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# Assessing the Effects of Structural Arrangements and Seedling Densities on the Growth and Yield-contributing Parameters of Boro Rice

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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**Abstract**

Planting geometry and the number of seedlings per hill may influence the growth and yield of transplanted Boro rice. A field experiment was conducted at the Agronomy Field Laboratory, University of Rajshahi, Bangladesh, from December 2022 to May 2023 to assess the individual and combined effects of these factors on BRRI dhan28. The experiment used a 4 × 4 factorial randomised complete block design (RCBD), comprising four structural arrangements ($A_1$: 25 cm + 25 cm, $A_2$: 20 cm + 30 cm, $A_3$: 15 cm + 35 cm and $A_4$: 10 cm + 40 cm) and four seedling densities ($S_1$: 1 seedling hill$^{-1}$, $S_2$: 2 seedlings hill$^{-1}$, $S_3$: 3 seedlings hill$^{-1}$ and $S_4$: 4 seedlings hill$^{-1}$) with 3 replications. The structural arrangement $A_1$ (25cm+25cm) recorded the highest values for most parameters, including plant height (89.17 cm), total tillers per plant (18.80), effective tillers per plant (15.27), panicle length (22.36 cm), panicle weight (14.35 g), spikelets per panicle (184.72), grains per panicle (144.11), filled grains per panicle (124.29), grain yield (5.42 t ha$^{-1}$), straw yield (7.02 t ha$^{-1}$), and biological yield (12.44 t ha$^{-1}$). With respect to seedling density, treatment $S_3$ (3 seedlings per hill) resulted in the highest values, including plant height (90.20 cm), number of tillers per plant (19.11), number of

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leaves per plant (15.50), effective tillers per plant (15.69), panicle length (23.33 cm), panicle weight (15.42 g), spikelets per panicle (196.15), grains per panicle (149.33), filled grains per panicle (130.57), grain yield (5.79 t $ha^{-1}$), straw yield (7.39 t $ha^{-1}$), and biological yield (13.18 t $ha^{-1}$). The results showed that $A_1$ and $S_3$, both individually and in combination, produced the highest values for most of the measured parameters. These findings emphasise the importance of optimising both planting arrangement and seedling density for improving the growth, resource efficiency and yield potential of Boro rice. The study offers agronomists and rice farmers a potential approach to improving Boro rice productivity under the experimental conditions, namely a 25cm + 25 cm arrangement with three seedlings per hill.

*Keywords: Boro rice; structural arrangement; seedling number; yield components; grain yield; resource use efficiency; sustainability.*

## 1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops worldwide, serving as the primary food source for nearly half of the global population (Mishra *et al*., 2025). Approximately 3.5 billion people around the world depend on rice as a staple food, making it a vital source of nutrition and livelihood for nearly half the global population (Mohapatra *et al*., 2025). It is one of the oldest domesticated crops and has served as a cornerstone of human civilization, especially in Asia. Rice belongs to the Gramineae (Poaceae) family and has a high tillering capacity, which is directly related to productivity. The economic, nutritional, and cultural importance of rice is particularly pronounced in Asia, where it constitutes the cornerstone of food security and rural livelihoods (Alam *et al*., 2024). Rice is rich in carbohydrates, contains moderate amounts of protein and provides essential micronutrients such as calcium, magnesium, iron, and vitamins, including B-complex, E, and thiamine (Mukka *et al*., 2025). Its high nutritional value and versatility make it indispensable in daily diets across diverse regions. In Bangladesh, rice is more than a food source; it is the backbone of the national economy (Islam *et al*., 2024). Approximately 77% of the country's population resides in rural areas, where rice cultivation remains the primary agricultural activity and a critical source of employment and income generation (Emran *et al*., 2021).

Among the three major rice-growing seasons in Bangladesh (Aus, Aman and Boro), the Boro season contributes the most to total production (Al Mamun *et al*., 2021). Grown between December and May, Boro rice is cultivated under irrigated conditions, making it less susceptible to rainfall variability. The expansion of irrigation facilities, such as shallow tube wells and submersible pumps, has significantly boosted Boro cultivation. High-yielding modern varieties such as BRRI dhan28 and BRRI dhan29 dominate this season. However, sustaining and improving productivity in the face of increasing input costs and environmental stresses require precise agronomic management, particularly concerning transplanting geometry and seedling density (Shah & Wu, 2019).

Plant arrangement, or structural arrangement, is a critical agronomic factor that influences plant population density, intraspecific competition, light interception, and resource utilisation (Tokatlidis, 2022). Improper arrangement may lead to yield reductions of 25-30% due to suboptimal tillering, poor canopy architecture, and increased weed competition (Daba & Mekonnen, 2022). Wider spacing can facilitate intercultural operations and enhance individual plant growth, yet it may also reduce the number of plants per unit area, leading to underutilisation of land. In contrast, narrower spacing increases plant population but may cause excessive competition for light, nutrients, and water, resulting in mutual shading, lodging, and lower grain yield (Chen *et al*., 2019). Rice field studies have reported that planting geometry can influence crop yield and nutrient uptake under specified nutrient-management conditions (Singh *et al*., 2024). Transplanting-density trials have also indicated that rice grain-yield responses to hill density may differ across production environments (Andrianary *et al*., 2024).

The number of seedlings transplanted per hill is another influential factor in determining rice productivity (Deng *et al*., 2022). Tiller formation, plant nutrient uptake and plant vigour are influenced by seedling density. Although a moderate number of seedlings can help balance competition and improve canopy structure, both excessively dense and sparse stands can have adverse effects. An excessive number of seedlings per hill increases mutual shading, resource competition, and the risk of lodging, which collectively reduce grain yield while increasing straw output (Wu *et al*., 2022). On the other hand, planting too few seedlings may result in inadequate tiller numbers and suboptimal land coverage, leaving space for weeds and reducing panicle density (Chaudhary *et al*., 2023). Balancing seedling density is therefore important for achieving efficient resource use and crop production. Research on transplanted Aman rice has additionally linked tillering dynamics with panicle production and grain yield (Akter *et al*., 2025). A study of late-season rice under experimental warming further reported that the number of seedlings per hill influenced yield responses, indicating that these effects may depend on growing conditions (Xiong *et al*., 2025).

Although plant arrangement and seedling density have been investigated separately in Boro rice, relatively few studies have examined their combined effects on the production of Boro rice varieties such as BRRI dhan28. Addressing this knowledge gap may help develop locally relevant recommendations for improving rice productivity under the current agro-ecological conditions in Bangladesh.

Therefore, the present study aimed to examine the individual and combined effects of different structural arrangements and numbers of seedlings per hill on the growth and yield of Boro rice. The study was designed to assess the most suitable transplanting geometry and number of seedlings per hill for achieving higher grain yield. It also aimed to examine the interaction between these two factors and their effects on growth traits and yield components in relation to efficient and sustainable rice production.

## 2. Materials and Methods

### 2.1 Experimental Site and Agro-Climatic Conditions

The field experiment was conducted at the Agronomy Field Laboratory, Department of Agronomy and Agricultural Extension, University of Rajshahi, from December 2022 to May 2023 to examine the yield and yield-contributing traits of the Boro rice cultivar BRRI dhan28 under different structural arrangements and numbers of seedlings per hill.

The experimental field was located on the western side of the Faculty of Agriculture building, University of Rajshahi (24°22′36″ N latitude and 88°38′27″ E longitude) with an elevation of 20 m above sea level. The soil of the site is part of the Gopalpur series within Agro-Ecological Zone 11 (AEZ-11) and is sandy loam in texture with a pH of 8.4. The field had good drainage and levelling and was not prone to flooding. The area has a subtropical climate, with moderate to high temperatures and high rainfall (April to September), followed by lower rainfall and temperatures (October to March).

### 2.2 The Experimental Design and Treatments

The experiment was laid out in a randomised complete block design (RCBD) with three replications. The experiment included two factors: (1) structural arrangement, with four levels: $A_1$: 25 cm + 25 cm, $A_2$: 20 cm + 30 cm, $A_3$: 15 cm + 35 cm, $A_4$: 10 cm + 40 cm; and (2) number of seedlings per hill, with four levels: $S_1$: 1 seedling hill$^{-1}$; $S_2$: 2 seedlings hill$^{-1}$; $S_3$: 3 seedlings hill$^{-1}$; and $S_4$: 4 seedlings hill$^{-1}$. There were 16 treatment combinations, each randomly allocated within each replication. Each plot measured 10 m² (4.0 m x 2.5 m), resulting in 48 experimental plots.

### 2.3 Seedling Raising, Field Preparation and Fertilizer Management

Seeds of BRRI dhan28 were collected from BRRI, Rajshahi, and healthy, disease-free seeds were selected. After soaking the seeds for 24 h, they were kept in moist, dark conditions for 48 h to allow sprouting. On 14 December 2022, sprouted seeds were sown evenly in a well-prepared seedbed. Good nursery management practices were followed to maintain seedling vigour. Land preparation in the main field began on 12 January 2023 using a power tiller, followed by three harrowing and laddering operations. Weeds, stubble and residues were removed by hand and the land was levelled before layout of the plots. Fertilisers were applied at the recommended rates of 220 kg ha$^{-1}$ of urea, 100 kg ha$^{-1}$ of triple super phosphate (TSP), 70 kg ha$^{-1}$ of muriate of potash (MOP), 60 kg ha$^{-1}$ of gypsum and 10 kg ha$^{-1}$ of zinc sulphate. During final land preparation, all fertilisers except urea were applied as a basal dose. To maximise nitrogen availability at critical crop growth stages, urea was split into three applications at 14, 30 and 50 days after transplanting (DAT).

### 2.4 Transplanting and Crop Management

Seedlings were carefully uprooted from the seedbed on 25 January 2023, when they were 35 days old. The seedbed was irrigated the day before uprooting to minimise root damage. The seedlings were transplanted in the puddled plots based on the combinations of treatments. Missing and dead seedlings were replaced one week after transplanting with healthy seedlings from the same stock. To maintain weed-free plots, two hand-weedings were carried out at 20 and 40 DAT. Irrigation was maintained at a 6 cm water level during the early phase and a 10-13 cm level during the later phase to promote the development of the crop. The plots were drained 15 days before harvest to facilitate grain maturity. Plants were monitored regularly throughout the growth stages to assess their health and condition, and no lodging was observed.

### 2.5 Harvesting and Data Collection

Harvesting began when approximately 80% of the grains were golden yellow (physiologically mature). Five hills were randomly selected from each plot, excluding borders, to record growth and yield attributes. In addition, a 1 m² area was harvested from the centre of each plot on 7 May 2023. The harvested plants were tied into labelled bundles and sun-dried before being threshed using a foot-operated threshing machine. Grain yield (kg ha$^{-1}$) and straw yield were determined at a moisture content of 14%. Both growth and yield parameters were recorded. Growth parameters were measured at different stages and included plant height, tiller number, leaf number and number of panicles. At harvest, data were recorded for plant height, number of effective and non-effective tillers, panicle length and weight, number of spikelets, florets, grains (filled and unfilled), and 1000-grain weight. Yield parameters, such as grain yield, straw yield, biological yield, and harvest index, were calculated using standard formulae:

Biological yield (kg ha$^{-1}$) = Grain yield + Straw yield,

$$\text{Harvest index (\%)} = \frac{Grain\ yield}{Biological\ yield} \times 100$$

### 2.6 Statistical Analysis

All data were collected and statistically analysed using SPSS version 26.0 and MS Excel 2021. The Pearson correlation coefficient heatmap was generated in the Origin Pro 2025 software. The significance of differences among treatment means was assessed using Duncan's New Multiple Range Test (DMRT) at the specified significance level (Gomez & Gomez, 1984).

## 3. Result and Discussion

Rice plant height under different structural arrangements ($A_1$-$A_4$) and seedling numbers ($S_1$-$S_4$) at different days after transplanting (DAT) (20, 40, 60, 80, 100 and harvest) indicated that structural arrangement and seedling number significantly influenced growth.

Across all measurement periods, the $A_1$ configuration produced the tallest plants, measuring 89.17cm and the $A_4$ configuration produced the shortest plants, measuring 83.87cm. With respect to seedling number, $S_3$ recorded the greatest plant height, increasing from 30.80 cm at 20 DAT to 90.20 cm at harvest, suggesting a positive effect of moderate seedling density on root growth and nutrient absorption. The interaction between structural arrangement and seedling number also influenced plant height: $A_1S_3$ produced the tallest plants, reaching 92.10 cm at harvest, whereas $A_4S_1$ produced the shortest plants (81.07cm) during the experiment (Fig. 1).

The increased plant height under $A_1S_3$ may be attributed to the optimum spatial arrangement and moderate seedling density, which may have improved light interception, root development, and water and nutrient uptake while reducing excessive competition among hills for water, nutrients, and other growth resources. The optimised arrangement also provided sufficient growing space for proper root expansion, facilitating better uptake of water and nutrients and consequently promoting vegetative growth and stem elongation. In contrast, the shorter plants under $A_4$ may have resulted from comparatively less efficient utilisation of available growth resources and greater intra-specific competition. In contrast, the shorter plants under $A_4S_1$ may have resulted from less efficient resource utilisation and comparatively unfavourable plant spacing. A moderate number of seedlings per hill may have provided a favourable balance between plant-to-plant competition and resource availability. Under these conditions, plants could develop a relatively extensive root system and efficiently absorb water and nutrients, which enhanced cell division, cell elongation, and overall vegetative growth. Excessively low or high seedling numbers may disrupt this balance, either by underutilising available resources or by increasing competition for light, nutrients, water, and space. The $A_1S_3$ interaction produced the tallest plants, reaching 92.10 cm at harvest, suggesting that the beneficial effects of suitable structural arrangement and moderate seedling density were complementary. Similar effects of plant spacing and seedling number on rice plant height and growth have been reported by Ram *et al.* (2014).

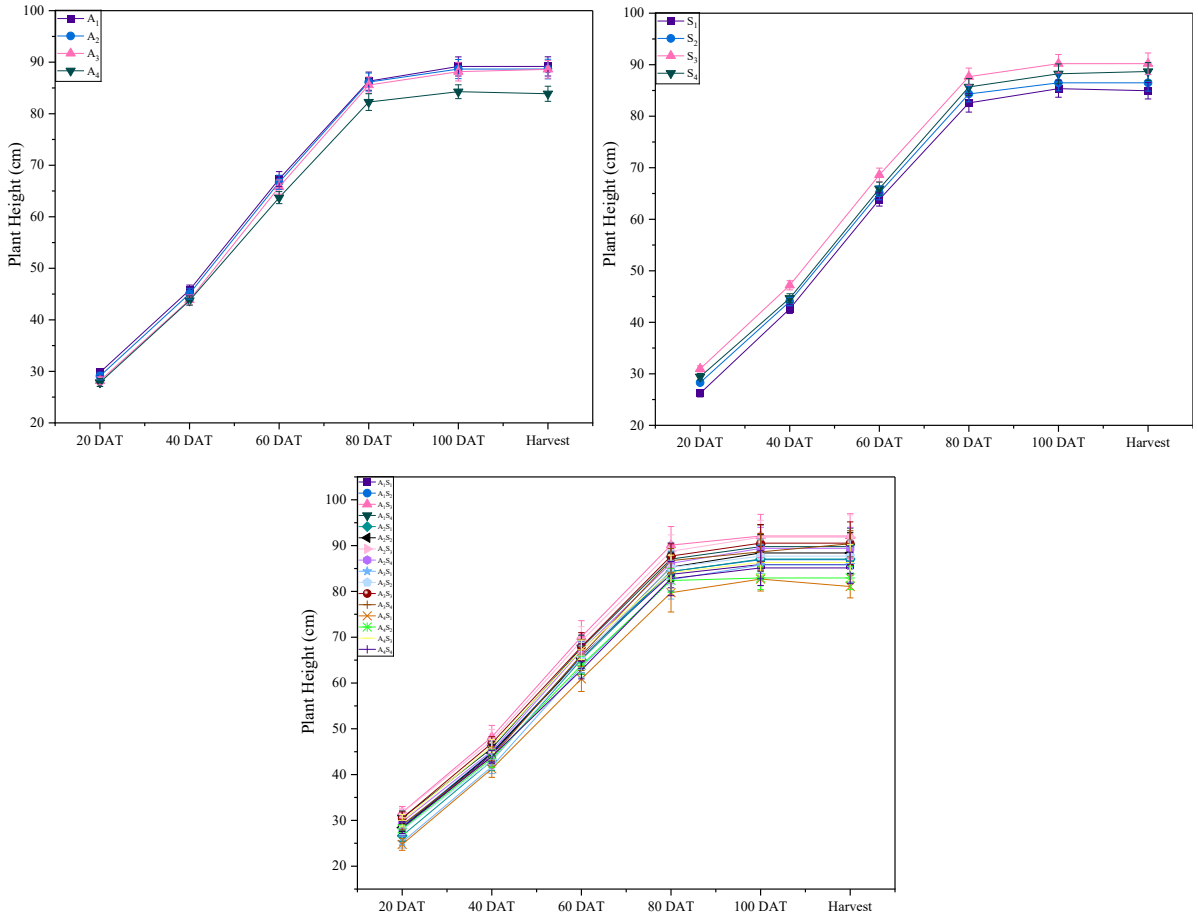



**Fig. 1. Effect of structural arrangement, number of seedlings hill$^{-1}$ and their interaction on plant height of rice at different DAT**

At the first measurement, the highest number of leaves was recorded under structural arrangement $A_2$ (6.08 leaves), whereas the lowest was recorded under $A_4$ (5.5 leaves). Differences among arrangements gradually narrowed, and by 80 DAT, $A_1$ showed a slight advantage in leaves per plant (14.91); however, the number of leaves per plant differed little among arrangements. Marked differences in leaf number were observed among the seedling-per-hill treatments, with $S_3$ (three seedlings per hill) recording the highest leaf counts of 6.67 at 20 DAT and 15.5 at 80 DAT, compared with the lowest counts under $S_1$ (one seedling per hill). The interaction between structural arrangement and seedling number indicated that $A_1$ gave the highest leaf numbers at the measured stages, including 7 leaves at 20 DAT and 16.32 leaves at 80 DAT (Fig 2).

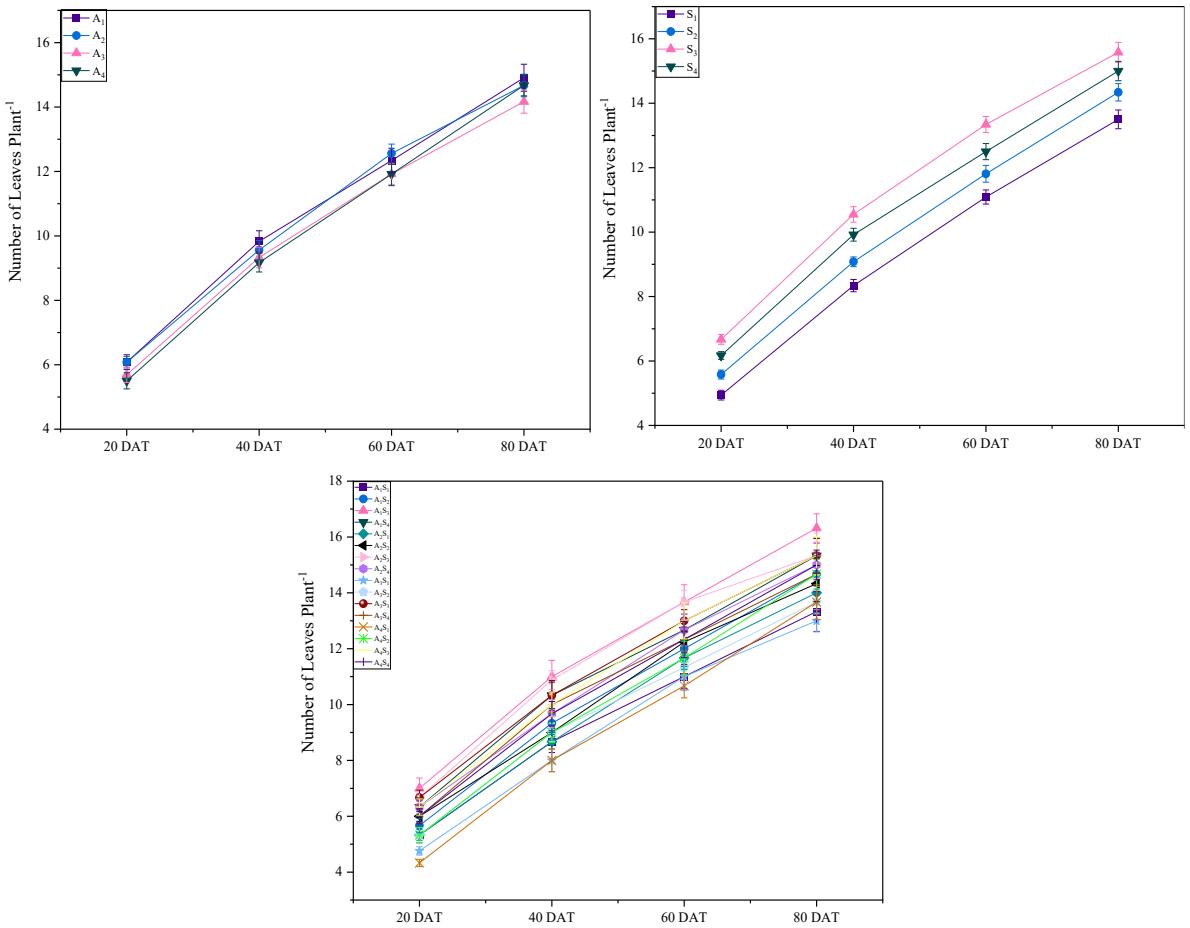



**Fig. 2. Effect of structural arrangement, number of seedlings hill$^{-1}$ and their interaction on number of leaves plant$^{-1}$ of rice at different DAT**

The effect of structural arrangement on tillers per rice plant was assessed at different days after transplanting (20, 40, 60, 80 and 100 DAT). At 20 DAT, $A_1$ recorded the highest mean tiller number (2.48 tillers per plant), which was 20.48 % higher than $A_4$ (2.05 tillers) and 5.5 % higher than $A_2$ and $A_3$ (2.32 tillers). This trend continued at 40 and 60 DAT, with $A_1$ recording the highest tiller counts of 5.05 and 12.98, respectively. At 80 DAT, differences in tiller number among treatments were not statistically significant; however, by 100 DAT, the differences were significant, with $A_1$ having 18.80 and $A_4$ having 17.66 tillers (which represents a difference of 6.46%). Tiller number was also strongly influenced by seedling density. $S_3$ consistently produced the most tillers, starting from 2.80 at 20 DAT to 19.11 at 100 DAT. The lowest density ($S_1$) recorded lower tiller counts, ranging from 1.41 to 17.55 during the same time. It was found that the increase at 20 DAT for $S_3$ over $S_1$ was particularly noticeable for 98.59% but this decreased as plants grew. The $A_1S_3$ combination recorded the highest tiller numbers, particularly in the interaction analysis. $A_1S_3$ produced 3.11 tillers per plant at 20 DAT, which was 133.8% more than the lowest-tillering treatment, $A_4S_1$, with a value of 1.33. This combination also produced more tillers than the other treatments at 40, 60, 80 and 100 DAT. Differences among the other treatments were also observed, although they were less pronounced than those between $A_1S_3$ and $A_4S_1$ (Fig. 3).

Tiller numbers did not differ significantly among the structural arrangements; however, $A_1$ consistently produced the greatest number of tillers per plant during the growing season, with 18.80 tillers at 100 DAT. The higher number of tillers under $A_1$ may be attributed to its more favourable spatial arrangement, which provided better access to light, nutrients, water, and growing space, thereby encouraging tiller initiation and development. Conversely, the lowest tiller count was observed in arrangement $A_4$ with 17.66 tillers at the same stage representing a 6.06% lower tiller count than $A_1$. The number of tillers was significantly affected by seedling density. The maximum tiller number was observed at the intermediate seedling density ($S_3$) with 19.11 tillers per plant at 100 DAT. This was significantly higher than the lowest value under $S_1$, which recorded 17.55 tillers with an 8.89% difference. The maximum tiller production under $S_3$ suggests that moderate seedling density created a favourable balance between plant competition and resource availability. Similar effects of plant spacing and seedling number on tillering in rice have been reported by Inaba and Kitano (2005). An interaction between structural arrangement and seedling density was also observed for tiller development. The treatment combination $A_1S_3$ had the highest number of tillers per plant (19.66) at 100 DAT which differed significantly from the other treatments. The highest tiller number under $A_1S_3$ suggests that the combination of suitable arrangement and moderate seedling density provided favourable conditions for root growth, nutrient uptake, and tiller initiation, resulting in greater tiller production. On the other hand, the arrangement $A_4S_1$ recorded the lowest tiller counts at all growth stages, indicating the effects of suboptimal arrangement and low seedling numbers (Table 1).

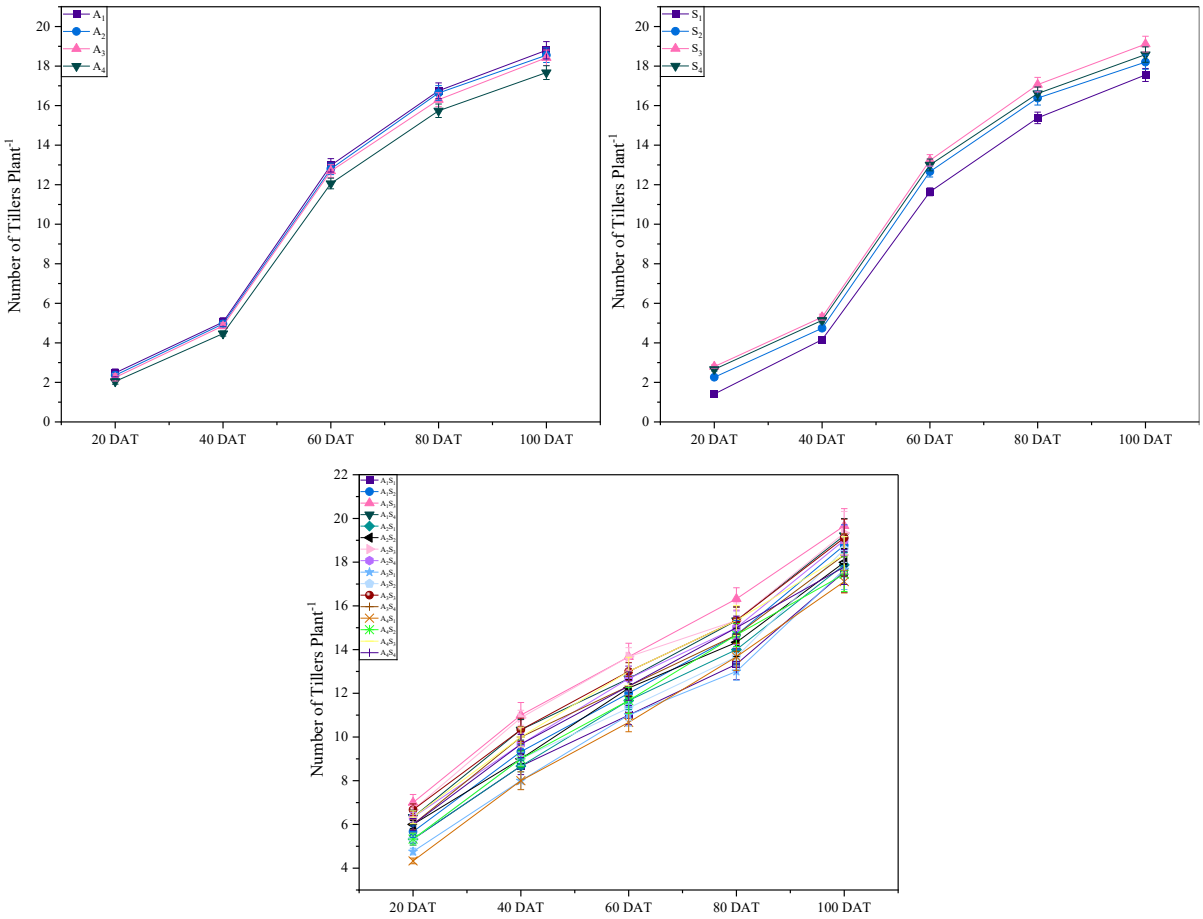



**Fig. 3. Effect of structural arrangement, number of seedlings hill$^{-1}$ and their interaction on number of tillers plant$^{-1}$ of rice at different DAT**

**Table 1. Effect of structural arrangement, number of seedlings hill$^{-1}$ and their interaction on different growth and reproductive characters of rice**

| Structural Arrangement | Number of total tillers plant$^{-1}$ | Number of effective tillers plant$^{-1}$ | Number of non-effective tillers plant$^{-1}$ | Panicle length (cm) | Panicle weight (g) |
|---|---|---|---|---|---|
| **$A_1$** | 18.8±0.42 | 15.28±0.33 | 3.61±0.11 | 22.36±0.51 | 14.35±0.43 |
| **$A_2$** | 18.55±0.39 | 15.11±0.34 | 3.5±0.1 | 22.13±0.51 | 14.05±0.48 |
| **$A_3$** | 18.43±0.39 | 14.66±0.32 | 3.66±0.1 | 21.97±0.5 | 13.94±0.46 |
| **$A_4$** | 17.67±0.37 | 14.34±0.32 | 3.74±0.12 | 21.18±0.53 | 13.46±0.37 |
| **LS** | NS | NS | NS | NS | NS |
| **Number of Seedlings** | | | | | |
| **$S_1$** | 17.55±0.33b | 13.98±0.29c | 3.84±0.14a | 20.5±0.44c | 12.48±0.25b |
| **$S_2$** | 18.11±0.37ab | 14.66±0.32bc | 3.53±0.11b | 21.53±0.42bc | 13.3±0.23b |
| **$S_3$** | 19.21±0.41a | 15.69±0.29a | 3.51±0.06b | 23.33±0.39a | 15.42±0.39a |
| **$S_4$** | 18.58±0.36ab | 15.05±0.28ab | 3.64±0.09ab | 22.28±0.44ab | 14.6±0.27a |
| **LS** | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| **Interaction Effects of Structural Arrangement and Number of Seedlings** | | | | | |
| **$A_1S_1$** | 17.55±0.79 | 14.67±0.73abc | 3.22±0.1de | 20.9±1.07ab | 12.95±0.52cdef |
| **$A_1S_2$** | 18.77±0.76 | 15±0.79abc | 3.78±0.2bcde | 22.03±1.17ab | 13.57±0.55cdef |
| **$A_1S_3$** | 19.66±1.04 | 16.11±0.49a | 3.55±0.18bcde | 23.69±0.72a | 15.88±0.79a |
| **$A_1S_4$** | 19.22±0.59 | 15.33±0.69abc | 3.88±0.2abc | 22.8±0.82ab | 15±0.46abc |
| **$A_2S_1$** | 17.88±0.55 | 14.22±0.57abc | 3.78±0.15bcde | 20.87±1.07ab | 12.54±0.64def |
| **$A_2S_2$** | 17.99±0.81 | 14.88±0.76abc | 3.11±0.16e | 21.63±0.87ab | 13.28±0.48cdef |
| **$A_2S_3$** | 19.33±0.99 | 15.77±0.81ab | 3.55±0.13bcde | 23.52±0.72a | 15.81±0.84a |
| **$A_2S_4$** | 19±0.77 | 15.55±0.55ab | 3.55±0.19bcde | 22.48±1.12ab | 14.55±0.75abcd |
| **$A_3S_1$** | 17.66±0.88 | 13.66±0.49bc | 4±0.16bc | 20.63±0.83ab | 12.35±0.56ef |
| **$A_3S_2$** | 18.22±0.66 | 14.55±0.66abc | 3.66±0.17bcd | 21.53±0.97ab | 13.17±0.59cdef |
| **$A_3S_3$** | 19.49±0.61 | 15.66±0.63ab | 3.44±0.16cde | 23.39±0.82a | 15.57±0.82ab |

| Structural Arrangement | Number of total tillers plant$^{-1}$ | Number of effective tillers plant$^{-1}$ | Number of non-effective tillers plant$^{-1}$ | Panicle length (cm) | Panicle weight (g) |
|---|---|---|---|---|---|
| **$A_3S_4$** | 18.33±0.94 | 14.77±0.45abc | 3.55±0.19bcde | 22.33±1.01ab | 14.69±0.46abc |
| **$A_4S_1$** | 17.11±0.77 | 13.37±0.42c | 4.34±0.2a | 19.58±0.88b | 12.09±0.37f |
| **$A_4S_2$** | 17.45±0.92 | 14.22±0.64abc | 3.55±0.16bcde | 20.92±0.66ab | 13.16±0.46cdef |
| **$A_4S_3$** | 18.34±0.83 | 15.22±0.62abc | 3.52±0.11bcde | 22.73±1.2ab | 14.4±0.76abcde |
| **$A_4S_4$** | 17.78±0.62 | 14.55±0.66abc | 3.56±0.11bcde | 21.5±0.97ab | 14.17±0.64abcdef |
| **LS** | NS | 0.05 | 0.05 | 0.05 | 0.05 |
| **CV (%)** | 10.37 | 8.12 | 2.18 | 12.26 | 8.34 |

*In a column figure having similar letter (s) do not differ significantly as per DMRT by 5% level of significance. LS= Level of Significance, NS= Non-significant, CV= Co-efficient of variance, $A_1$= 25cm+25cm, $A_2$= 20cm+30cm, $A_3$=15cm+35cm, $A_4$= 10cm+40cm, $S_1$= 1 Seedling hill$^{-1}$, $S_2$= 2 Seedlings hill$^{-1}$, $S_3$= 3 Seedlings hill$^{-1}$ and $S_4$= 4 Seedlings hill$^{-1}$*

Effective tillers, which directly contribute to yield, followed the same trend: the highest numbers were recorded under arrangement $A_1$ and density $S_3$, indicating that both factors influenced tiller number and productivity. No significant differences were observed in non-effective tiller numbers, indicating that the treatments mainly affected the development of productive tillers. In addition, yield components such as panicle length and panicle weight differed significantly with seedling density and the interaction between arrangement and seedling density. The $A_1S_3$ treatment had the highest plant density and recorded the longest panicles (23.69 cm) and the heaviest panicle weight (15.88 g), further indicating the importance of seedling density and planting arrangement for grain yield. Treatment $A_1$ (184.72) had the highest number of spikelets per panicle while treatment $A_4$ (176.06) had the lowest although this difference was not significant; this observation may be attributable to similar nutrient uptake or genetic stability. A significant effect of planting density (seedling number) on spikelet number was observed, with 197.12 spikelets were produced at $S_3$. The $A_1S_3$ interaction produced the highest spikelet count (200.20), whereas $A_4S_1$ produced the lowest (161.38), suggesting that plant population and the way the plants are arranged had an effect on the distribution of resources and the production of spikelets. Similarly, the number of florets per panicle increased at the higher density ($S_3$ with 35.69) and was significantly lower at the low density ($S_1$ with 28.55), demonstrating that seedling density influenced panicle development and reproductive growth, whereas structural arrangements appeared to have a comparatively smaller effect. Similar findings were reported by Liu *et al*. (2025), who demonstrated that seedling number per hill and plant spacing significantly affected rice panicle traits, including branch number and grain number. Deng *et al*. (2022) also reported that modifying the number of seedlings per hill and planting pattern influenced rice canopy structure and reproductive performance. Grain number per panicle varied slightly among arrangements but was significantly higher under $S_3$ (149.33) than under $S_1$ (132.96), and the $A_1S_3$ interaction resulted in the highest grain count (151.11). The number of filled grains followed a similar trend, with $A_1S_3$ (133.44) having the highest and $A_4S_1$ (110.98) having the lowest, indicating that the appropriate combination of planting arrangement and seedling density may promote grain development and increase the proportion of effectively filled grains. These findings are consistent with Wu *et al*. (2025), who demonstrated that the combined effects of seedling number per hill and plant spacing influenced rice yield formation, panicle biomass allocation, and source–sink relationships. The number of unfilled grains per panicle varied with arrangement and seedling density (Table 2).

**Table 2. Effect of structural arrangement, number of seedlings hill$^{-1}$ and their interaction on yield contributing characters of rice**

| Structural Arrangement | Number of spikelets panicle$^{-1}$ | Number of florets panicle$^{-1}$ | Number of total grains panicle$^{-1}$ | Number of filled grains panicle$^{-1}$ | Number of unfilled grains panicle$^{-1}$ |
|---|---|---|---|---|---|
| **$A_1$** | 184.72±5.09 | 33.7±1.1 | 144.11±3.33 | 124.29±3.21 | 19.9±0.69ab |
| **$A_2$** | 180.79±5.06 | 32.89±0.95 | 143.86±3.31 | 123.55±3.13 | 20.97±0.66a |
| **$A_3$** | 180.14±5.08 | 32.37±0.95 | 141.93±3.27 | 121.29±2.95 | 19.99±0.57ab |
| **$A_4$** | 176.06±4.83 | 31±0.98 | 137.12±3.17 | 118.74±2.92 | 18.39±0.76b |
| **LS** | NS | NS | NS | NS | 0.05 |
| **Number of Seedlings** | | | | | |
| **$S_1$** | 165.67±3.14b | 28.55±0.61c | 133.61±2.73c | 113.15±2.22c | 19.81±1.13ab |
| **$S_2$** | 172.2±3.51b | 32.17±0.66b | 139.14±2.74bc | 118.47±2.41bc | 20.66±0.38a |
| **$S_3$** | 197.12±4.08a | 35.69±0.82a | 149.34±3.12a | 131.23±2.37a | 18.77±0.39b |
| **$S_4$** | 186.71±3.2a | 33.53±0.62b | 144.93±2.85ab | 125.02±2.42ab | 20±0.6ab |
| **LS** | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| **Interaction Effects of Structural Arrangement and Number of Seedlings** | | | | | |
| **$A_1S_1$** | 172.5±7.78bcdef | 29.67±1.2def | 138.56±7.33ab | 116.19±5.24bcd | 22.36±1.18ab |
| **$A_1S_2$** | 174.97±9.26abcdef | 32.78±1.68bcde | 141.46±7.49ab | 120.33±6.37abcd | 21.12±0.85abcde |
| **$A_1S_3$** | 200.2±10.01a | 37.77±2a | 151.11±6.81a | 133.44±5.39ab | 17.67±0.8f |
| **$A_1S_4$** | 191.2±7.73abcde | 34.56±1.06abc | 145.29±6.55ab | 127.21±6.53abcd | 18.44±0.58def |
| **$A_2S_1$** | 164.93±5.04ef | 29.44±0.9bcde | 137.23±4.19ab | 113.44±5.67cd | 23.79±0.86a |
| **$A_2S_2$** | 173.83±8.92abcdef | 32.47±1.72bcde | 139.42±7.38ab | 119.33±4.82abcd | 20.08±0.71bcdef |
| **$A_2S_3$** | 197.63±10.14abc | 35.78±1.61ab | 150.68±7.73a | 134.64±4.24a | 18.67±0.57def |
| **$A_2S_4$** | 186.77±6.73abcdef | 33.87±1.69abcd | 148.1±6.68a | 126.77±3.87abcd | 21.32±0.96abcd |
| **$A_3S_1$** | 163.87±7.39f | 28.22±1.45ef | 132.84±4.19ab | 111.99±4.04cd | 18.25±0.91ef |
| **$A_3S_2$** | 171.47±6.02cdef | 32.77±1.03bcde | 139.33±4.89ab | 118.99±6.3abcd | 20.33±1.04bcdef |
| **$A_3S_3$** | 199.03±6.27ab | 35±1.58abc | 149.56±7.48a | 129.97±3.97abc | 19.59±0.79bcdef |
| **$A_3S_4$** | 186.17±8.39abcdef | 33.47±1.21abcd | 145.98±7.49ab | 124.22±5.6abcd | 21.77±1.15abc |
| **$A_4S_1$** | 161.38±6.52f | 26.88±1.21f | 125.81±5.08b | 110.98±5dabcd | 14.83±0.76g |

| Structural Arrangement | Number of spikelets panicle$^{-1}$ | Number of florets panicle$^{-1}$ | Number of total grains panicle$^{-1}$ | Number of filled grains panicle$^{-1}$ | Number of unfilled grains panicle$^{-1}$ |
|---|---|---|---|---|---|
| **$A_4S_2$** | 168.53±7.6def | 30.66±1.08cdef | 136.33±4.92ab | 115.22±4.05cd | 21.12±0.65abcde |
| **$A_4S_3$** | 191.63±10.14abcd | 34.22±1.54abcd | 146±6.58ab | 126.86±6.51abcd | 19.14±0.86cdef |
| **$A_4S_4$** | 182.7±5.58abcdef | 32.22±1.3bcde | 140.33±4.29ab | 121.88±5.5abcd | 18.45±0.75def |
| **LS** | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| **CV (%)** | 8.27 | 6.86 | 8.4 | 6.86 | 11.13 |

*In a column figure having similar letter (s) do not differ significantly as per DMRT by 5% level of significance. LS= Level of Significance, NS= Non-significant, CV= Co-efficient of variance, $A_1$= 25cm+25cm, $A_2$= 20cm+30cm, $A_3$=15cm+35cm, $A_4$= 10cm+40cm, $S_1$= 1 Seedling hill$^{-1}$, $S_2$= 2 Seedlings hill$^{-1}$, $S_3$= 3 Seedlings hill$^{-1}$ and $S_4$= 4 Seedlings hill$^{-1}$*

Thousand-grain weight varied slightly among structural arrangements and seedling densities: higher values were recorded under $A_1$ (22.48 g) and $S_3$ (22.89 g), whereas lower values were recorded under $S_1$ (21.20 g) and $A_4$ (21.26 g), representing differences of 5.7% and 7.9%, respectively. The interaction between structural arrangement and seedling number hill$^{-1}$ also affected grain weight, where the $A_1S_3$ treatment produced the highest weight of 23.20 g which was 14.57% higher than that under $A_4S_1$. These results suggest that an appropriate combination of planting arrangement and seedling density may contribute to improved grain development. Similarly, Wu *et al*. (2022) demonstrated that seedling number per hill and row spacing influenced rice yield components, although the magnitude and statistical significance of the response varied with the growing season.

Grain yield followed a similar trend: $A_1$ recorded the highest yield (5.42 t ha$^{-1}$), which was significantly higher than the yield under $A_4$ (4.97 t ha$^{-1}$); the yield under $S_3$ (5.79 t ha$^{-1}$) was 26.97% higher than that of $S_1$. The interaction effect was significant, and the maximum grain yield of 6.12 t ha$^{-1}$ was recorded under $A_1S_3$, which was 28.44% higher than $A_4S_1$. The highest grain yield was obtained from the 25 cm + 25 cm structural arrangement combined with 3 seedlings hill$^{-1}$. The higher grain yield under this treatment may be associated with the favourable plant population and growth environment created by the wider, uniform spacing. The 25 cm + 25 cm arrangement provided sufficient space for individual hills to develop properly, thereby reducing excessive competition among plants for light, water, nutrients and growing space. At the same time, the use of three seedlings per hill maintained an adequate plant population, facilitated better uptake and utilisation of water and nutrients, allowed greater penetration of sunlight into the crop canopy and supported the development of productive tillers. These favourable growth conditions resulted in better reproductive development and efficient partitioning of assimilates towards the grains. Consequently, the combined improvement in yield-contributing characters contributed to higher grain yield under the 25 cm + 25 cm structural arrangement with 3 seedlings hill$^{-1}$. In Bangladesh, Khan (2022) also demonstrated that seedling number per hill significantly affected grain yield and several yield-contributing characters of BR16 aus rice.

Straw and biological yields were also highest under treatments $A_1$ and $S_3$, respectively, with the highest combined values recorded under the $A_1S_3$ interaction (7.83 t ha$^{-1}$ straw and 13.95 t ha$^{-1}$ biological yield) which were significantly higher than the lowest values. These results may be associated with canopy development and biomass accumulation arising from a favourable balance of resource availability and competition. The harvest index (HI), expressed as the ratio of grain yield to biological yield, followed a different pattern, with the highest value in $A_4$ (44.76%), although differences among treatments were generally small and were not always significant (Table 3).

**Table 3. Effect of structural arrangement, number of seedlings hill$^{-1}$ and their interaction on yield of rice**

| Structural Arrangement | Thousand grain weight (g) | Grain yield (t ha$^{-1}$) | Straw yield (t ha$^{-1}$) | Biological yield (t ha$^{-1}$) | Harvest Index (%) |
|---|---|---|---|---|---|
| **$A_1$** | 22.48±0.46 | 5.42±0.2 | 7.06±0.22a | 12.47±0.4a | 43.37±0.63 |
| **$A_2$** | 22.36±0.45 | 5.24±0.17 | 6.93±0.2a | 12.18±0.34ab | 43.05±0.7 |
| **$A_3$** | 22.14±0.41 | 5.06±0.17 | 6.76±0.18a | 11.83±0.33ab | 42.77±0.54 |
| **$A_4$** | 21.26±0.49 | 4.97±0.16 | 6.15±0.23b | 11.12±0.35b | 44.75±0.77 |
| **LS** | NS | NS | 0.05 | 0.05 | NS |
| **Number of Seedlings** | | | | | |
| **$S_1$** | 21.2±0.41b | 4.56±0.1b | 6.01±0.17b | 10.57±0.2c | 43.19±0.9 |
| **$S_2$** | 22.01±0.42ab | 4.86±0.09b | 6.4±0.14b | 11.26±0.21b | 43.16±0.49 |
| **$S_3$** | 22.89±0.44a | 5.79±0.12a | 7.43±0.16a | 13.22±0.23a | 43.81±0.58 |
| **$S_4$** | 22.33±0.49ab | 5.48±0.12a | 7.06±0.19a | 12.54±0.25ab | 43.78±0.75 |
| **LS** | 0.05 | 0.05 | 0.05 | 0.05 | NS |
| **Interaction Effects of Structural Arrangement and Number of Seedlings** | | | | | |
| **$A_1S_1$** | 21.73±0.78 | 4.73±0.21def | 6.32±0.33cde | 11.05±0.14e | 42.86±2.39 |
| **$A_1S_2$** | 22.2±0.78 | 4.98±0.26cdef | 6.64±0.2bcde | 11.62±0.47cde | 42.81±0.56 |
| **$A_1S_3$** | 23.2±1.16 | 6.12±0.22a | 7.83±0.35a | 13.95±0.45a | 43.89±1.25 |
| **$A_1S_4$** | 22.77±1.2 | 5.82±0.2ab | 7.44±0.3ab | 13.26±0.46ab | 43.9±0.75 |
| **$A_2S_1$** | 21.53±1.1 | 4.62±0.21def | 6.24±0.32cdef | 10.86±0.13ef | 42.59±2.31 |
| **$A_2S_2$** | 23.02±0.73 | 4.92±0.15cdef | 6.65±0.24bcde | 11.57±0.39cde | 42.53±0.14 |
| **$A_2S_3$** | 23.07±0.93 | 5.84±0.29ab | 7.46±0.34ab | 13.3±0.53ab | 43.9±1.26 |
| **$A_2S_4$** | 22.6±1.02 | 5.6±0.18abc | 7.38±0.33ab | 12.98±0.21ab | 43.19±1.82 |
| **$A_3S_1$** | 21.3±0.65 | 4.52±0.24ef | 6.11±0.25def | 10.63±0.47ef | 42.49±0.74 |
| **$A_3S_2$** | 21.8±0.98 | 4.77±0.19def | 6.42±0.2cde | 11.19±0.34e | 42.62±0.86 |
| **$A_3S_3$** | 23.03±0.7 | 5.63±0.25abc | 7.37±0.23ab | 13±0.08ab | 43.29±1.85 |
| **$A_3S_4$** | 22.43±1.01 | 5.33±0.27bcd | 7.15±0.25abc | 12.48±0.43bcd | 42.69±1.23 |

| Structural Arrangement | Thousand grain weight (g) | Grain yield (t ha$^{-1}$) | Straw yield (t ha$^{-1}$) | Biological yield (t ha$^{-1}$) | Harvest Index (%) |
|---|---|---|---|---|---|
| **$A_4S_1$** | 20.25±0.91 | 4.36±0.22f | 5.37±0.27f | 9.73±0.3f | 44.83±2.07 |
| **$A_4S_2$** | 21.02±0.85 | 4.76±0.21def | 5.9±0.31ef | 10.66±0.4ef | 44.68±1.63 |
| **$A_4S_3$** | 22.25±1.14 | 5.58±0.17abc | 7.06±0.32abcd | 12.64±0.45bc | 44.18±0.81 |
| **$A_4S_4$** | 21.52±1.14 | 5.19±0.21bcde | 6.27±0.32cdef | 11.46±0.15de | 45.33±2.25 |
| **LS** | NS | 0.05 | 0.05 | 0.05 | NS |
| **CV (%)** | 12.5 | 2.86 | 3.75 | 3.41 | 13.86 |

*In a column figure having similar letter (s) do not differ significantly as per DMRT by 5% level of significance. LS= Level of Significance, NS= Non-significant, CV= Co-efficient of variance, $A_1$= 25cm+25cm, $A_2$= 20cm+30cm, $A_3$=15cm+35cm, $A_4$= 10cm+40cm, $S_1$= 1 Seedling hill$^{-1}$, $S_2$= 2 Seedlings hill$^{-1}$, $S_3$= 3 Seedlings hill$^{-1}$ and $S_4$= 4 Seedlings hill$^{-1}$*

## 4. Pearson Correlation Coefficient

The correlation analysis in Fig. 4 shows significant positive relationships among rice growth parameters, yield components and final grain yield. Plant height at harvest was positively associated with grain, straw and biological yields and with panicle traits, suggesting an association between taller plants and productivity. Likewise, leaf number at 80 DAT and tiller number at 100 DAT showed strong positive relationships with spikelet number, filled grains, panicle weight, effective tillers and grain yield, suggesting that these traits were associated with yield formation. Spikelet number, filled grains, panicle weight and grain yield were associated with effective tiller number, highlighting its relationship with reproductive development. Panicle length, spikelets per panicle and filled grains per panicle also showed positive relationships with grain yield and biological yield, highlighting the importance of panicle development and grain filling in yield enhancement. Furthermore, straw and biological yields were closely related to grain yield, indicating an association between vegetative growth and reproductive output in total dry-matter production.

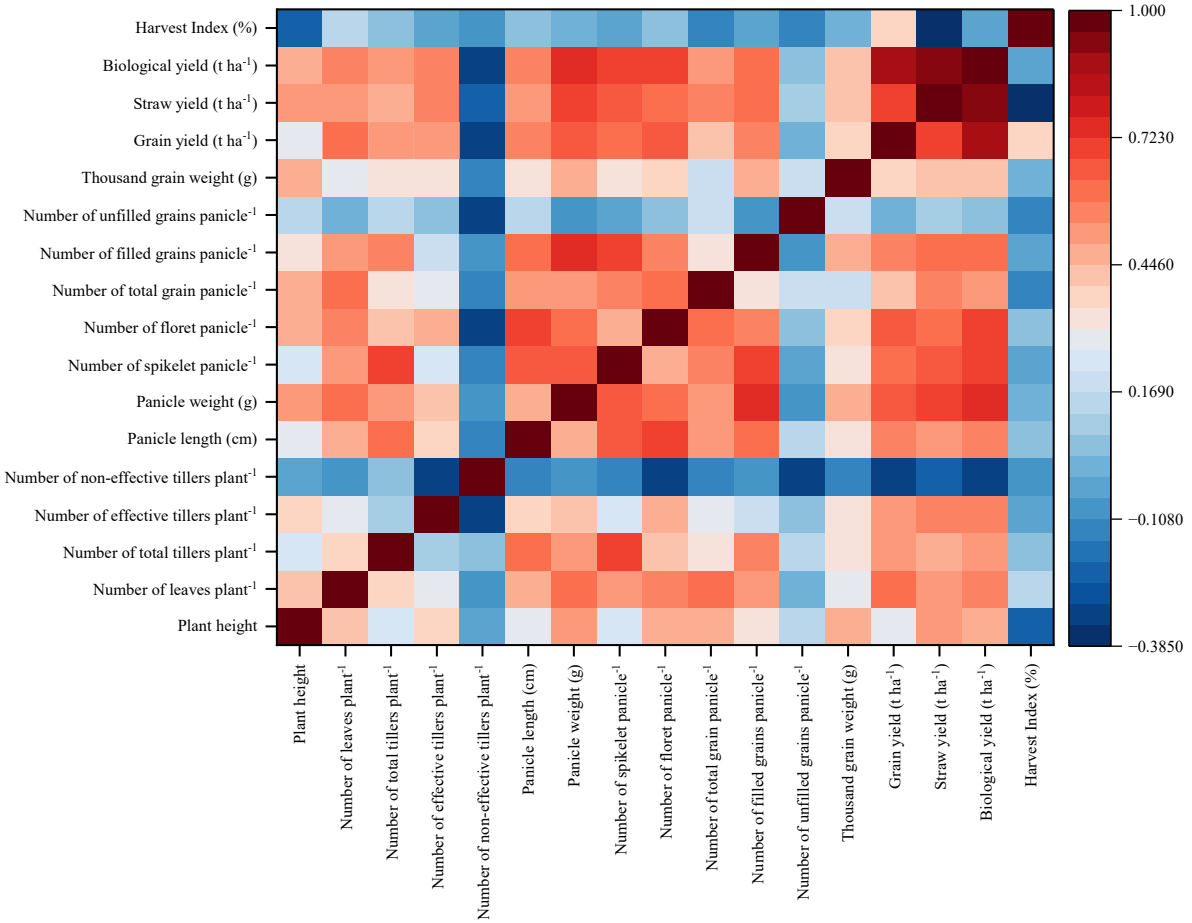



**Fig. 4. Pearson correlation coefficient heatmap**

## 5. Study Limitations

This experiment was conducted at one location, during one Boro season and with one rice variety (BRRI dhan28); therefore, the findings should not be generalised to other varieties, seasons, or production environments without further testing. Light interception, canopy development, resource-use efficiency, and economic returns were not measured directly. Future trials conducted across

different locations and seasons should include these measurements and an economic assessment to determine the robustness and practical value of the recommended treatment.

## 6. Conclusion and Recommendation

This study demonstrated that the growth and yield performance of Boro rice (BRRI dhan28) could be significantly improved through a combination of planting geometry and seedling density. Among the treatments, the $A_3$ (25 cm +25 cm) structural arrangement with three seedlings per hill ($S_3$) recorded the highest values for several growth and yield parameters, including the tallest plant height (92.10 cm), the highest number of tillers per plant (19.66 at 100 DAT), the greatest number of leaves per plant (16.00 at 80 DAT), the maximum number of effective tillers per plant (16.11), the longest panicle length (23.69 cm), the heaviest panicle weight (15.88 g), the highest number of spikelets per panicle (200.20), the greatest number of florets per panicle (37.77), the maximum number of grains per panicle (151.11), the highest number of filled grains per panicle (133.44), the greatest grain yield (6.12 t $ha^{-1}$), the highest straw yield (7.83 t $ha^{-1}$), and the maximum biological yield (13.95 t $ha^{-1}$). These findings emphasise the role of structural arrangement and plant population management in rice productivity under the field conditions of this study. The higher grain yield (6.12 t/ha) recorded with the 25cm + 25cm structural arrangement and 3 seedlings per hill may be explained by the favourable growing conditions created by this treatment. This planting arrangement provided enough space for the plants to grow properly and reduced excessive competition among hills for sunlight, water, nutrients, and space. The uniform distribution of plants under the $A_1$ structural arrangement may also have facilitated better penetration and interception of solar radiation, which enhanced photosynthetic activity and dry matter accumulation. Moreover, the availability of adequate space around each hill may have favoured healthy root growth and efficient utilisation of soil nutrients and moisture. At the same time, three seedlings per hill ($S_3$) helped maintain an adequate plant population and encouraged the production of productive tillers. The plants could also develop their roots and canopy more effectively under this arrangement, resulting in better use of available soil moisture and nutrients. These favourable conditions may have contributed to better development of yield-contributing characters and increased grain yield. Thus, the 25 cm +25 cm structural arrangement with 3 seedlings per hill appeared to provide a suitable balance between plant population and available growth resources, making it a favourable planting arrangement for obtaining higher Boro rice yield under the conditions of the present study. This finding is consistent with Thawait *et al.* (2014), who reported improved growth, yield attributes and grain yield of rice under wider spacing with an appropriate number of seedlings per hill. Future studies should explore the long-term effects of optimised planting geometry and seedling density across different rice varieties and seasons to validate consistency and resilience under varying environmental conditions. Additionally, integrating these practices with modern nutrient management, water-saving technologies, and mechanised transplanting methods could further enhance sustainability and scalability in rice production systems. Investigating the economic viability and labour implications of the recommended practices would also benefit adoption by farmers.

## Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

## Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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