7.

In the year 2021, the treatment with raised bed recorded significantly higher grain and straw yield (6458 and 7410kg ha^{-1}) over the flat bed (6200 and 7077 kg ha^{-1}). Similar trend was also observed in the second year (2022) where the earlier recorded an average grain and straw yield of 5205 and 6952 kg ha^{-1}.

The pooled data showed that raised bed recorded higher grain and straw yield (5831 and 7181 kg ha^{-1}) over flat bed and the results were similar to Uphoff *et al.* (2011) [17] and Zhang *et al.* (2009) [20]. Raised bed facilitated better initial growth which later led to overall improvement in yield paraments and finally yield.

The treatment with polythene mulching performed better in both the years with a significant yield difference. Higher grain and straw yield (6655 and 7611 kg ha^{-1}) and (5343 and 7118 kg ha^{-1}) was recorded in the year 2021 and 2022, respectively over without mulching (6003 and 6876 kg ha^{-1}) and (4915 and 6660 kg ha^{-1}) in the year 2021 and 2022, respectively. The results agreed with Jabran *et al*., 2015 [6] and Xu *et al*., 2007 [19]. Along with moisture conservation, enhanced nutrient availability, effective weed control, the higher response of physiological parameters may be the additional gain for increasing in grain yield in the polythene mulching treatment, which had been proved with the research done Lu *et al.* (2000) [10].

Precision nitrogen management had significant effect on grain and straw yield of aerobic rice in both the years. Treatment N_1 recorded higher grain and straw yield (6916 and 7865 kg ha^{-1}) and which was showed on par results with N_2 (6646 and 7646 kg ha^{-1}). GreenSeeker guided nitrogen management recorded (6331 and 7325 kg ha^{-1}, grain and straw yield, respectively) which was next best treatment. Nano urea foliar application (6072 and 7033 kg ha^{-1}) and RDN (5681 and 6349 kg ha^{-1}) recorded lower grain and straw yield.

Similar results were recorded in the year 2022, grain and straw yield of aerobic rice recorded in N_1 (5554 and 7375 kg ha^{-1}), SSNM (5382 and 7275 kg ha^{-1}), Green seeker (5059 and 6950 kg ha^{-1}), nano urea (4928 and 6708 kg ha^{-1}) and RDN (4720 and 6138 kg ha^{-1}), respectively.

The pooled data revealed that 19 and 22 percent of grain and straw yield increment was possible by adopting precision nitrogen management technique like Nutrient expert and SSNM. Nitrogen significantly influences the development of grains in rice. It plays a crucial role in the formation of the panicle, where the rice grains are produced. Proper nitrogen management can contribute to increased grain yield and quality. These results are in conformity with findings of other researchers (Dobermann *et al*., 2002, Biradar *et al.* 2006) [3, 2] and Maheshwari *et al.*, 2007) [11]. Singh *et al.* (2009) [16] compared SSNM in rice and wheat with farmer's fertilizer practice and found that average increase in rice and wheat yield was achieved by SSNM as Nutrient Expert. Wang *et al*. (2001) [18] found that the performance of SSNM has consistently improved grain yield by about 10-15 percent compared to the farmers' fertilizer practice.

Table 1: Number of tillers plant^{-1} of aerobic rice at 30 DAS influenced by different sowing methods, mulching and precision nitrogen management

Treatment	**Number of tillers plant^{-1} at 30 DAS**								
Sowing methods (S)	**Mulching (M)**								
	2021			**2022**			**Pooled**		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	5.32	5.84	5.58	5.24	6.04	5.64	5.28	5.94	5.61
S_2: Flat bed	5.38	5.36	5.37	5.44	5.76	5.60	5.41	5.56	5.48
Mean	5.35	5.60		5.34	5.90		5.34	5.75	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	NS	0.08	0.49	NS	0.03	0.19	NS	0.06	0.34
M	NS	0.07	0.27	NS	0.15	0.60	NS	0.11	0.43
S x M	NS	0.10	-	NS	0.22	-	NS	0.16	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	5.30	5.90	5.60	5.40	6.05	5.72	5.35	5.97	5.66
N_2: SSNM	5.50	5.75	5.62	5.40	6.15	5.77	5.45	5.95	5.70
N_3: GreenSeeker	5.40	5.45	5.42	5.45	5.60	5.52	5.42	5.52	5.47
N_4: Nano urea	5.35	5.45	5.40	5.40	5.80	5.60	5.37	5.62	5.50
N_5: RDN	5.20	5.45	5.32	5.05	5.90	5.47	5.12	5.67	5.40
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	NS	0.12	0.36	NS	0.11	0.33	NS	0.10	0.29
N x M	NS	0.17	-	NS	0.16	-	NS	0.14	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	5.75	5.45	5.60	5.75	5.70	5.72	5.75	5.57	5.66
N_2: SSNM	5.50	5.75	5.62	5.75	5.80	5.77	5.62	5.77	5.70
N_3: GreenSeeker	5.65	5.20	5.42	5.70	5.35	5.52	5.67	5.27	5.47
N_4: Nano urea	5.60	5.20	5.40	5.55	5.65	5.60	5.57	5.42	5.50
N_5: RDN	5.40	5.25	5.32	5.45	5.50	5.47	5.42	5.37	5.40
N x S	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	0.17	-	NS	0.16	-	NS	0.14	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	5.30	5.30		5.10	5.70		5.20	5.50	
S_1N_2	5.20	5.80		5.40	5.40		5.30	5.60	
S_1N_3	5.40	5.40		5.60	5.30		5.50	5.35	
S_1N_4	5.60	5.10		5.20	5.60		5.40	5.35	
S_1N_5	5.10	5.30		4.90	5.20		5.00	5.25	
S_2N_1	6.20	5.60		6.40	5.70		6.30	5.65	
S_2N_2	5.80	5.70		6.10	6.20		5.95	5.95	
S_2N_3	5.90	5.00		5.80	5.40		5.85	5.20	
S_2N_4	5.60	5.30		5.90	5.70		5.75	5.50	
S_2N_5	5.70	5.20		6.00	5.80		5.85	5.50	
S x M x N	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	0.25	-	NS	0.23	-	NS	0.20	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

Table 2: Number of tillers plant^{-1} of aerobic rice at 90 DAS influenced by different sowing methods, mulching and precision nitrogen management

Treatment	**Number of tillers plant^{-1} at 90 DAS**								
Sowing methods (S)	**Mulching (M)**								
	2021			**2022**			**Pooled**		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	51.35	57.03	54.19	58.54	65.02	61.78	54.95	61.02	57.99
S_2: Flat bed	46.10	55.90	51.00	52.55	63.73	58.14	49.33	59.81	54.57
Mean	48.72	56.46		55.55	64.37		52.14	60.42	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	**	0.16	0.99	**	0.19	1.13	**	0.17	1.06
M	**	0.55	2.15	**	0.60	2.36	**	0.57	2.26
S x M	NS	0.77	-	NS	0.85	-	NS	0.81	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	52.55	61.71	57.13	59.91	70.35	65.13	56.23	66.03	61.13
N_2: SSNM	50.81	59.45	55.13	57.93	67.77	62.85	54.37	63.61	58.99
N_3: GreenSeeker	48.95	56.34	52.65	55.80	64.23	60.02	52.38	60.29	56.33
N_4: Nano urea	46.80	53.54	50.17	53.36	61.04	57.20	50.08	57.29	53.69
N_5: RDN	44.51	51.28	47.89	50.74	58.46	54.60	47.63	54.87	51.25
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	**	1.32	3.81	**	1.33	3.84	**	1.33	3.82
N x M	NS	1.87	-	NS	1.88	-	NS	1.88	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	58.60	55.66	57.13	66.81	63.46	65.13	62.70	59.56	61.13
N_2: SSNM	57.05	53.21	55.13	65.04	60.66	62.85	61.04	56.94	58.99
N_3: GreenSeeker	54.38	50.91	52.65	62.00	58.04	60.02	58.19	54.47	56.33
N_4: Nano urea	51.55	48.80	50.17	58.76	55.64	57.20	55.15	52.22	53.69
N_5: RDN	49.38	46.41	47.89	56.29	52.91	54.60	52.84	49.66	51.25
N x S	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	1.87	-	NS	1.88	-	NS	1.88	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	54.96	50.15		62.65	57.18		58.80	53.67	
S_1N_2	54.24	47.38		61.84	54.02		58.04	50.70	
S_1N_3	51.76	46.14		59.01	52.60		55.39	49.37	
S_1N_4	49.16	44.44		56.05	50.66		52.61	47.55	
S_1N_5	46.64	42.38		53.17	48.32		49.90	45.35	
S_2N_1	62.25	61.17		70.96	69.73		66.61	65.45	
S_2N_2	59.86	59.04		68.24	67.31		64.05	63.18	
S_2N_3	57.00	55.68		64.99	63.48		61.00	59.58	
S_2N_4	53.93	53.16		61.48	60.61		57.70	56.88	
S_2N_5	52.12	50.44		59.42	57.50		55.77	53.97	
S x M x N	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	2.64	-	NS	2.67	-	NS	2.65	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

Table 3: Leaf area index of aerobic rice at 30 DAS influenced by different sowing methods, mulching and precision nitrogen management

Treatment	**Leaf area index (LAI) at 30 DAS**								
Sowing methods (S)	**Mulching (M)**								
	2021			**2022**			**Pooled**		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	0.115	0.113	0.114	0.115	0.116	0.116	0.115	0.115	0.115
S_2: Flat bed	0.112	0.116	0.114	0.119	0.114	0.117	0.116	0.115	0.115
Mean	0.114	0.115		0.117	0.115		0.115	0.115	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	NS	0.001	-	NS	0.001	-	NS	0.002	-
M	NS	0.002	-	NS	0.001	-	NS	0.002	-
S x M	NS	0.001	-	NS	0.002	-	NS	0.002	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	0.118	0.115	0.117	0.116	0.118	0.117	0.117	0.117	0.117
N_2: SSNM	0.109	0.106	0.107	0.118	0.120	0.119	0.113	0.113	0.113
N_3: GreenSeeker	0.118	0.117	0.117	0.110	0.112	0.111	0.114	0.114	0.114
N_4: Nano urea	0.109	0.122	0.115	0.121	0.112	0.117	0.115	0.117	0.116
N_5: RDN	0.116	0.114	0.115	0.122	0.114	0.118	0.118	0.114	0.116
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	NS	0.003	-	NS	0.003	-	NS	0.003	-
N x M	NS	0.004	-	NS	0.004	-	NS	0.004	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	0.117	0.116	0.117	0.120	0.114	0.117	0.118	0.115	0.117
N_2: SSNM	0.106	0.108	0.107	0.120	0.118	0.119	0.113	0.113	0.113
N_3: GreenSeeker	0.119	0.116	0.117	0.113	0.109	0.111	0.115	0.112	0.114
N_4: Nano urea	0.114	0.116	0.115	0.114	0.119	0.117	0.114	0.118	0.116
N_5: RDN	0.116	0.114	0.115	0.112	0.123	0.118	0.114	0.118	0.116
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N x S	NS	0.004	-	NS	0.004	-	NS	0.004	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	0.120	0.116		0.116	0.116		0.118	0.116	
S_1N_2	0.111	0.107		0.115	0.121		0.113	0.113	
S_1N_3	0.121	0.114		0.111	0.108		0.116	0.111	
S_1N_4	0.106	0.111		0.118	0.124		0.112	0.118	
S_1N_5	0.118	0.113		0.116	0.127		0.117	0.120	
S_2N_1	0.114	0.116		0.124	0.113		0.119	0.114	
S_2N_2	0.102	0.110		0.126	0.115		0.114	0.112	
S_2N_3	0.116	0.118		0.114	0.110		0.115	0.114	
S_2N_4	0.122	0.121		0.111	0.114		0.116	0.118	
S_2N_5	0.114	0.114		0.108	0.119		0.111	0.117	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S x M x N	NS	0.005	-	NS	0.006	-	NS	0.005	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

Table 4: Leaf area index of aerobic rice at 90 DAS influenced by different sowing methods, mulching and precision nitrogen management

Treatment	**Leaf area index (LAI) at 90 DAS**								
Sowing methods (S)	**Mulching (M)**								
	2021			**2022**			**Pooled**		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	4.87	5.12	4.99	5.06	5.32	5.19	4.96	5.22	5.09
S_2: Flat bed	4.63	5.04	4.84	4.81	5.24	5.03	4.72	5.14	4.93
Mean	4.75	5.08		4.94	5.28		4.84	5.18	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	**	0.01	0.05	**	0.01	0.05	**	0.01	0.05
M	**	0.03	0.11	**	0.03	0.12	**	0.03	0.11
S x M	NS	0.04	-	NS	0.04	-	NS	0.04	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	4.98	5.42	5.20	5.18	5.64	5.41	5.08	5.53	5.30
N_2: SSNM	4.92	5.20	5.06	5.11	5.40	5.26	5.02	5.30	5.16
N_3: GreenSeeker	4.71	5.03	4.87	4.90	5.22	5.06	4.81	5.13	4.97
N_4: Nano urea	4.62	4.92	4.77	4.80	5.11	4.95	4.71	5.01	4.86
N_5: RDN	4.51	4.84	4.68	4.69	5.04	4.86	4.60	4.94	4.77
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	**	0.08	0.24	**	0.11	0.31	**	0.09	0.27
N x M	NS	0.12	-	NS	0.15	-	NS	0.13	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	5.22	5.18	5.20	5.43	5.39	5.41	5.33	5.28	5.30
N_2: SSNM	5.10	5.01	5.06	5.30	5.21	5.26	5.20	5.11	5.16
N_3: GreenSeeker	4.95	4.79	4.87	5.15	4.97	5.06	5.05	4.88	4.97
N_4: Nano urea	4.88	4.65	4.77	5.07	4.84	4.95	4.97	4.75	4.86
N_5: RDN	4.81	4.55	4.68	5.00	4.73	4.86	4.90	4.64	4.77
N x S	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	0.12	-	NS	0.15	-	NS	0.13	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	4.97	4.99		5.17	5.19		5.07	5.09	
S_1N_2	4.95	4.89		5.15	5.08		5.05	4.99	
S_1N_3	4.86	4.57		5.05	4.75		4.95	4.66	
S_1N_4	4.81	4.42		5.00	4.59		4.91	4.50	
S_1N_5	4.74	4.29		4.93	4.45		4.84	4.37	
S_2N_1	5.48	5.37		5.69	5.58		5.58	5.48	
S_2N_2	5.25	5.14		5.46	5.34		5.36	5.24	
S_2N_3	5.05	5.00		5.25	5.20		5.15	5.10	
S_2N_4	4.94	4.89		5.13	5.08		5.04	4.99	
S_2N_5	4.87	4.82		5.06	5.01		4.97	4.92	
S x M x N	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	0.16	-	NS	0.21	-	NS	0.19	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

Table 5: Influenced of different sowing methods, mulching and precision nitrogen management on days to 50 percent flowering of aerobic rice

Treatment	Days to 50 percent flowering								
Sowing methods (S)	**Mulching (M)**								
	2021			**2022**			**Pooled**		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	96.44	100.28	98.36	97.18	101.26	99.22	96.81	100.77	98.79
S_2: Flat bed	96.74	99.64	98.19	97.70	100.66	99.18	97.22	100.15	98.69
Mean	96.59	99.96		97.44	100.96		97.02	100.46	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	NS	1.01	-	NS	0.01	-	NS	0.51	-
M	**	0.48	1.89	**	0.49	1.91	**	0.48	1.90
S x M	NS	0.68	-	NS	0.69	-	NS	0.69	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	101.07	103.57	102.32	102.07	104.82	103.45	101.57	104.20	102.88
N_2: SSNM	98.97	101.87	100.42	98.97	103.07	101.02	98.97	102.47	100.72
N_3: GreenSeeker	97.07	99.57	98.32	97.67	100.17	98.92	97.37	99.87	98.62
N_4: Nano urea	90.82	96.12	93.47	92.22	96.77	94.50	91.52	96.45	93.98
N_5: RDN	95.02	98.67	96.84	96.27	99.97	98.12	95.65	99.32	97.48
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	*	2.04	5.88	*	1.98	5.69	*	2.01	5.79
N x M	NS	2.89	-	NS	2.79	-	NS	2.84	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	103.12	101.52	102.32	104.37	102.52	103.45	103.75	102.02	102.88
N_2: SSNM	101.47	99.37	100.42	101.57	100.47	101.02	101.52	99.92	100.72
N_3: GreenSeeker	97.57	99.07	98.32	98.12	99.72	98.92	97.85	99.40	98.62
N_4: Nano urea	92.37	94.57	93.47	93.42	95.57	94.50	92.90	95.07	93.98
N_5: RDN	97.27	96.42	96.84	98.62	97.62	98.12	97.95	97.02	97.48
N x S	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	2.89	-	NS	2.79	-	NS	2.84	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	101.82	100.32		102.32	101.82		102.07	101.07	
S_1N_2	99.32	98.62		98.62	99.32		98.97	98.97	
S_1N_3	96.42	97.72		97.22	98.12		96.82	97.92	
S_1N_4	89.22	92.42		90.72	93.72		89.97	93.07	
S_1N_5	95.42	94.62		97.02	95.52		96.22	95.07	
S_2N_1	104.42	102.72		106.42	103.22		105.42	102.97	
S_2N_2	103.62	100.12		104.52	101.62		104.07	100.87	
S_2N_3	98.72	100.42		99.02	101.32		98.87	100.87	
S_2N_4	95.52	96.72		96.12	97.42		95.82	97.07	
S_2N_5	99.12	98.22		100.22	99.72		99.67	98.97	
S x M x N	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
	NS	4.09	-	NS	3.95	-	NS	4.02	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

Table 6: Grain yield of aerobic rice influenced by different sowing methods, mulching and precision nitrogen management

Treatment	Grain yield (kg ha^{-1})								
	Mulching (M)								
Sowing methods (S)	2021			2022			Pooled		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	6194	6722	6458	5012	5397	5205	5603	6059	5831
S_2: Flat bed	5812	6588	6200	4817	5289	5053	5314	5938	5626
Mean	6003	6655		4915	5343		5459	5999	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	**	4.71	28.69	*	11.24	68.37	**	4.09	24.88
M	**	90.13	353.90	**	40.93	160.73	**	30.56	119.97
S x M	NS	127.46	-	NS	57.89	-	NS	43.21	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	6644	7189	6916	5300	5809	5554	5972	6499	6235
N_2: SSNM	6277	7015	6646	5214	5550	5382	5745	6282	6014
N_3: GreenSeeker	5803	6859	6331	4721	5397	5059	5262	6128	5695
N_4: Nano urea	5714	6430	6072	4694	5163	4928	5204	5796	5500
N_5: RDN	5578	5783	5681	4645	4796	4720	5111	5290	5201
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	**	158.65	457.03	**	141.98	408.98	**	139.96	403.17
N x M	NS	224.37	-	NS	200.78	-	NS	197.93	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	6994	6838	6916	5615	5494	5554	6305	6166	6235
N_2: SSNM	6814	6477	6646	5487	5277	5382	6150	5877	6014
N_3: GreenSeeker	6476	6186	6331	5148	4970	5059	5812	5578	5695
N_4: Nano urea	6235	5909	6072	4982	4875	4928	5608	5392	5500
N_5: RDN	5772	5590	5681	4792	4648	4720	5282	5119	5201
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N x S	NS	224.37	-	NS	200.78	-	NS	197.93	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	6738	6550		5354	5246		6046	5898	
S_1N_2	6580	5974		5322	5105		5951	5539	
S_1N_3	6016	5590		4871	4570		5443	5080	
S_1N_4	5950	5479		4793	4595		5371	5037	
S_1N_5	5690	5467		4721	4568		5206	5017	
S_2N_1	7251	7127		5876	5741		6563	6434	
S_2N_2	7049	6981		5651	5449		6350	6215	
S_2N_3	6936	6782		5425	5369		6180	6075	
S_2N_4	6520	6340		5170	5155		5845	5747	
S_2N_5	5854	5713		4863	4729		5358	5221	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S x M x N	NS	317.31	-	NS	283.95	-	NS	279.91	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

Table 7: Straw yield of aerobic rice influenced by different sowing methods, mulching and precision nitrogen management

Treatment	Straw yield (kg ha⁻¹)								
Sowing methods (S)	Mulching (M)								
	2021			2022			Pooled		
	M_0	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**	**M_0**	**M_1**	**Mean**
S_1: Raised bed	7138	7682	7410	6819	7085	6952	6979	7383	7181
S_2: Flat bed	6615	7540	7077	6501	7151	6826	6558	7345	6951
Mean	6876	7611		6660	7118		6768	7364	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S	**	19.15	116.50	**	0.66	4.04	**	9.87	60.03
M	**	80.67	316.76	**	64.14	251.86	**	60.63	238.08
S x M	NS	114.09	-	NS	90.71	-	NS	85.75	-
Nitrogen Management (N)	M_0	M_1	Mean	M_0	M_1	Mean	M_0	M_1	Mean
N_1: NE	7647	8083	7865	7120	7629	7375	7383	7856	7620
N_2: SSNM	7277	8016	7646	7073	7477	7275	7175	7746	7461
N_3: GreenSeeker	6774	7877	7325	6586	7313	6950	6680	7595	7138
N_4: Nano urea	6596	7469	7033	6364	7051	6708	6480	7260	6870
N_5: RDN	6088	6610	6349	6157	6118	6138	6122	6364	6243
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N	**	163.10	469.85	**	176.96	509.76	**	117.41	338.23
N x M	NS	230.66	-	NS	250.26	-	NS	166.05	-
Nitrogen Management (N)	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
N_1: NE	7925	7804	7865	7408	7341	7375	7667	7573	7620
N_2: SSNM	7844	7449	7646	7310	7239	7275	7577	7344	7461
N_3: GreenSeeker	7492	7159	7325	7077	6823	6950	7284	6991	7138
N_4: Nano urea	7195	6870	7033	6848	6567	6708	7022	6719	6870
N_5: RDN	6593	6105	6349	6118	6157	6138	6356	6131	6243
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
N x S	NS	230.66	-	NS	250.26	-	NS	166.05	-
Sowing methods (S) and Nitrogen Management (N)	M_0	M_1		M_0	M_1		M_0	M_1	
S_1N_1	7700	7594		7142	7099		7421	7346	
S_1N_2	7594	6960		7133	7013		7363	6986	
S_1N_3	7099	6449		6799	6373		6949	6411	
S_1N_4	6845	6347		6621	6107		6733	6227	
S_1N_5	6453	5723		6402	5912		6427	5817	
S_2N_1	8151	8015		7675	7584		7913	7799	
S_2N_2	8094	7937		7487	7466		7791	7702	
S_2N_3	7885	7869		7354	7272		7620	7571	
S_2N_4	7546	7393		7075	7027		7310	7210	
S_2N_5	6734	6487		5834	6403		6284	6445	
	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%	F-test	S Em ±	CD @ 5%
S x M x N	NS	326.21	-	NS	353.92	-	NS	234.83	-

S_1 = Raised bed	S_2 = Flat bed
M_0= Without polythene mulching	M_1= With polythene mulching
N_1 =Nutrient Expert (NE)	N_2 = Site specific nutrient management (SSNM)
N_3 = GreenSeeker	N_4 = Nano urea
N_5 = Recommended dose of nitrogen (RDN)	NS = Non-Significant

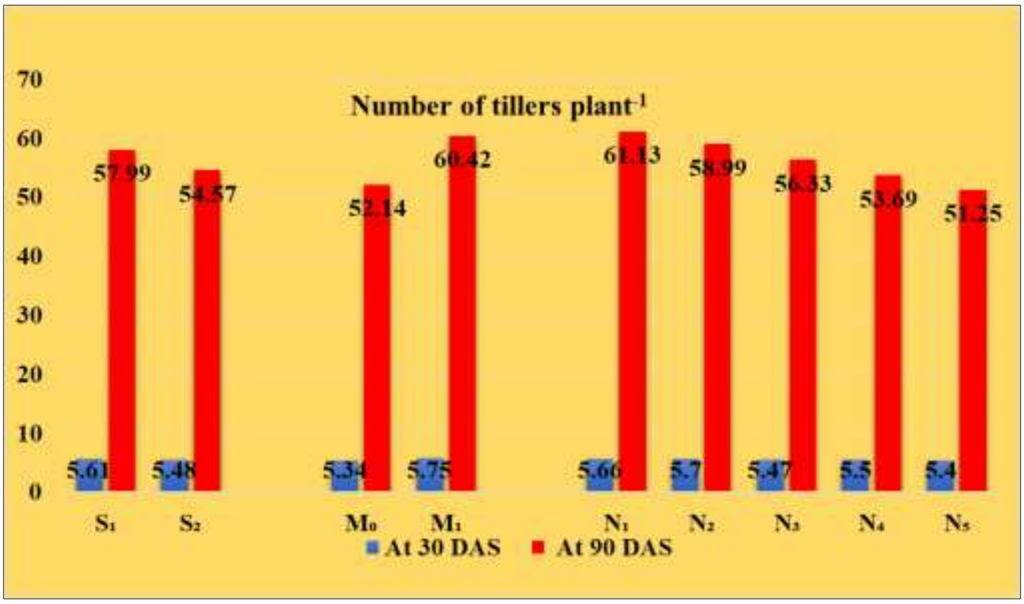

Fig 1: Number of tillers plant^{-1} as influenced by different methods of sowing, mulching and precision nitrogen management practices (pooled data of 2021 and 2022)

Plate 1: General view of the experimental plot at 60 DAS

Conclusion

It is evident from the present investigation that raised bed, polythene mulching and precision nitrogen management through Nutrient Expert enhanced number of tillers plant^{-1}, leaf area index, days to 50 percent flowering, grain yield and straw yield. Sustainable aerobic rice cultivation with raised beds, polythene mulching, and nitrogen control can be a promising way to increase nutrient use efficiency, address food security and other challenges of modern agriculture, promoting both environmental and economic sustainability.

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Conflict of interest

The authors declare that they have no conflict of interest.

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