Research Article

Resilient Nursery Practice for Enhanced Rice (BRRI dhan89) Productivity in the Old Brahmaputra Floodplain (AEZ-9), Bangladesh

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Abstract | Developing resilient nursery practices is essential to enhance seedling vigor, transplanting success, and overall productivity of BRRI dhan89 rice under stress-prone growing conditions in Bangladesh. The rice variety BRRI dhan89 was used in a field trial at the Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh, during the *Boro* season, which ran from December 2021 to May 2022. The experiment comprised of two factors, *viz.*, Factor A (seeding density): (i) low density 100 g m^{-2},(ii) medium density 150 g m^{-2},(iii) high density 200 g m^{-2}; and Factor B (nursery nutrient management):(i) No nutrient applied, (ii) N @ 6 g m^{-2},(iii) P @ 5 g m^{-2},(iv) K @ 3 g m^{-2},(v) N @ 6 g m^{-2} + P @ 5 g m^{-2} + K @ 3 g m^{-2}, (vi) Compost @ 1 kg m^{-2}. The experiment was conducted using three replications of the randomized fully block design. The highest root length (5.50 cm), seedling dry weight (86.35 mg), plant height (110.03 cm) number of total tillers hill^{-1} (9.65), number of effective tillers hill^{-1} (8.87), number grains panicle^{-1} (99.07), grain yield (5.86 t ha^{-1}), and straw yield (6.04 t ha^{-1}) were obtained from the seeding density of 100 g m^{-2} seed rate. Shoot length (16.52 cm) and 1000-grain weight (26.38 g) were obtained from 150 g m^{-2} seed rate. The highest number of effective tillers hill^{-1} was obtained from 100 g m^{-2} seeding density with N+P+K in nursery bed, which eventually resulted in the highest grain yield (6.06 t ha^{-1}). The results also revealed that seedlings obtained from low seeding density (100 g m^{-2}) with fertilization of N @ 6 g m^{-2} + P @ 5 g m^{-2} + K @ 3 g m^{-2} in the nursery performed better in terms of seedling growth and thereby produced the highest grain yield of BRRI dhan89.

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Introduction

For millions of people, rice (*Oryza sativa* L.) is a source of life, culture, tradition, and a living, making it the most valuable commodity in the world (Mohapatra *et al.*, 2025). It is eloquently upheld the need to heighten awareness of the role in alleviating poverty and malnutrition (Asha *et al.*, 2025). Rice is the staple food for about 156 million people of Bangladesh. With a population growth rate of two million people year, Bangladesh's overall population is expected to reach 238 million by 2050 (Rahman *et al*., 2025; Soma *et al*., 2023). Rice cultivation in Bangladesh thrives due to the country's predominantly low-lying terrain, humid climate, and abundant monsoon rainfall (Imran *et al*., 2025). Rice is cultivated year-round in Bangladesh across three distinct growing seasons: aus (summer), aman (monsoon), and boro (winter) (Jesia *et al*., 2025). To feed this constantly growing population, more rice must be produced overall. Bangladesh produces 33.80 million tons of rice annually, using around 84.67% of the country's planted land. According to BBS (2022) aus and aman rice production are 30,00,857 and 149,58,390 tons respectively. According to BBS (2021) boro production is 4.154-ton hectare^{-1}. So, we need to increase per unit rice production.

The demand for rice is rising in response to the continuous population growth. Rice production is predicted to need to rise by 50–60% by 2025 in order to meet population growth-related demand (Mia *et al*., 2024; Jamal *et al*., 2023). It's possible that conventional fertilizer management alone won't be sufficient to supply the world's enormous food needs. The time to look for novel methods that can ensure greater yields with less degradation of natural resources has come (Islam *et al*., 2024; Shiferaw *et al*., 2009). Due to inadequate management techniques and nutrient imbalances, rice yield per hectare is steadily declining (Mia *et al*., 2023; Tan *et al*., 2005). Producing healthy and vigorous seedlings is the most important factors for obtaining high yield in rice (Salam *et al*., 2022; Mahajan *et al*., 2017).

An essential component of transplanted rice is nursery management. The standard procedure for growing rice is to raise it in a nursery before relocating it to the main field (Choudhary & Machavaram, 2022; Ferdous *et al*., 2018). Although it has been done for many years, farmers often do not use any fertilizer in rice nurseries, and there are no appropriate fertilizer recommendations for rice nurseries (Hasan *et al*., 2018; Sarangi *et al*., 2015). Only the primary field management of rice has received significant study attention thus far, with little focus on nursery management. Effective nursery management will influence how the crop behaves in field (Paul *et al*., 2017; Grossnickle and MacDonald, 2018). Rice nursery management is generally less costly than primary field management (Sarwar *et al*., 2014).

A balanced diet in the nursery is crucial for producing healthy rice seedlings, among other aspects of nursery management (Singh *et al*., 2005). The management of nutrients in the nursery bed affects rice yield, growth, and development. By investing a little money to raise robust and healthy seedlings in the nursery, the farmer can reap an extra 1 to 2 t ha^{-1} in benefits from the rice crop (Hossen *et al*., 2025; Adhikari *et al*., 2013). Increasing the nursery's fertility level results in a considerable rise in seedling length, root length, dry weight, root number, and seedling growth (Singh *et al*., 2005).

Another crucial element that affects the healthy growth and vigor of rice seedlings is the seeding density in the nursery. Weaker seedlings are produced in nursery beds with high seeding densities because of competition between the plants for light, nutrients, and water (Niraula and Timilsina, 2020). The ideal seed rate in a nursery bed allows the plant to use more nutrients and sunlight to grow its aerial and subsurface parts more effectively (Islam *et al*., 2024; Jana *et al*., 2016). When a larger seed rate is utilized at the nursery level, the rice crop's yield and yield components suffer, whereas when a lower seeding rate is used at the nursery, the yield increases (Sidddika *et al*., 2024; He *et al*., 2018). Accordingly, to improve rice development and yields, the right seeding density and nutrient management in the nursery bed are required (Mondal *et al*., 2021).

Nutrient management and seeding density approaches have a significant impact on creating superior, healthy, and quality seedlings as well as enhancing the crop yield of winter rice (Sarangi *et al*., 2014). Low nursery planting density combined with improved fertilizer management can result in higher seedling vigor. The yield of robust seedlings was noticeably higher (Forhad *et al*., 2023). However, despite these findings, limited research has systematically examined the combined effects of nursery seeding density and integrated nutrient management on seedling quality and subsequent yield of winter rice under local agro-ecological conditions. Moreover, the optimum interaction between seeding density and nutrient supply for producing vigorous seedlings remains insufficiently documented.

Table 1: *Physical and chemical characteristics of the experimental field*

Sand (mm)	Silt (mm)	Clay (mm)	Textured	PD (g/cc)	BD (g/cc)	Porosity (%)	pH	OM (%)	N (%)	P (ppm)	K (meq%)	S (ppm)	Zn (ppm)	B (ppm)	EC (ds/m)
20	67	13	Silt loam	2.60	1.35	46.67	6.80	1.29	0.101	26.00	0.14	15	0.60	0.25	1.23

Source: The findings of the mechanical examination of the first soil sample conducted at Bangladesh Agricultural University's Department of Soil Science in Mymensingh.

In order to ensure optimal growth and yield of rice, it is therefore preferable to use an integrated method for satisfying the nutrient need of the rice seedling plants. This would essentially comprise applying nutrients by maintaining a proper seeding density in the nursery bed. Based on the above facts the present study was undertaken withe following objectives: to evaluate the effect of nursery seeding density and nutrient management on seedling growth and yield of winter rice and to identify the optimum nursery seeding density and suitable nutrient management for obtaining higher yield of winter rice.

Materials and Methods

Experimental site

The trial site was 18 meters over mean level of the ocean and took place at 24°42'55" N latitude and 90°25'47" E longitude. The experiment was laid out in the field no. 2 of the wetland block of Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh from December 2021 to May 2022.

Experimental soil

Within the agro-ecological zone of the non-calcareous dark gray riverbank soil of the Old Brahmaputra Floodplain is the place (AEZ–9; UNDP and FAO, 1988). The soil belongs to the silt-loam texture class, with a pH of 6.8, an electrical conductivity (EC) of 1.23 ds m-1, 1.29% organic carbon, 0.101% N, P 26 ppm, K 0.14% meq, S 15 ppm, Zn 0.60 ppm, and B 0.25 ppm. The tested soil's morphological, chemical, and physical characteristics (0–15 cm depth) appear in Table 1.

Climate and weather condition

The information about the weather conditions that existed during the crop growing period is displayed in Table 2. A hot, humid monsoon season with considerable rainfall from June to October, a hot, humid season with high humidity from April to June, and a comparatively chilly and dry winter season from November to March define the site's subtropical climate. During the experimental period, the monthly mean maximum temperature ranged from 23.46°C to 32 °C and the monthly mean minimum temperature ranged from 12.6°C to 23.9°C. The relative humidity ranged from 73.61 to 84.12 percent and a total rainfall of 139.3 mm was received during the crop growth period.

Experiment treatment

Factor A- Nursery seeding density (3): Low density (100 g m^{-2}) (S_1), Medium density (150 gm^{-2}) (S_2), High density (200 gm$^{-2)}$ (S_3). Factor B- Nursery nutrient management: No nutrient applied (N_1), Nitrogen (N) @ 6 gm^{-2} (N_2), Phosphorous(P) @5 gm^{-2} (N_3), Potassium (K) @ 3 gm^{-2}(N_4), Nitrogen (N) @ 6 gm^{-2} + Phosphorous (P) @5 gm^{-2} + Potassium (K) @ 3 gm^{-2} (N_5), Compost 1 kgm^{-2} (N_6).

Table 2: *Weather data regarding monthly average air temperature, rainfall, relative humidity and sunshine hours at the experimental site during November 2021 to May 2022*

Month	Monthly avg. temp (°C)			Rainfall (mm)	Relative humidity (%)	Sunshine (hrs)
	Max	Min	Average			
November 2021	30.00	19.20	24.60	5.9	82.00	210.3
December 2021	26.3	14.00	20.15	4.3	83.40	189.9
January 2022	26.28	12.15	19.22	0.00	84.35	227.2
February 2022	27.03	15.54	21.28	1.17	83.00	164.8
March 2022	29.82	17.70	23.76	1.90	73.19	208.2
April 2022	31.65	22.30	27.00	2.22	77.67	193.5
May 2022	32.50	23.33	29.00	2.30	75.00	195.10

Source: Department of Water Management and Irrigation, Weather Yard, Bangladesh Agricultural University Mymensingh

Experiment design

Three replications of the randomized completely block design (RCBD) were used to set up the experiment in both the nursery and the main field.

Plant material used

The planting material for this investigation was the high-yielding winter rice cultivar BRRI dhan89. In 2018, this was published by the Bangladesh Rice Research Institute (BRRI). Somaclonal variation was used to create this variant. The variety was developed from crossing between BRRI dhan29 and *Oryzarufipogon*. The duration of the variety is 154-158 days and it has a yield potential of 8.0 -9.7 t ha^{-1}. This variety is recommended for *boro* (winter) season. This cultivar is harvested between the middle of April and the beginning of May. It can withstand mild wilt disease. Plant height is 106 cm. Thousand grain weight is 24.4 g. Grain size is medium and slender.

Seed collection and sprouting

BRRI dhan89 rice seeds were gathered from Bangladesh Agricultural University's Agronomy Field Laboratory in Mymensingh. The seeds spent a full day submerged in water in a bucket. After removing these seeds from the water, they were securely covered with gunny sacks. The seeds began to grow after 48 hours, and within the following 72 hours, they were ready to be sown.

Nursery raising

On December 5, 2021, a series of ploughing and laddering was used to prepare the nursery bed. Following the seeding density (SD) according to treatment, sprouted seeds were planted on elevated wet nursery beds that were 1.0 m long and 0.5 m wide. The nursery was fertilized using compost, muriate of potash (K), triple super phosphate (P), and urea (N) in accordance with the procedures. The bed was equipped with drainage channels to remove any surplus water.

Main field preparation

On January 13, 2022, the field was prepped by tractor plowing and then cross-harrowing to crush the soil. Then, on January 15, 2022, three consecutive ploughings and cross plowing were used to puddle at a suitable water level. All uprooted weeds were removed from the field after ploughing and laddering. The field layout was completed on 17 January 2022 following the final site preparation.

Fertilizer application

Fertilizers like N, P, K, and S were applied at rates of 200, 100, 70, and 60 kg ha^{-1} in the form of urea, TSP, MoP, and gypsum, respectively (FRG, 2018). When the area was finally prepared, all of the TSP, MoP, and gypsum was applied. At 15, 40, and 60 DAT, urea was applied in three equal amounts.

Uprooting of seedlings

The nursery bed was irrigated one day before uprooting the seedlings. The seedlings were uprooted on 17 January 2022 for avoiding much mechanical injury to the roots.

Transplanting of seedlings in the field

The seedlings of 45 days were transplanted in the main field on 17 January 2022 following the spacing 25 cm × 15 cm with 3 seedlings $hill^{-1}$.

Herbicide application

The main field was sprayed with a pre-emergence herbicide, Pretilachlor @ 400 mL $acre^{-1}$ at five days after transplanting.

Gap filling

Some seedlings died off after seven days of transplanting, so healthy seedlings from the nursery bed were planted to fill the void left by the dead seedlings.

Irrigation and drainage

A thin layer of water was kept at the time of transplanting for better establishment of the seedlings. From the third day onwards, 2 to 3 cm depth of water was maintained up to the panicle initiation stage except at the time of top dressing of urea, where the water was drained out and re-irrigated to maintain 5 cm depth of water. After dough stage, water was entirely drained out to enhance maturity and make harvesting easier.

Weeding

Two weeding's of the plots were carried out with the aid of manual labor. 30 days following transplanting, the first-hand weeding was completed, and 20 days following the first, the second one.

Plant protection

Carbotaf 5G @ 2 ml L-1 (200 L ha^{-1}) and Regent 3GR @ 2 ml L^{-1} (200 L ha^{-1}) were sprayed to treat some instances of stem borer and brown plant hopper.

Sampling, harvesting and processing

When almost 80% of the seeds had become golden

Table 3: *Effect of SD on RL, SL and SDW of BRRI dhan89*

SD	RL (cm)		SL (cm)		SDW (cm)	
	20DAS	40DAS	20DAS	40DAS	20DAS	40DAS
S_1	2.53	5.50a	9.42	15.69 b	32.24a	86.35a
S_2	2.60	5.44a	9.23	16.52a	32.18a	77.86 b
S_3	2.34	5.12 b	9.55	15.67 b	30.34 b	81.53 b
Sx	0.12	0.15	0.13	0.19	0.41	1.99
Level of significance	NS	*	NS	**	**	**
CV (%)	14.13	8.27	4.17	3.66	3.86	7.32

** =Significant at 5% level of probability, NS = non-significant*
In a column figure with same letter or without letter do not differ significantly whereas figure with dissimilar letter differ significantly as per DMRT. S_1= Low density (100 g m^{-2}), S_2= Medium density (150 gm^{-2}), S_3= High density (200 gm^{-2}).

Table 4: *Effect of nursery NM on RL, SL and SDW of BRRI dhan89*

NM	RL (cm)		SL (cm)		SDW (cm)	
	20DAS	40DAS	20DAS	40DAS	20DAS	**40DAS**
N_1	2.16 b	4.55 c	9.23 bc	15.86 b	27.08 e	68.22 d
N_2	2.28 b	4.66 c	9.17 c	15.37 bc	29.94 d	76.35 c
N_3	2.50ab	5.27 b	9.55ab	16.83a	30.77 cd	81.98 bc
N_4	2.62a	5.42 b	9.13 c	15.71 bc	31.63 c	82.53 b
N_5	2.77a	6.26a	9.89a	16.83a	35.92a	93.63a
N_6	2.63a	5.96a	9.43 bc	15.17 c	34.16 b	88.77a
Sx	0.17	0.21	0.18	0.28	0.58	2.83
Level of significance	**	**	**	**	**	**
CV (%)	14.13	8.27	4.17	3.66	3.86	7.32

N_1= No nutrient applied, N_2= Nitrogen (N) @ 6 gm^{-2}, N_3= Phosphorous(P) @5 gm^{-2}, N_4= Potassium (K) @ 3 gm^{-2}, N_5= Nitrogen (N) @ 6 gm^{-2} + Phosphorous (P) @5 gm^{-2} + Potassium (K) @ 3gm^{-2}, N_6= Compost 1 kgm^{-2}.

yellow, the crop was fully mature and ready for harvest. In order to collect the required data on different plant characteristics and yield metrics, five hills (apart from border hills) were preselected at random from each plot and uprooted before to harvest. The crops were harvested manually on 11 May 2022 from each plot to record the yields of grain and straw yields. Each plot's harvested crop was taken to the threshing floor after being individually wrapped and appropriately marked. A pedal thresher was used to thresh the crops. Grains were washed and sun-dried. Straws were appropriately sun-dried as well. Lastly, the grain yield was translated to tons per hectare after being corrected to 14% moisture.

Data collection parameters

The following data were recorded. Seedling growth parameters: Shoot Length (SL), Root Length (RL), Seedling dry weight (SDW). Crop characteristics, yield parameters and yield: Plant height (PH), Total tillers $hill^{-1}$ (TT), Effective tillers $hill^{-1}$ (ET), Non-effective tillers $hill^{-1}$ (NET), Total spikelets $panicle^{-1}$ (SPP), Grains $panicle^{-1}$ (GPP), 1000-grain weight (TGW), Grain yield (GY), Straw yield (SY), Harvest Index (HI)

Harvest index

It represents the grain-to-biological yield ratio and was computed using the formula below:

Statistical analysis

They compiled and tabulated the information collected for statistical analysis. For the Analysis of Variance (ANOVA), the statistical software tool MSTAT-C was utilized. The mean differences between the treatments were ascertained using Duncan's Multiple Range Test (Gomez and Gomez, 1984). RStudio was used for data visualization, while Microsoft Excel was employed to organize the dataset for analysis (R Core Team, 2022).

Table 5: *Interaction effects of SD and nursery NM on RL, SL and SDW of BRRI dhan89*

SD x NM	RL (cm)		SL (cm)		SDW (cm)	
	20DAS	40DAS	20DAS	40DAS	20DAS	40DAS
S_1N_1	2.20	4.13 f	9.22	15.15	28.88 ij	69.19
S_1N_2	2.40	4.22 ef	9.18	15.37	30.09 ghi	80.64
S_1N_3	2.50	5.93abc	9.53	17.34	30.96 fgh	86.07
S_1N_4	2.60	5.96ab	8.88	15.04	31.43 efg	86.96
S_1N_5	2.83	6.43a	10.09	16.55	36.93 a	99.74
S_1N_6	2.68	6.32a	9.61	14.72	35.14ab	95.50
S_2N_1	2.46	4.80 def	8.98	16.42	26.18 k	65.76
S_2N_2	2.53	4.96 d	9.05	15.90	32.58 def	73.64
S_2N_3	2.56	4.96 d	9.20	17.18	32.16 ef	74.66
S_2N_4	2.66	5.22 cd	9.34	16.63	31.97 efg	75.26
S_2N_5	2.80	6.40a	9.76	17.43	35.96ab	91.80
S_2N_6	2.63	6.33a	9.04	15.58	34.23 bcd	86.06
S_3N_1	1.83	4.72 def	9.48	16.03	26.19 k	69.70
S_3N_2	1.90	4.81 def	9.27	14.84	27.17 jk	74.78
S_3N_3	2.45	4.93 de	9.92	15.96	29.19 hi	85.20
S_3N_4	2.60	5.09 d	9.18	15.46	31.50 efg	85.38
S_3N_5	2.69	5.96ab	9.81	16.52	34.88 bc	89.36
S_3N_6	2.58	5.23 bcd	9.66	15.20	33.10 cde	84.76
Sx	0.29	0.36	0.32	0.48	0.99	4.89
Level of significance	NS	**	NS	NS	**	NS
CV (%)	14.13	8.27	4.17	3.66	3.86	7.32

Results

Seedling growth parameters

RL

At 20 DAS, seedling RL of BRRI dhan89 was not significantly affected by SD. But, numerically the maximum seedling RL (2.60 cm) was recorded with 150 g m^{-2} SD and the minimum one (2.34 cm) was found in 200 g m^{-2} SD (Table 3).Nutrient management (NM) had a significant effect on the RL, and N+P+K treatment produced the highest RL (2.77cm) followed by N, P, K and compost, each these particular treatments were discovered to be much more higher than the control treatment (Table 4). Interaction between SD and NM did not produce any significant effect on RL at all (Table 5).

At 40 DAS, seedling RL was significantly affected by nursery SD. The RL (5.50 cm) was recorded with 100 g seeds m^{-2} followed by 150 g seeds m^{-2} and 200 g seeds m^{-2} (Table 3). had a significant effect on the RL. The N+P+K treatment resulted in the highest RL (6.26 cm) followed by N, P, K and compost; and each these particular treatments were discovered to be much higher than the control treatment (Table 4). Interaction between SD and NM produced significant effect on RL. SD of (100 gm^{-2}) and N+P+K treatment combination produced the highest RL (6.43 cm) followed by each these particular treatments were discovered to be much higher than the control treatment (Table 5).

SL

At 20 DAS, no significant effect of SD was found on seedling SL of BRRI dhan89. But, numerically the maximum SL (9.55 cm) was recorded with 200 g m^{-2} SD and the minimum one (9.23 cm) was obtained from 150 g m-$^{-2}$ SD (Table 3). NM had a significant effect on the SL and N+P+K treatment produced the highest SL (9.89 cm) followed by N, P, K and compost (Table 4). Interaction between SD and NM did not produce any significant effect on SL (Table 5).

At 40 DAS, SD had significant effect on seedling SL. SD of 150 g m^{-2} performed the best in terms of SL (16.52 cm) on the other hand, 100 g m^{-2} performed the worst (15.69 cm) (Table 3). NM exerted a significant effect on the SL of rice seedling. The maximum SL

Table 6: *Effect of SD on yield contributing characters and yield of BRRI dhan89*

SD	PH (cm)	TT (no.)	ET (no.)	NET (no.)	SPP (no.)	GPP (no.)	TGW (g)	SY (t ha^{-1})	HI (%)
S_1	110.03	9.65a	8.87a	0.78	106.34	99.07	26.18	6.04	49.31
S_2	107.52	8.98 b	8.21 c	0.76	104.60	98.48	26.38	5.94	48.88
S_3	106.61	9.11 b	8.30 b	0.80	104.42	98.02	26.11	5.87	48.93
Sx	1.66	0.12	0.05	0.09	2.39	0.64	0.16	0.16	0.71
Level of significance	NS	**	**	NS	NS	NS	NS	NS	NS
CV (%)	4.62	3.88	1.69	6.09	6.83	1.94	1.83	8.25	4.32

(16.83 cm) was recorded with P and N+P+K followed by N, P and which was at per with K and compost and each these particular treatments were discovered to be much higher than the control treatment (Table 4). Interaction between SD and NM did not produce significant effect on SL either. However, numerically the longest SL (17.43 cm) was found when 150 g m^{-2} SD was used with N+P+K applied in nursery (Table 5).

SDW

At 20 DAS, the SDW of BRRI dhan89 was significantly affected by SD. SD of 100 g m^{-2} produced the highest SDW (32.18 mg) which was statistically similar with 150 g m^{-2} and the lowest SDW (30.34 mg) was produced by 200 g m^{-2} (Table 3). The NM had a significant effect on SDW. Application of N+P+K resulted in the highest SDW (35.92 mg), followed by N, P which was at par with K and compost and all these treatments performed better than to the control treatment (Table 4). The interplay between SD and NM had significantly influenced on the SDW of BRRI dhan89. Best SDW (36.93 mg) was recorded at 100 g m^{-2} SD with application of N+P+K in nursery bed (Table 5).

At 40 DAS, rice SDW was significantly affected by SD. The highest SDW (86.35 mg) was observed with SD of 100 g m^{-2}, the lowest one (77.86 mg) was recorded at 150 g m^{-2} which was statistically similar with 200 gm^{-2} (Table 3). NM exhibited a significant effect on the SDW and N+P+K produced the highest seedling weight (93.63mg) whereas application of cowdung resulted the statistically similar SDW (Table 4). There was no significant effect of the interaction between SD and NM of SDW. However, numerically the highest SDW (99.74 mg) was produced when SD of 100 g m^{-2} interacted with N+P+K (Table 5).

Crop characteristics, yield parameters and yield

Effect of SD

Different seeding densities had no significant effect on PH of BRRI dhan89. However, numerically the tallest plant (110.03 cm) was obtained from the 100 g m^{-2} treatment, whereas the shortest one (106.61 cm) was recorded with the 200 g m^{-2} treatment (Table 6). The effect of SD on TT was significant. The highest TT (9.65) was produced in 100 g m^{-2} treatment, while the lowest one (8.98) was recorded in 150 g m^{-2} treatment (Table 6). ET, one of the yield parameters, was significantly affected by SD. The highest ET (8.87) were obtained with 100 g m^{-2} SD and the minimum ET (8.21) were obtained with 150 g m^{-2} SD (Table 6). The SD treatments can be categorized as 100 g m^{-2}>150 g m^{-2}> 200 gm^{-2}depending on the decreasing ET. SD showed no significant effect on NET of rice. SD of 100 g m^{-2}produced the highest number of NET (0.80) and the lowest NET (0.76) was obtained in the 150 g seeds m^{-2} (Table 6). SD had no significant effect on GPP of BRRI dhan89. SD performed the highest (99.07) with 100 g m^{-2} while performed the lowest with (98.02)200g m^{-2} (Table 6). The number of total SPP was not significantly affected by SD. But, numerically the maximum number of total SPP (106.34) was observed in 100 g m^{-2} treatment and the minimum number of total SPP (104.42) was produced by 150 g m^{-2} treatment (Table 6). Effect of SD on TGW of BRRI dhan89 was not significantly affected by SD. However, numerically the highest TGW (26.38 g) of winter rice was obtained when seed were sown with 150 g m^{-2} SD and the lowest TGW (26.11 g) was recorded when the seed were sown with 200 g m^{-2} SD (Table 6). The data on GY reveal significant differences due to SD used in the rice nursery bed. The GY of rice was increased significantly, with the decreased SD. The highest GY (5.86 t ha^{-1}) was recorded when 100 g m^{-2} seeds were sown while, 150 g m^{-2} and 200 g m^{-2} seeding densities resulted in the yield of 5.67 t ha^{-1} and 5.61 t ha^{-1}, respectively (Figure 1A). Effect of SD the effect of SD on SY was not significant of BRRI dhan89. But, numerically the highest SY (6.04 t ha^{-1}) was observed in 100g m^{-2} treatment and the lowest SY (5.87 t ha^{-1})

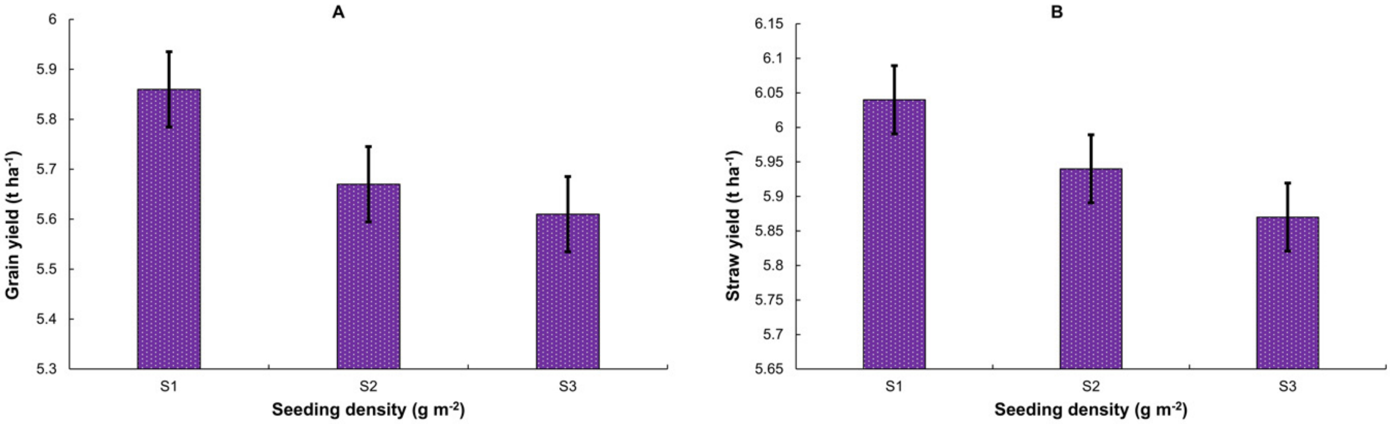

Figure 1: *Effect of seeding density on grain yield and straw yield of winter rice*

Table 7: *Effect of nursery NM on yield contributing characters and yield of BRRI dhan89*

NM	PH (cm)	TT (no.)	ET (no.)	NET (no.)	SPP (no.)	GPP (no.)	TGW (g)	SY (t ha^{-1})	HI (%)
N_1	105.79	8.90 c	8.04 d	0.85	103.56	95.54 c	26.13	5.78	48.87
N_2	108.41	9.18 bc	8.37 c	0.81	105.16	98.05 b	26.16	5.96	49.11
N_3	107.57	9.13 bc	8.37 c	0.76	104.58	98.71 b	26.18	5.96	49.00
N_4	107.97	9.22 bc	8.47 bc	0.74	104.82	98.60 b	26.08	5.95	49.04
N_5	110.31	9.71a	8.94a	0.77	106.94	100.82a	26.49	6.11	49.09
N_6	108.30	9.34 b	8.57 b	0.77	105.65	99.45ab	26.30	5.94	49.14
Sx	2.35	0.17	0.07	0.13	3.39	0.90	0.23	0.23	0.99
Level of significance	NS	**	**	NS	NS	**	NS	NS	NS
CV (%)	4.62	3.88	1.69	6.09	6.83	1.94	1.83	8.25	4.32

found in 200 g m^{-2} treatment (Figure 1B). It was found that the HI was not statistically significant in all the treatments. However, numerically the highest HI (49.31%) was found in 100 g m-$^{-2}$ and a minimum one (48.88%) was found in 150 g m^{-2} (Table 6).

Effect of NM

Effect of NM on rice PH was not significant. However, numerically the tallest plant (110.31 cm) was found in N+P+K treatment and the shortest one (105.79 cm) was obtained from the control treatment (Table 7). TT was not significantly affected by different NM. However, numerically the highest TT (9.71) was produced when N+P+K was applied and the lowest one (8.90) was produced when no nutrient was applied (Table 7). NM had significant effect on ET of winter rice variety of BRRI dhan89. The highest ET (8.94) were recorded with N+P+K and the lowest one (8.04) was obtained from control (Table 7). The treatments for NM like K, Compost, P and N showed statistically similar effect on the ET. NM had no significant effect on NET production of winter rice variety of BRRI dhan89. However, numerically the highest number of NET (0.85) was recorded with control and lowest number of NET (0.74) was recorded for K (Table 7). NM had significant effect on GPP of rice. The N+P+K treatment performed the best (100.82) and the control treatment performed the poorest (95.54); the effects of the other treatments on GPP were statistically comparable (Table 7). The effect of different NM on the number of total SPP was not significant. However, numerically the maximum number of total SPP (106.94) was obtained with N+P+K treatment and the minimum one (103.56) was recorded with no nutrient (Table 7). NM had no significant effect on TGW of BRRI dhan89. However, numerically the highest TGW (26.49 g) of winter rice was observed when N+P+K was applied and the lowest TGW (26.08 g) was recorded for K treatment applied in nursery bed (Table 7). GY of BRRI dhan89 was significantly affected by NM. The various nutrient treatments given to the rice nursery resulted in notable variances, according to the GY statistics (Table 7). With increased fertilizer, the GY significantly increased. The highest GY (5.89 t ha-^{1}) was seen when N+P+K was given, which was at par with that of N (5.73 t ha-$^{-1}$), followed by statistically similar (5.72t ha^{-1}) treatment but significantly superior

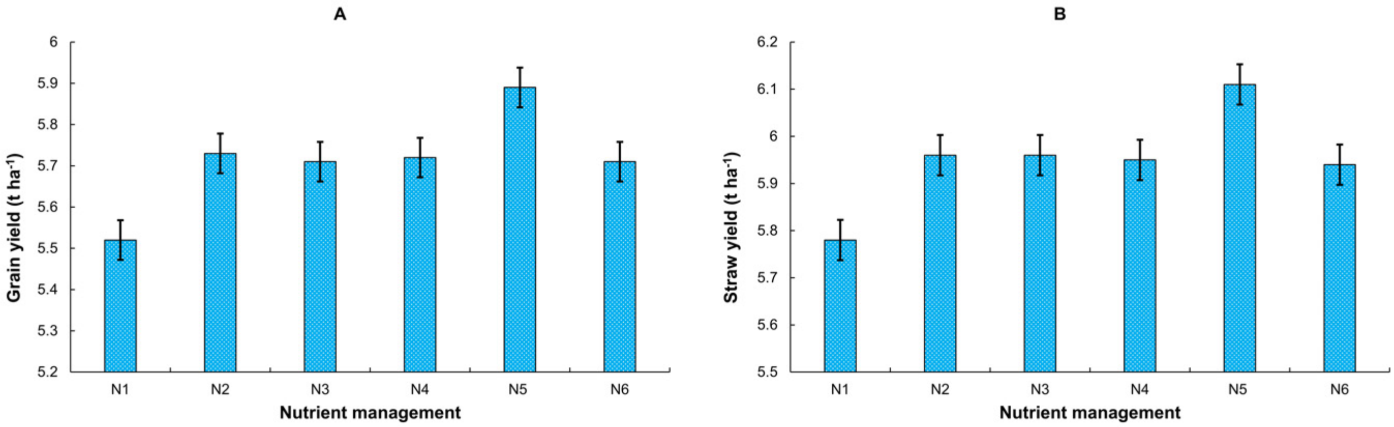

Figure 2: *Effect of nursery nutrient management on grain yield and straw yield of winter rice*
N_1= No nutrient applied, N_2= Nitrogen (N) @ 6 gm^{-2}, N_3= Phosphorous(P) @5 gm^{-2}, N_4= Potassium (K) @ 3 gm^{-2}, N_5= Nitrogen (N) @ 6 gm^{-2} + Phosphorous (P) @5 gm^{-2} + Potassium (K) @ 3gm^{-2}, N_6= Compost 1 kgm^{-2}.

Table 8: *Interaction effects of SD and nursery NM on yield contributing characters and yield of BRRI dhan89*

SD x NM	PH (cm)	TT (no.)	ET (no.)	NET (no.)	SPP (no.)	GPP (no.)	TGW (g)	GY (t ha^{-1})	SY (t ha^{-1})	HI (%)
S_1N_1	107.38	9.45	8.53 ef	0.91	104.74	94.26	26.05	5.68	5.97	48.77
S_1N_2	110.48	9.40	8.65 de	0.75	106.57	99.89	26.00	5.80	6.00	49.13
S_1N_3	109.48	9.50	8.83 cd	0.66	105.89	99.96	26.45	5.93	6.03	49.67
S_1N_4	109.15	9.60	8.85 cd	0.75	106.78	98.90	26.21	5.86	5.98	49.57
S_1N_5	112.20	10.10	9.26a	0.83	107.79	101.64	26.32	6.06	6.33	48.89
$S_{1N}6$	111.50	9.88	9.11ab	0.76	106.27	99.81	26.04	5.85	5.91	49.85
$S_{2N}1$	105.83	8.60	7.83 jk	0.76	103.00	96.44	26.31	5.43	5.68	48.84
S_2N_2	108.73	9.13	8.30 fgh	0.83	105.32	96.68	26.59	5.67	5.91	49.13
$S_{2N}3$	107.32	8.85	8.05 ij	0.80	103.24	97.79	26.16	5.56	5.95	48.44
S_2N_4	107.95	9.01	8.25 ghi	0.76	104.40	99.79	26.25	5.71	6.00	48.71
S_2N_5	109.23	9.41	8.66 cde	0.75	106.92	100.71	26.49	5.85	6.05	49.30
S_2N_6	106.08	8.86	8.16 hi	0.70	104.72	99.52	26.52	5.80	6.08	48.85
S_3N_1	104.15	8.65	7.76 k	0.88	102.95	95.93	26.02	5.46	5.69	48.99
S_3N_2	106.00	9.03	8.18 hi	0.85	103.58	97.59	25.90	5.72	5.98	49.05
S_3N_3	105.92	9.05	8.23 ghi	0.81	104.61	98.38	25.93	5.65	5.90	48.89
S_3N_4	106.80	9.05	8.33 fgh	0.71	103.28	97.10	25.79	5.58	5.86	48.85
S_3N_5	109.48	9.63	8.90 bc	0.73	106.11	100.10	26.67	5.74	5.96	49.06
S_3N_6	107.32	9.28	8.43 efg	0.85	105.97	99.03	26.36	5.50	5.83	48.73
Sx	4.07	0.29	0.12	0.23	5.86	1.56	0.39	0.08	0.40	1.73
Level of significance	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
CV (%)	4.62	3.88	1.69	6.09	6.83	1.94	1.83	1.76	8.25	4.32

to the rest of the treatments under this study (Figure 2A). SY of BRRI dhan89 rice was not significantly affected by the NM. Numerically, the highest SY (6.11 t ha^{-1}) was found when N+P+K was applied and the lowest one (5.78 t ha^{-1}) was obtained when control treatment was applied in the nursery (Figure 2B). The data show that the HI was not significantly affected by NM. Numerically the highest HI (49.14%) was found in compost and a minimum one (48.87%) was found in control treatment (Table 7).

Interaction effect of SD and NM

The interactions between SD and NM that significantly failed to affect PH of rice. Numerically the tallest plant (112.20 cm) was obtained from the interaction of S_1N_5 and the shortest one (104.15 cm) was found in the interaction of S_3N_1 (Table 8). Interaction between SD and NM had no significant effect on total tiller per hill. However, numerically the highest TT (10.10) was produced in the interaction of S_1N_5 and the lowest one (8.60) was found in treatment combination of S_2N_1 (Table 8). The interaction between SD and NM exerted significant effect on ET. The best performance (9.26) was recorded with the combination of S_1N_5 and the worst performance (7.76) was obtained from the interaction of S_3N_1 (Table 8). NET was not significantly affected by the interaction between SD and NM. Numerically the highest (0.91) and lowest (0.66) NET were recorded for S_1N_1 and S_1N_3 (Table 8). The interaction between SD and NM had no significant effect on grain panicle^{-1} of winter rice. However, numerically the maximum grains per panicle (101.64) were recorded for the S_1N_5 treatment combination and the minimum GPP (105.03) were recorded for the S_3N_1 combination (Table 8). The interaction effect of SD and NM on the number of total SPP was not significant. Numerically, the highest number of total SPP (107.79) was observed in S_1N_5 and the lowest number of total SPP (103) was obtained from the interaction of S_2N_1 (Table 8). The interaction between SD and NM had no significance on grains per panicle of BRRI dhan89 either. However, the results revealed that numerically the highest TGW (26.67 g) of BRRI dhan89 was obtained from the combination of S_3N_5 and the lowest one (25.79 g) was recorded from interaction of S_3N_4 (Table 8). The interaction effect of SD and NM on GY of BRRI dhan89 was not significant. However, numerically the maximum GY (6.06 t ha^{-1}) was recorded with the combination of S_1N_5 and the minimum one (5.43 t ha^{-1}) was recorded by S_2N_1 (Table 8). No significant variation in SY was found due to interaction between SD and NM practices. However, numerically the highest straw (6.33 t ha^{-1}) yield was recorded with the combination of S_1N_5 and the lowest one (5.68 t ha^{-1}) was obtained from the interaction of S_2N_1 (Table 8). No significant variation in HI was found due to interaction between SD and NM practices. But, numerically the highest HI (49.85 %) was recorded with the combination of S_1N_6 and the lowest one (48.88 %) was obtained from S_2N_3 (Table 8).

PC, correlation and heatmap analysis

The characteristics that best capture the effect of SD on winter rice seedling growth and yield were identified using Principal Component Analysis. Figure 3 displays the bi-plot of the first two principal components along with the variable loadings. With 76.1% of the variation explained by the first principal component (PC1), represented by the x-axis, and 23.9% by the second principal component (PC2), represented by the y-axis. PC1 is highly positively correlated with the TT, ET, HI, SPP, GY, PH, SY, and GPP variables. They have a high positive link with one another, as seen by their clustering. TGW and NET are more aligned with PC2. NET and TGW have negative correlation with TT, ET, HI, SPP, GY, PH, SY, GPP.

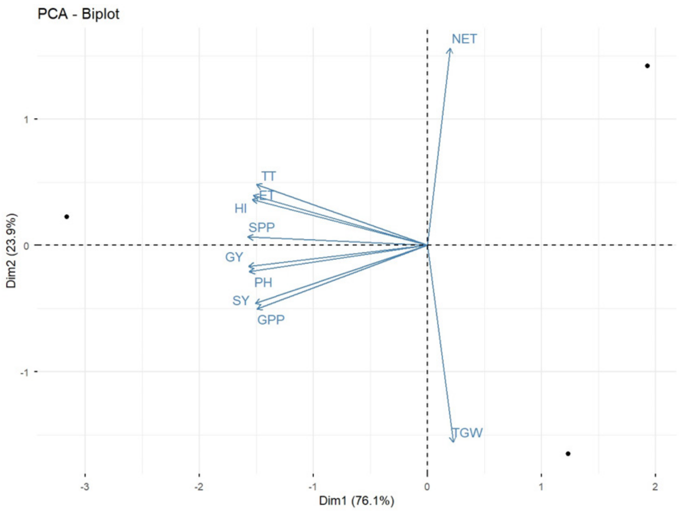

Figure 3: *Bi-plot of principal component analysis (PCA) showing the first two principal components (PC 1 and PC 2)*

For PCA, data on growth, yield and yield contributing attributes under seeding density. The grey dots are indicating three residue treatments, like 1 = Low density (100 g m^{-2}), 2 = Medium density (150 gm^{-2}), 3 = High density (200 gm^{-2}). Where, PH= Plant height (cm), TT= Total tiller hill^{-1}, ET= Number of effective tillers hill^{-1}, NET= Number of non-effective tillers hill^{-1}, GPP= Grain panicle^{-1} (cm), SPP= Sterile Spikelets panicle^{-1}, TGW= 1000-grain weight (g), GY= Grain yield (t ha^{-1}), SY= Straw yield (t ha^{-1}), HI= Harvest index (%).

The characteristics that best characterize the influence of NM on the growth and yield of winter rice seedlings were identified using Principal Component Analysis. Figure 4 displays the bi-plot of the first two principal components along with the variable loadings. First principal component (PC1), which makes up 83.7% of the overall variance, is represented by the x-axis, while second principal component (PC2), which makes up 9.5% of the total variance, is represented by the y-axis. The variables GY, SY, GPP, HI, PH, ET, TT, and SPP are strongly positively correlated with PC1. NET is more aligned with PC2 and have a negative correlation with GY, SY, GPP, HI, PH, ET, TT, SPP.TGW is closer to origin. Treatment 3 and 4 are strongly influenced by PC2 and is distinct from other observations and treatment 2 and 6 is strongly influenced by PC1 and is distinct from other observations while treatment 1 and 5 are closer to the origin, indicating they have more average values for the principal components.

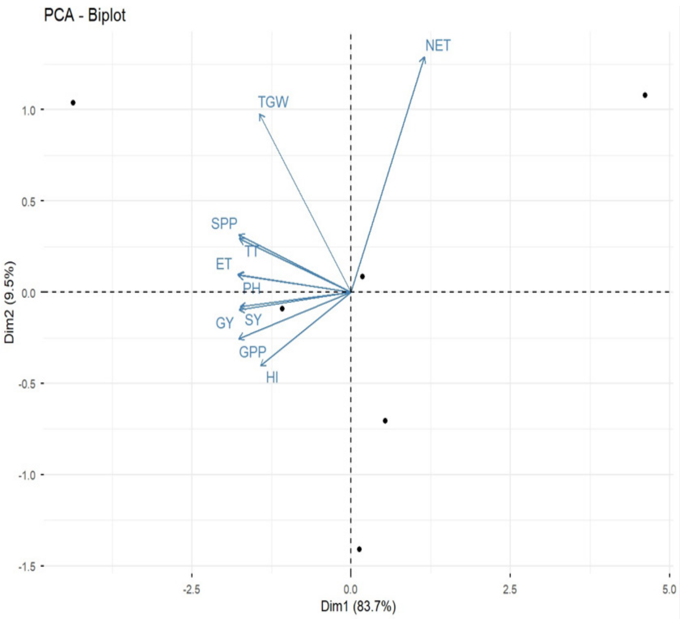

Figure 4: *Bi-plot of principal component analysis (PCA) showing the first two principal components (PC 1 and PC 2)*
For PCA, data on growth, yield and yield contributing attributes under nutrient management. The grey dots are indicating six residue treatments, like 1 = No nutrient applied, 2 = Nitrogen (N) @ 6 gm^{-2}, 3 = Phosphorous(P) @5 gm^{-2}, 4 = Potassium (K) @ 3 gm^{-2}, 5 = Nitrogen (N) @ 6 gm^{-2} + Phosphorous (P) @5 gm^{-2} + Potassium (K) @ 3gm^{-2} and 6 = Compost 1 kgm^{-2}.

A correlation was performed to identify the impact of SD on seedling growth and yield of winter rice (Figure 5). The analysis revealed that PH was strongly positively correlated with GY (P < 0.05, r = 1.00), GPP showed a strong positive correlation with SY (P < 0.05, r = 1.00), and ET was strongly correlated with both HI and TT (P < 0.05, r = 1.00). PH was associated with higher GY, while GPP corresponded to increased SY. Moreover, higher ET was linked to improved HI and TT, indicating that these traits are closely interrelated and contribute to overall productivity.

A correlation was performed to identify the impact of NM on seedling growth and yield of winter rice (Figure 6). GY showed a strong positive correlation (P < 0.01) with GPP (r = 0.95), SPP (r = 0.94), ET (r = 0.96), TT (r = 0.93) and PH (P < 0.001 and r = 0.98). Similarly, SY exhibited a strong positive correlation (P < 0.01) with, GPP (r = 0.94), SPP (r = 0.92), ET (r = 0.97), PH (r = 0.94), TT (r = 0.92), and GY (P < 0.001 and r = 1.00). Moreover, GPP was strongly correlated (P < 0.01) with SPP, PH, and TT (r = 0.93) as well as with ET (r = 0.96). Likewise, SPP showed strong positive correlations (P < 0.001) with PH and ET (r = 0.98), TT (r = 0.99), and TGW (P < 0.05 and r = 0.87), while PH was strongly correlated (P < 0.01) with ET and TT (r = 0.96). In addition, ET exhibited strong positive correlations with TT (P < 0.001 and

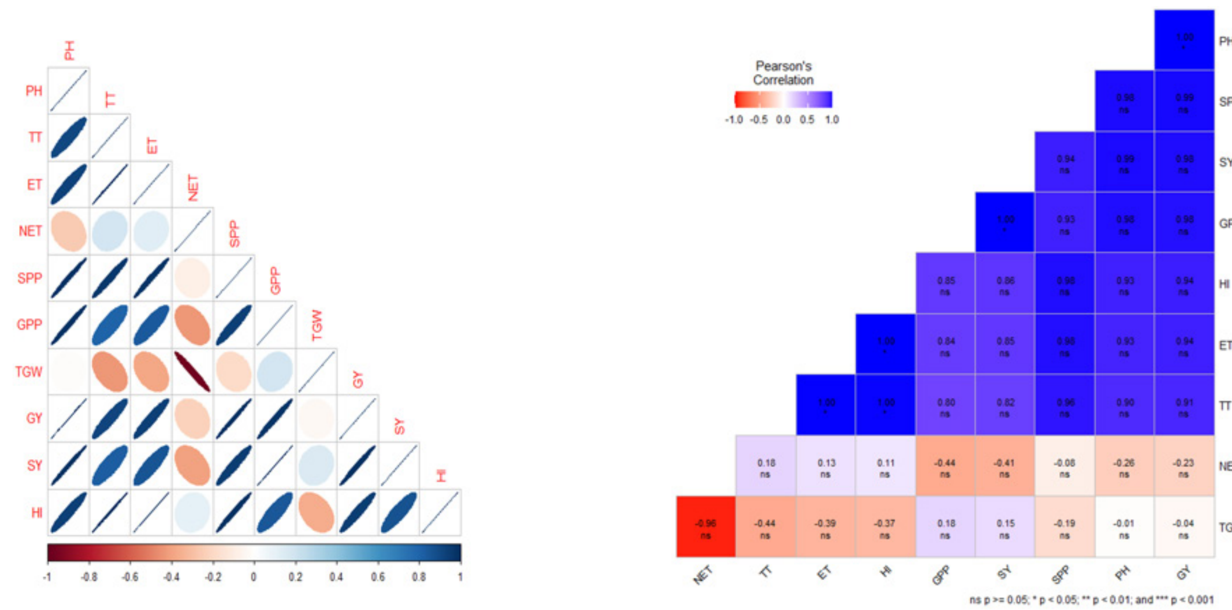

Figure 5: *Pearson correlation analysis of growth, yield and yield contributing traits in rice under seeding density on seedling growth and yield of winter rice.*
****, **, * and NS (Not Significant) represent probability of ≤0.001, ≤0.01, ≤0.05 and >0.05, respectively, strong positive correlation (r= 0.61-1.00), moderate positive correlation ((r= 0.30-0.60), and normal correction (r= 0.01-0.29).*

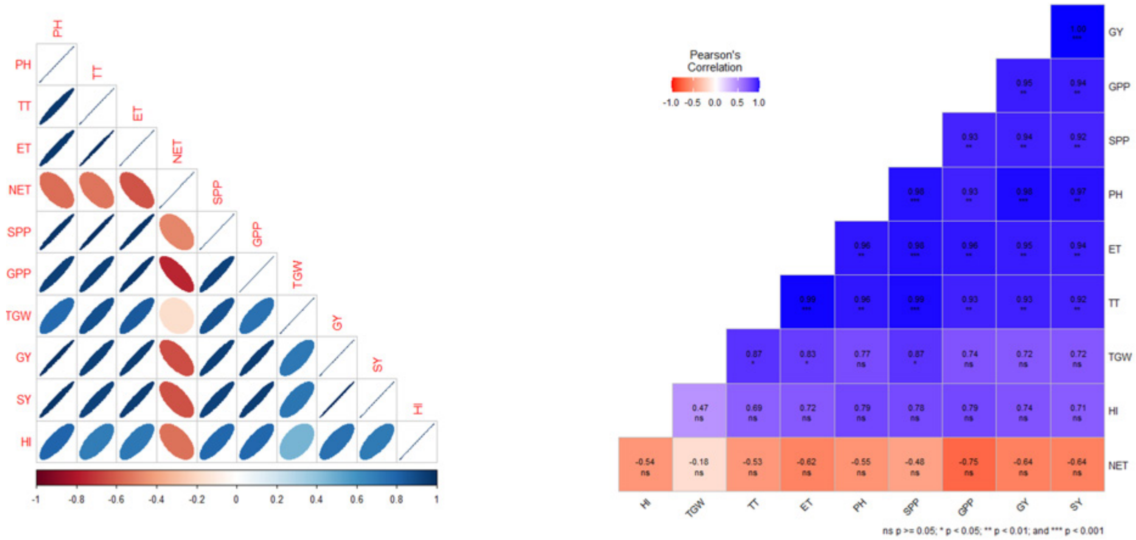

Figure 6: *Pearson correlation analysis of growth, yield and yield contributing traits in rice under nutrient management on seedling growth and yield of winter rice.*

****, **, * and NS (Not Significant) represent probability of ≤0.001, ≤0.01, ≤0.05 and >0.05, respectively, strong positive correlation (r= 0.61-1.00), moderate positive correlation ((r= 0.30-0.60), and normal correction (r= 0.01-0.29).*

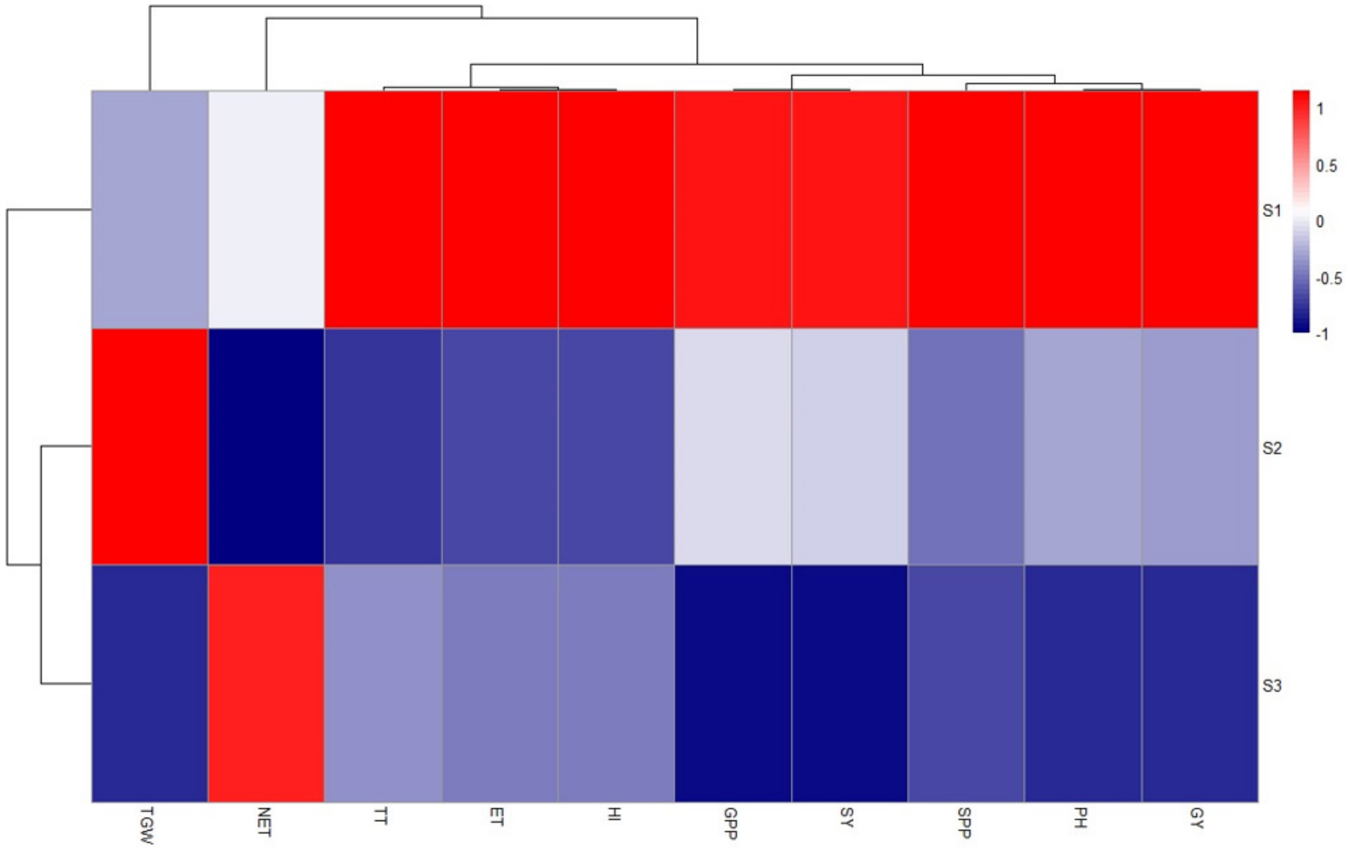

Figure 7: *Heat map analysis of the impact of nursery seeding density on seedling growth and yield of winter rice. Red signifies high and blue low, whereas colors show relative values from -1 to +1*

For PCA, data on growth, yield and yield contributing attributes under seeding density. The grey dots are indicating three residue treatments, like 1 = Low density (100 g m^{-2}), 2 = Medium density (150 gm^{-2}), 3 = High density (200 gm^{-2}). Where, PH= Plant height (cm), TT= Total tiller $hill^{-1}$, ET= Number of effective tillers $hill^{-1}$, NET= Number of non-effective tillers $hill^{-1}$, GPP= Grain $panicle^{-1}$ (cm), SPP= Sterile Spikelets $panicle^{-1}$, TGW= 1000-grain weight (g), GY= Grain yield (t ha^{-1}), SY= Straw yield (t ha^{-1}), HI= Harvest index (%).

r = 0.99) and TGW (P < 0.05 and r = 0.83). Finally, TT was strongly correlated (P < 0.05) with TGW (r = 0.87). GY showed strong positive correlations with PH, GPP, SPP, ET, and TT, indicating that taller plants with more grains and spikelets per panicle and higher numbers of tillers produce higher grain yield,

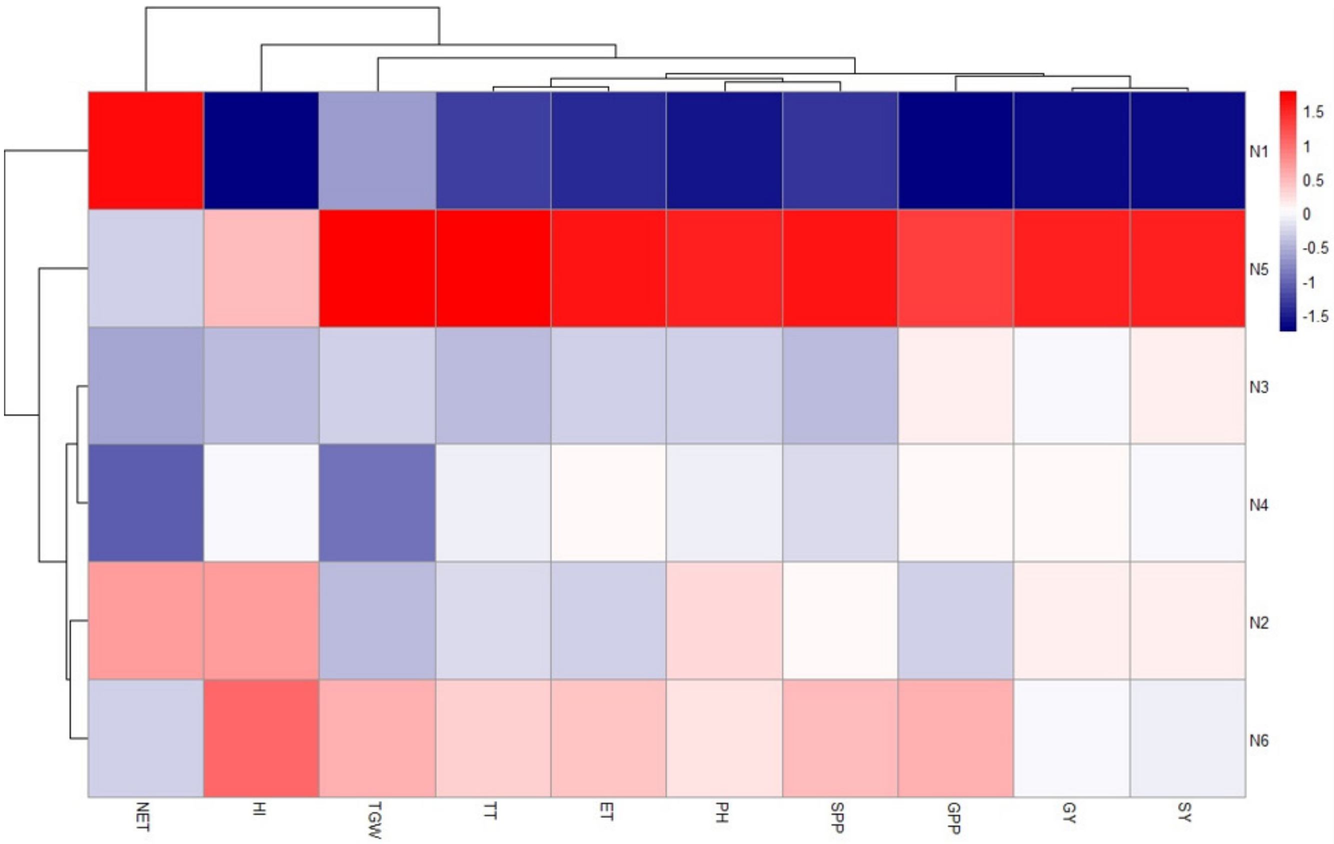

Figure 8: *Heat map analysis of the impact of nursery nutrient management on seedling growth and yield of winter rice. Red signifies high and blue low, whereas colors show relative values from −1 to +1*

N_1= No nutrient applied, N_2= Nitrogen (N) @ 6 gm^{-2}, N_3= Phosphorous(P) @5 gm^{-2}, N_4= Potassium (K) @ 3 gm^{-2}, N_5= Nitrogen (N) @ 6 gm^{-2} + Phosphorous (P) @5 gm^{-2} + Potassium (K) @ 3gm^{-2}, N_6= Compost 1 kgm^{-2}.

and SY was similarly associated with these traits. GPP and SPP were strongly correlated with PH, ET, TT, and TGW, reflecting that panicle structure, plant vigor, and grain weight are closely linked. Overall, all these traits are highly interrelated, and improvements in one are likely to enhance others, contributing to higher grain and straw yields.

To determine which traits best illustrate how nursery SD and NM affect winter rice seedling growth and yield, a heat map was employed. The y-axis shows the various treatments, and the x-axis shows the variables associated with vegetative and yield parameters (Figure 7). TT, ET, HI, GPP, SY, SPP, PH, and GY variables had a high contribution with Low density (100 g m^{-2}). TT, ET, HI, GPP, SY, SPP, PH, and GY variables represented the lowest contribution with High density (200 gm^{-2}). Light, moderate, and neutral associations between all the parameters were maintained by other treatments.

The variables that contribute to growth and yield are represented on the x-axis, and the various treatments are represented on the y-axis (Figure 8). Growth and yield contributing character like SY, GY, GPP, SPP, PH, ET, TT, and TGW demonstrated the highest contribution when Nitrogen (N) @ 6 gm^{-2} + Phosphorous (P) @5 gm^{-2} + Potassium (K) @ 3gm^{-2} was applied. No nutrient applied treatment showed the lowest SY, GY, GPP, SPP, PH, ET, TT, and HI while NET was highest. The associations between all the factors were light, moderate, and neutral in other treatments.

Discussion

Proper nursery management is essential for seedling growth and crop performance transplant rice. SD and NM are crucial factors for producing healthy seedling to survive in the main field. As proper SD and NM in nursery bed trigger the growth and quality of rice seedlings and ultimately increase rice yield.

The interaction between two SD and NM did not significantly influence the root height, shoot height and dry weight of the seedlings but, SD and NM solely influenced the SL and SDW. As SD decreased, a declining trend in seedling SL was noted. Because there was more competition for sunlight in the nursery bed, the tallest seedlings were generated at greater SD than at medium and low seeding densities. Significantly more emerging seedlings and dry matter were produced per unit area as a result of high-density sowing. There were more seedlings per unit area because there were more seeds sown per unit area, and more seedlings meant more dry matter was produced per unit area. Low density seeding, however, appears to have a greater per SDW. This resulted from healthy, strong seedlings in a low-density nursery that were free from competition.

Additionally, it was noted that the seedlings from the low-density nursery were more robust and had a darker green hue, particularly when N+P+K was applied in the nursery bed. However, Pathania *et al.* (2016) found higher SL in nursery at low SD compared to high SD. But according to Patra *et al.* (2014), larger SD promotes intra-seedling competition, producing tall, lanky seedlings with low vigor and no tillers. Before and after transplanting, rice plants' above- and below-ground traits differed according to seedling rates (Sasaki, 2004). Low nursery SD combined with better NM can result in better seedling vigor.

Manandhar *et al.* (2020) found that NM levels profoundly affected PH. A similar outcome on PH was also demonstrated by Roy *et al.* (2018). However, the PH of BRRI dhan89 did not exhibit any relevance in this investigation.

The interaction between the components resulted in a significant change in the amount of ET produced per square meter. The number of ET with low SD was considerably increased in the nursery by the application of N+P+K. Furthermore, compared to high SD, ET per square meter for lower density seeding was noticeably higher. Forhad *et al.* (2023) also noted that ET in the nursery increased as the SD decreased.

The interaction results revealed that under higher densities, application of N+P+K in nurseries had no much effect on ET per square meter, but had significant effect with low SD. Rani (2012) states that the most prolific tillers m^{-2} were produced in the nursery bed that received the proper amounts of nitrogen, FYM, and phosphorus.

There was no discernible difference in the number of grains per panicle between the SD and NM interactions. However, the characteristic was only impacted by SD and NM. Compared to high SD, low SD generated noticeably more grains per panicle. Similarly, Mustari (2013) claimed that the highest GPP was obtained from lower seed rate in nursery bed.

Depending on genetic composition, TGW is a significant yield contributor that is least impacted by growing conditions (Ashraf *et al.*, 1999). Neither of the factors viz., SD and nursery NM of had substantial differences for 1000 grain weight among each other. Similarly, interaction effect between the factors on TGW was non-significant. Nevertheless, compared to high density unfertilized nurseries, Forhad *et al.* (2023) saw higher TGW from low density fertilized nurseries.

The GY was only controlled by the SD and NM of the seedlings; the interactions between the two parameters had no discernible effect. Low SD produced the highest yield (5.86 t ha^{-1}) in the experiment comparing to medium and high SD. Forhad *et al.* 2023 opined that low SD at nursery bed resulted in a higher number of productive tillers and GY. Nursery fertilization raises yields by 23–30% in comparison to the control, claim Kyalo *et al.* (2020). Rice's GY and grain protein content are also enhanced by the prudent use of nitrogen fertilizer (Ray *et al.*, 2015).

The results clearly indicated that higher seedling density (SD) can substantially reduce grain yield (GY), suggesting that intense competition in the nursery adversely affects seedling growth. In the early stages of crop growth, De Datta (1980) found that an increase in SD was associated with an increase in intra-plant and inter-plant competition.

This present research shows no notable effect of either SD or NM on HI. Rani (2012) reported same concept for HI. However, Kyalo *et al.* (2020) showed HI were considerably different across the treatments.

Conclusions and Recommendations

The current research concludes that SD and NM in nursery beds have the ability to boost crop output and seedling growth. With the application of N 6 g m^{-2}+ P 5 g m^{-2}+ K 3 g m^{-2}, the SD of 100 g m^{-2} produced superior seedling growth, which in turn improved the yield parameters and ultimately enhanced yield among the various seeding densities and NM procedures used in the nursery. Confirmation and establishment of appropriate nursery management practices for winter rice require more thorough research.

Acknowledgements

We acknowledge the Agronomy Farm Lab, Department of Agronomy, BAU for providing logistics support to this research.

Novelty Statement

This study introduces a novel integration of seeding density and nursery nutrient management to evaluate their combined influence on the growth and yield of BRRI dhan89, a widely cultivated high-yielding rice variety in Bangladesh. While previous research has often examined these factors separately, this experiment uniquely demonstrates how optimized seedling density, when paired with balanced N-P-K fertilization in the nursery stage, can significantly enhance seedling vigor and subsequent field performance. The findings reveal that low seeding density combined with enriched nursery nutrition produces more robust seedlings, which translate into superior tillering capacity and grain yield. This integrated approach highlights an efficient, practical strategy for improving rice productivity, offering farmers a refined method to maximize returns through precise seed and nutrient management at the nursery level.

Author's Contribution

Md. Parvez Anwar: Conceptualization, Data Curation, Writing - review and editing, Project Administration.
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The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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