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Planting pattern and nitrogen management strategies: positive effect on yield and quality attributes of *Triticum aestivum* L. crop

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Abstract

Wheat (*Triticum aestivum* L.) is a staple food crop that plays a crucial role in global food security. A suitable planting pattern and optimum nitrogen (N) split management are efficient practices for improving wheat production. Therefore, an experiment was performed to explore the effect of N split management and sowing patterns on wheat at the Agronomy Research Farm, The University of Agriculture Peshawar, during rabi season 2020-21 and 2021-22. The treatments consisted of different nitrogen rates of 0, 80, 120, and 160 kg ha⁻¹ and planting patterns of W, M, broadcast and line sowing. The pooled analysis of both cropping seasons showed that application of 120 kg N ha⁻¹ increased spikelets spike⁻¹, grains spike⁻¹, 1000 grains weight, grain yield, grain N content, evapotranspiration and water use efficiency by 21.9, 16.7, 21.8, 70, 13, 19.9 and 40% as compared to control, respectively. In addition, W and M were observed the best management practices among all planting patterns. The M planting pattern enhanced chlorophyll a, b, carotenoids and evapotranspiration while W planting pattern improved yield components and yield of wheat as compared to broadcast planting patterns. The principal component analysis biplot showed a close association of M and W planting patterns with 120 kg N ha⁻¹ in most of the studied traits. Hence, it is concluded that split application of 120 kg N ha⁻¹ in W and M sowing patterns enhanced growth, biochemical traits and water use efficiency, reducing N fertilization from 160 to 120 kg ha⁻¹ while increasing grain yield of wheat. Hence, it is recommended that application of 120 kg N ha⁻¹ in combination with W and M planting patterns offer a sustainable approach to enhancing wheat production in the alkaline soil conditions of the Peshawar valley.

Keywords Nitrogen management, Evapotranspiration, Spatial arrangement, Water use efficiency

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Introduction

Wheat belongs to the family of Poaceae, widely produced grain and a primary nourishment for humans that occupies 3rd rank among the cereals and contributes 65% to food and 17% to feed worldwide [1]. It is one of the richest source of calories among major cereals with minute quantity of animal or legume protein [2] and contributing about 20% of the total dietary calories and proteins to human food [3]. The projected global population of 9.7 billion by 2050 demands for the expansion of wheat cultivation, hence, its needed to adapt cutting-edge agronomic practices that guarantee sustainable expansion of wheat cultivation with greater yield [4].

Nitrogen (N) fertilizer is known for its multifaceted impacts that plays a crucial role in chlorophyll formation, amino acid synthesis, and overall plant vigor for better growth and production [5]. Nitrogen management strategies optimize fertilizer consumption that improve quality and yield in a sustainable manner [6]. However, excessive use of N fertilizer may affect soil health and groundwater that cause lodging and degrading grains quality as well as increasing susceptibility to insects and diseases, affecting both human and environment health [7, 8] while the inadequate N fertilizer can result in stunted growth and low production [9]. Therefore, application of N at the right time to coincide with growth stages is crucial to enhance N uptake and assimilation for sustainable and quality production of wheat [10]. Nitrogen fertilizer is considered as one of the primary strategies for improving grain yield and protein content [11]. Nitrogen split application produce higher grain yield instead of single N dose application [12]. The efficient N dose splits together with the N application according to the crop requirement have been found effective for N uptake and utilization, which in turn producing greater biomass and grain yield [13]. Therefore, it is important to find agronomic management practices that increase efficiency of water and fertilizers to ensure sustainable crop production and healthy environment.

Management practices like adequate fertilizers application and optimized planting pattern have been observed to enhance N uptake by increasing root density of wheat [14]. The combination of narrow row spacing with higher N rates has enhanced N uptake and utilization, resulting in greater biomass and grain yield [12]. It has also reported that modified planting pattern can enhance N use efficiency and grain yield of wheat by increasing N uptake and number of tillers/spikes [15]. In addition, optimal planting pattern is an important practice that can increase soil moisture retention and decrease evaporation, particularly in water-limited regions, thus increasing water use efficiency and nutrient transportation during growth period of wheat [16]. The standard row-planting pattern can delay intraspecific competition with

the crop plants and begin interspecific competition with weeds, which increase initial growth of crop plants by consuming more natural resources [17]. Planting pattern is directly affected by light interception and evaporation and indirectly by water use efficiency. An appropriate planting pattern increasing planting canopy due to higher light interception and nutrient management suppresses weeds emergence, which in turn increase crop vegetative growth and final product [18].

Despite the known benefits of N management and planting patterns on wheat yield and quality, there still exist lack of research on the integration of these two agronomic practices to optimize wheat production. The potential research gap lies in understanding the synergistic effects of various planting patterns and N management strategies on wheat yield and yield components and overall sustainability. The hypothesis of the study was that integration of optimal planting patterns with precise N management would significantly enhance wheat yield, quality, evapotranspiration (ET) and water use efficiency (WUE) thus contributing to sustainable wheat production practices. To examine the hypothesis, in this context, this study aimed to establish an effective relationship between planting patterns and N rates for enhancing yield and yield attributes, quality parameters, evapotranspiration and water use efficiency. This approach will address current challenges in wheat cultivation that will provide future direction for sustainable management practices aimed at meeting global food demand.

Materials and methods

Experimental site and climate

A field experiment was performed to execute the effect of planting pattern and nitrogen (N) management effect on yield and yield components of wheat (*Triticum aestivum* L.) at Agronomy Research Farm, The University of Agriculture Peshawar, during rabi season 2020-21 and 2021-22. The research site is located at 34° N latitude and 71° E longitude, at an elevation of 358 m (Fig. 1).

The region is characterized by a semi-arid and subtropical climate, with an average annual precipitation of 403 mm. The summer months (May to September) typically experience an average maximum temperature of 40 °C and an average minimum temperature of 25 °C. In contrast, during the winter months (December to March), the average maximum temperature is 18.4 °C, and the average minimum temperature is 3 °C. The meteorological data of the experimental site during both agricultural year is summarized in Fig. 2.

Treatments and management

Experiment was conducted in randomized complete block split design in a 4×4 factorial scheme, consisting of four replications. The treatments consisted of four N

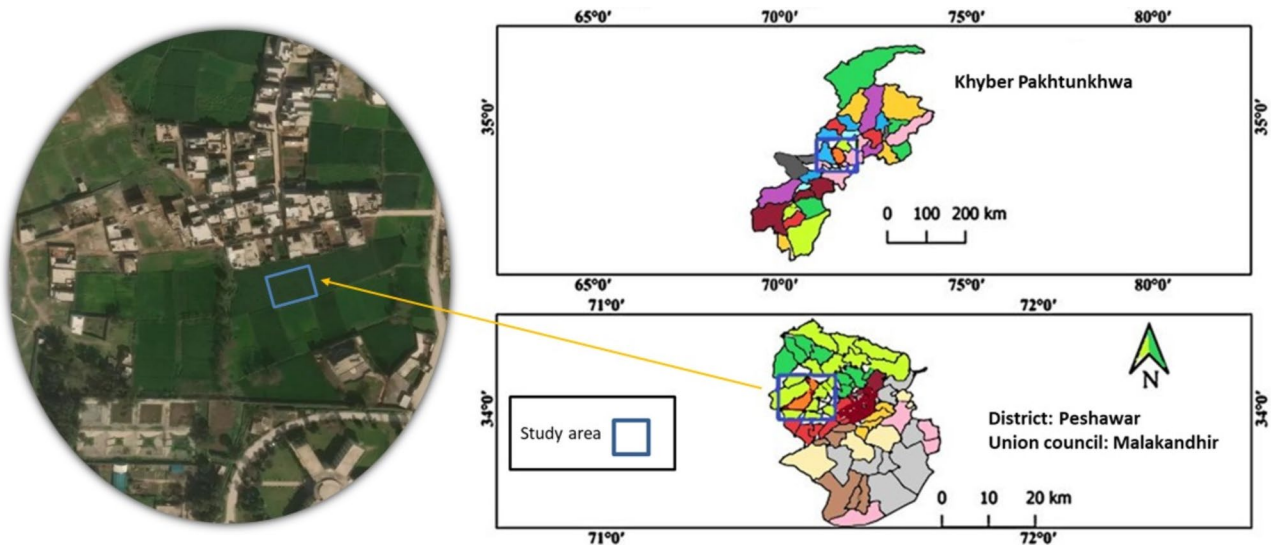


Fig. 1 Description of geographical location of the study area

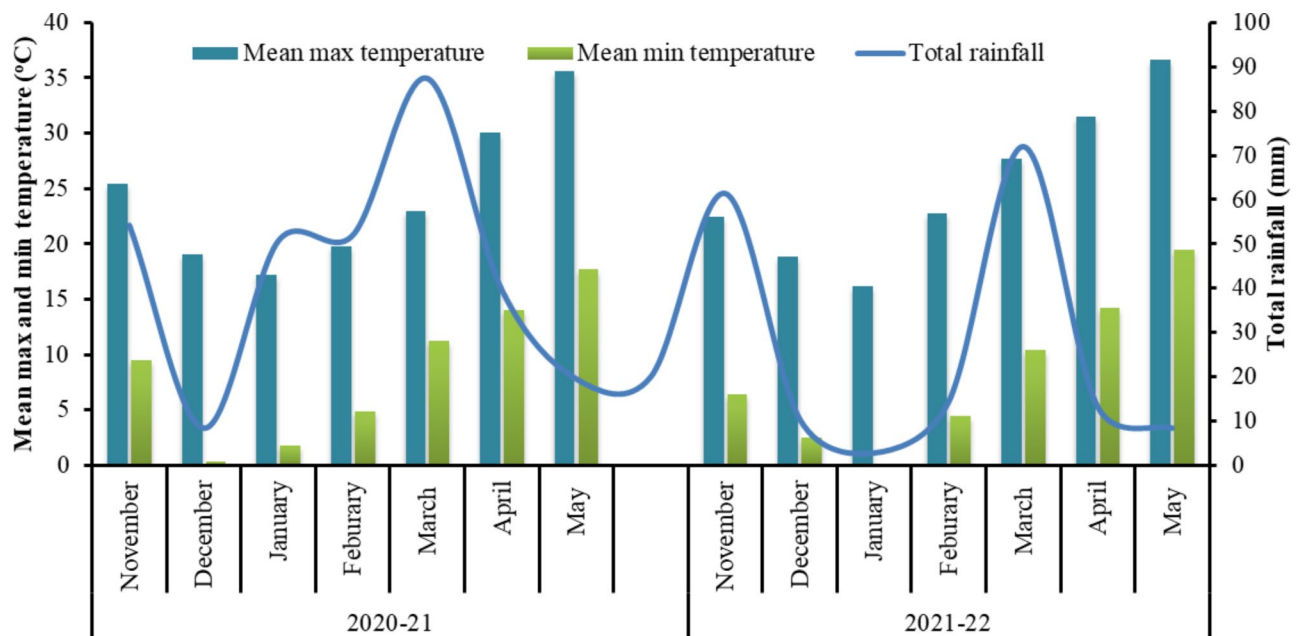


Fig. 2 Meteorological data of experimental site during 2020-21 and 2021-22 cropping seasons

rates as a main factor ($N_0=0$, $N_1=80$, $N_2=120$, $N_3=160$ kg ha^{-1}), applied from urea (46% N). Nitrogen rates were applied in three splits; 80 kg N ha^{-1} applied at once during sowing time, 120 kg N ha^{-1} applied in two splits: 2/3rd during sowing time and 1/3rd applied two weeks after emergence, 160 kg N ha^{-1} applied in two splits: 2/3rd during sowing time and 1/3rd at anthesis. The subfactor consisted of four planting pattern methods (broadcast, line planting, W planting and M planting (Fig. 3). The net plot size was 7.2 m^2 (3m \times 2.4 m) with 8 rows and a row-row distance of 30 cm. Sowing was carried out with manual drill. Wheat variety “Khaista 2017”, characterized

as stress-tolerant and high productive, was sown on 13th November 2020-21 and 15th November 2021-22. The recommended dose of phosphorus and potassium was applied as a basal dose of 80 and 60 kg ha^{-1} from diammonium phosphate and muriate of potash. Weeds population during crop growth was suppressed with application of Agritop 500 G/L^a at the rate of 0.43 kg a.i. ha^{-1} of MCPA (2-methyl-4-chlorophenoxyacetic acid). Irrigation needs of the crops are met through channels connected to the Kabul River. The crop was irrigated with flood irrigation system, first season crop was irrigated with 200 mm as compared to second season (100 mm).

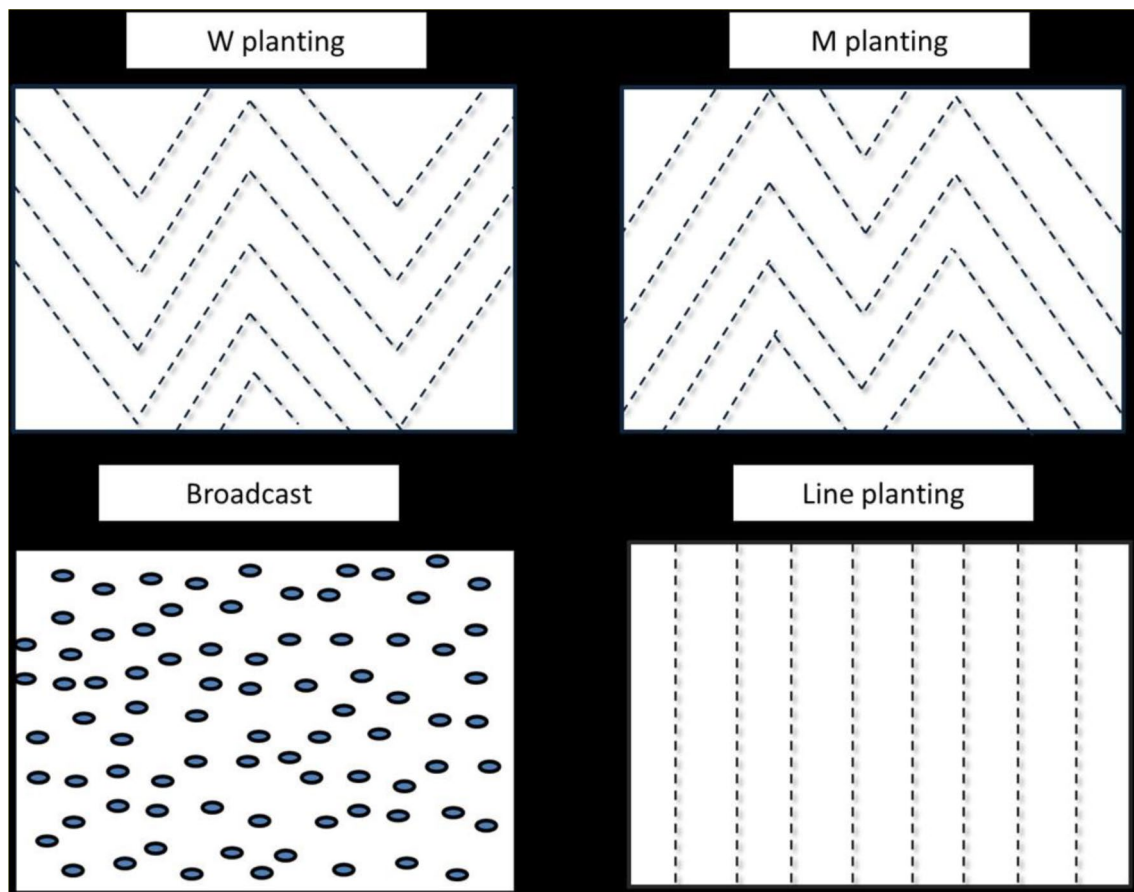


Fig. 3 Schematic diagram of different planting patterns

Harvesting in both experimental years was carried out in the mid of April, each season.

Observations and procedures

Agronomic traits

Plant height (cm) was determined by measuring 10 random tillers in each plot using a meter tape from the bottom to the tip. Productive tillers m^{-2} were quantified by enumerating tillers with spikes in the central row of each plot and converted to a per square meter basis. Spikelets and grain $spike^{-1}$ were recorded by selecting randomly spikes in each plot and enumerating the spikelets and grains on each spike. Thousand grains were counted and weighed using a precise electronic balance for 1000 grains weight (g). Biological and grain yield ($kg\ ha^{-1}$) was calculated by harvesting plot, followed by drying, weighing, threshing and converting the values to kilograms per hectare.

Grain nitrogen and uptake determination

A specific quantity of grains from each experimental unit was dried at 70 °C for 72 h in an airtight oven. The material was crushed into fine powder for the determination of total nitrogen content in grains using micro-Kjeldahl

method following the AOAC guidelines. The uptake of nitrogen was obtained by multiplying the grain yield by their respective grain nitrogen %.

Crop evapotranspiration (ET) and water use efficiency (WUE)

Precipitation (mm) and consumption of stored soil water (mm) in the 0–300 cm layer was used to calculate ET and WUE by the equations below.

$$ET = SW_0 - SW_1 + P$$

$$WUE (kg\ ha^{-1}\ mm^{-1}) = GY/ET$$

Here, SW_0 corresponds to the level of soil water storage before the initiation of sowing, whereas SW_1 represents the soil water storage post-harvest. The variable P is indicative of the amount of precipitation received during the wheat growth period. Water use efficiency was calculated from the fraction of grain yield into evapotranspiration.

Plants photosynthetic pigments

The chlorophyll content of the leaves was measured using a spectrophotometer (UV-4000, OR1, Germany). Fresh

Table 1 Pooled analysis of plant pigments (mg g^{-1}) of wheat as influenced by nitrogen rates and various planting patterns in 2020-21 and 2021-22

Treatments	Chlorophyll a (mg g^{-1})	Chlorophyll b (mg g^{-1})	Carotenoids (mg g^{-1})
Nitrogen (N) rates (kg ha^{-1})			
Control	6.62 c	3.94 c	7.1 c
N1=80	6.91 b	4.27 b	7.5 b
N2=120	7.27 a	4.52 b	7.8 a
N3=160	7.21 a	4.93 a	8.0 a
LSD _(0.05)	0.18	0.27	0.19
Planting patterns (P)			
Broadcast	6.44 c	4.06 c	7.2 c
Line-Planting	6.85 d	4.28 bc	7.7 b
M-planting	7.40 a	4.81 a	8.1 a
W-planting	7.21 b	4.51 b	7.4 c
LSD _(0.05)	0.18	0.27	0.19
N×P	ns	ns	ns

Means with different letters are statistically significant at P value equal or less than 0.05 using LSD test. Different means with similar letters are statistically non-significant. ns=non-significant

leaf samples were collected from each plot and kept in the dark at 4 °C for 48 h then extracted in 5 ml of an 80% acetone solution (v/v). The concentration of carotenoid, total chlorophyll, and chlorophyll (Chl a and Chl b) were measured at absorbance (A) of wavelength 663.2, 646.8, and 470 nm. The concentrations of carotenoids, Chl a, and Chl b, were calculated using protocols of Lichtenthaler [19], and expressed in mg g^{-1} of fresh leaf weight (FW).

$$\text{Chl a (mg g}^{-1}\text{)} = 12.25A_{663.2} - 2.79A_{646.8}$$

$$\text{Chl b (mg g}^{-1}\text{)} = 21.50A_{646.8} - 5.10A_{663.2}$$

$$\text{Total Carotenoids (mg g}^{-1}\text{)} = 1000A_{470} - 1.82\text{Chl a} - 85.02\text{Chl b}$$

Statistical analysis

Data analysis and means of each category were compared using the Least Significant Difference (LSD) test at P value equal or less than 0.05 ($P \leq 0.05$) [20]. Scatter plots were drawn using Excel 2010 while PCA was performed using Origin pro-2024.

Results

Weather data showed that total precipitation was higher during first cropping season - as compared to second cropping season (Fig. 1). The highest maximum mean temperature was recorded in the month of March in both years. The lowest minimum mean temperature was recorded in the month of December and January during first and second cropping seasons, respectively (Fig. 1). Nitrogen rates and planting patterns influenced different attributes of wheat in pooled analysis of 2020-21

Table 2 Pooled analysis of yield related traits of wheat as influenced by nitrogen rates and various planting patterns in 2020-21 and 2021-22

Treatments	Plant height (cm)	Productive tillers m^{-2}	Spikelets spike ⁻¹	Grains spike ⁻¹	1000 grains weight (g)
Nitrogen (N) rates (kg ha^{-1})					
Control	83.4 d	207 d	16.9 d	42 d	36 d
N1=80	91.6 c	240 c	18.6 c	46 c	40 c
N2=120	97.7 b	292 a	20.6 a	49 a	45 a
N3=160	99.7 a	267 b	19.3 b	48 b	42 b
LSD _(0.05)	1.6	8	0.6	1	2
Planting patterns (P)					
Broadcast	90.2 c	228 c	17.8 c	45 b	38 c
Line-planting	92.7 b	253 b	18.5 b	46 b	40 b
M-planting	95.0 a	262 a	19.3 a	47 a	40 b
W-planting	94.5 a	263 a	19.8 a	47 a	43 a
LSD _(0.05)	1.6	8	0.6	1	2
N×P	ns	ns	**	***	ns

Means with different letters are statistically significant at P value equal or less than 0.05 using LSD test. Different means with similar letters are statistically non-significant. ns=non-significant. ** = $P < 0.01$ and *** = $P < 0.001$

and 2021-22 cropping (Supply Table 1). The treatments showed different responses to various attributes of wheat while the interaction between treatments and years was not significant for the studied attributes (Supply Table 1).

Plant photosynthetic pigments

The data analysis showed that plant photosynthetic pigments of wheat leaf were significantly different, when subjected to various N rates in different planting patterns. The interaction between N rates and planting patterns (N×P) was not significant for chlorophyll a and b and carotenoids in leaves (Table 1).

Application of N at the rates of 120 and 160 kg ha^{-1} increased chlorophyll a content by 9.81% and 8.91%, respectively as compared to control. Leaf chlorophyll b and carotenoid contents were increased by 25.12% and 12.67% with application of N at the rate of 160 kg ha^{-1} as compared to control. In addition, among the planting patterns, M-planting pattern was observed with highest leaf chlorophyll a (14.91%), chlorophyll b (18.47%) carotenoids (12.50%) content as compared to broadcasting sowing method.

Yield attributes

The pooled analysis indicated that application of various N rates in different planting patterns showed significant differences on plant height and yield attributes of wheat while the interaction between N rates and planting patterns was non-significant except for spikelets spike⁻¹ and grain spike⁻¹ (Table 2).

Plant height was increased by 19.52% with application of 160 kg N ha^{-1} while productive tillers and 1000 grains

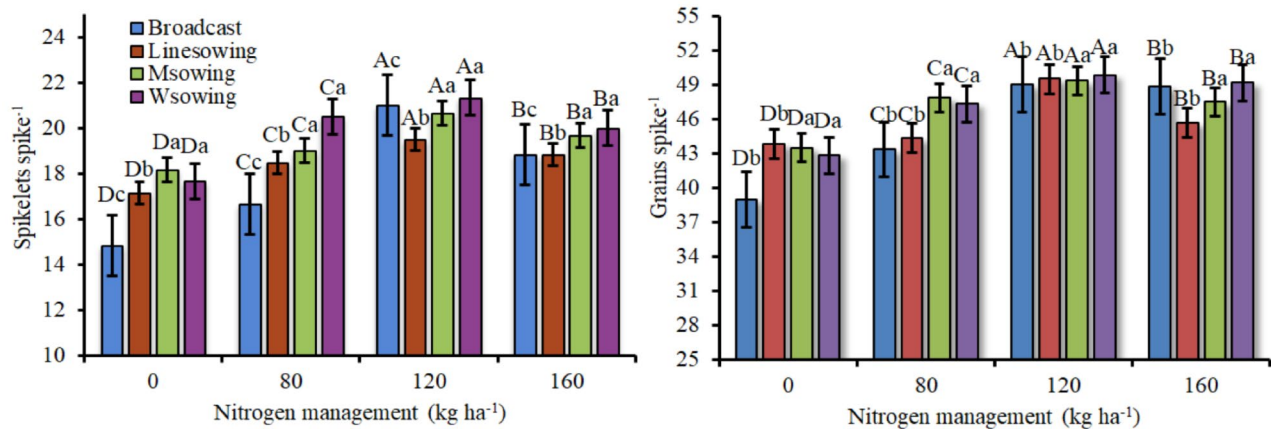


Fig. 4 Interactive effect of nitrogen rates and sowing patterns on spikelets spike⁻¹ and grains spike⁻¹ (Fig. 4a, and 4b respectively). Error bars indicate the standard error of the mean. The uppercase letters are used for nitrogen rates interactions within each planting patterns, whereas lowercase letters are used for the planting pattern within each nitrogen rates. The identical alphabetic letters do not differ from each other, as analyzed by LSD (nitrogen rates; $p < 0.05$) and (planting pattern; $p < 0.05$) test for both years. ($n = 4$ replications)

Table 3 Pooled analysis of evapotranspiration and water use efficiency of wheat as influenced by nitrogen rates and various planting patterns in 2020-21 and 2021-22

Treatments	Evapotranspiration (mm)	Water use efficiency (kg ha ⁻¹ mm ⁻¹)
Nitrogen (N) rates (kg ha⁻¹)		
Control	306 d	5.60 d
N1 = 80	330 c	6.36 c
N2 = 120	367 a	7.86 a
N3 = 160	340 b	7.19 b
LSD _(0.05)	6	0.24
Planting patterns (P)		
Broadcast	323 d	6.37 c
Line-planting	330 c	6.71 b
M-planting	352 a	6.93 a
W-planting	338 b	6.98 ab
LSD _(0.05)	6	0.24
N×P	**	ns

Means with different letters are statistically significant at P value equal or less than 0.05 using LSD test. Different means with similar letters are statistically non-significant. ns = non-significant. ** = $P < 0.01$ and *** = $P < 0.001$

weight were increased by 41.06 and 25% with application of 120 kg N ha⁻¹ as compared to control (Table 2). The M-planting pattern increased plant height by 5.32%, which was statistically not different from the W-planting pattern as compared to other planting patterns. Similarly, the W-planting pattern increased productive tillers and 1000 grains weight by 15.35 and 13.16% as compared to broadcasting, respectively. The interaction of N rates and planting pattern showed that spikelets spike⁻¹ and grain spike⁻¹ were increased with the N application at the rate of 120 kg ha⁻¹ in the M and W-planting patterns as compared to other treatments (Fig. 4a and b). The

lowest spikelets spike⁻¹ and grain spike⁻¹ were observed in broadcasting sowing method without N application.

Biological and grain yield

Analysis of the data revealed that biological and grain yield was significantly affected by different N rates and planting patterns (Supply Table 3). The interaction between N rates and planting patterns was also found significant. Biological yield was increased by 35.06% with application of 160 kg N ha⁻¹, while grain yield was improved by 70.52% with application of 120 kg N ha⁻¹ as compared to control. M-planting pattern increased biological and grain yield by 9.33 and 10.57% as compared to broadcasting, respectively. Similarly, the W-planting pattern increased biological and grain yield by 10.53 and 14.40% as compared to broadcasting, respectively. The interaction of N rates and planting pattern showed that grain and biological yield were increased with the N application at the rate of 120 and 160 kg ha⁻¹, respectively in the M and W-planting patterns as compared to other treatments (Fig. 5a and b).

Grain nitrogen content and uptake

Pooled analysis showed that grain N content and its uptake was significantly affected by different N rates, while planting pattern had significant effect on grain N content and had no effect on grain N uptake (Supply Table 3). The interaction between N rates and planting patterns was found significant. Grain N content was increased by 13.04% with application of 120 kg N ha⁻¹, while grain N uptake was increased by 40.0% with application of 160 kg N ha⁻¹ as compared to control. M-planting pattern increased grain N content by 6.1%, which was statistically not different from the W-planting pattern as compared to other planting patterns. The interaction of

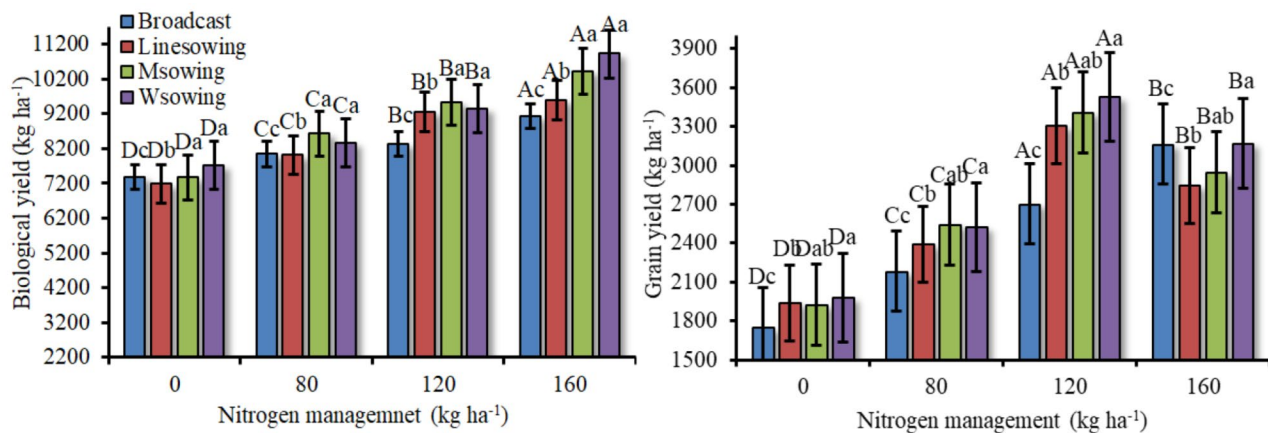


Fig. 5 Interactive effect of nitrogen rates and sowing patterns on grain and biological yield (kg ha⁻¹) (Fig. 5a and b, respectively). Error bars indicate the standard error of the mean. The uppercase letters are used for nitrogen rates interactions within each planting patterns, whereas lowercase letters are used for the planting pattern within each nitrogen rates. The identical alphabetic letters do not differ from each other, as analyzed by LSD (nitrogen rates; $p < 0.05$) and (planting pattern; $p < 0.05$) test for both years. ($n = 4$ replications)

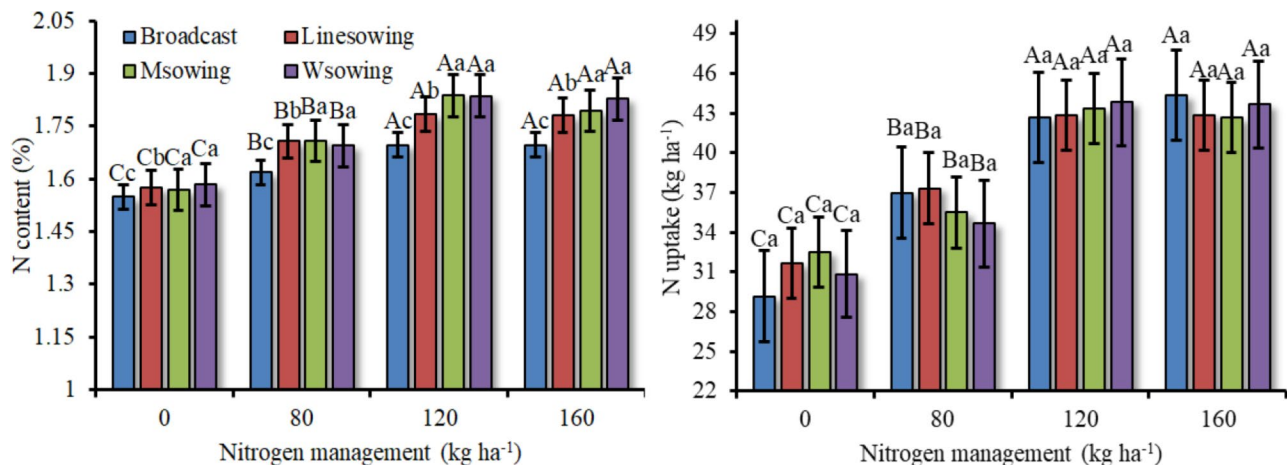


Fig. 6 Interactive effect of nitrogen rates and sowing patterns on nitrogen content and N uptake (Fig. 6a and b, respectively). Error bars indicate the standard error of the mean. The uppercase letters are used for nitrogen rates interactions within each planting patterns, whereas lowercase letters are used for the planting pattern within each nitrogen rates. The identical alphabetic letters do not differ from each other, as analyzed by LSD (nitrogen rates; $p < 0.05$) and (planting pattern; $p < 0.05$) test for both years. ($n = 4$ replications)

N rates and planting pattern showed that grain N content was increased with the N application at the rate of 120 kg ha⁻¹, in the M and W-planting patterns as compared to other treatments (Fig. 6a and b). The lowest grain N content and grain N uptake were observed in broadcasting sowing method without N application.

Crop evapotranspiration and water use efficiency

The pooled analysis indicated that application of various N rates in different planting patterns showed significant differences on crop evapotranspiration (ET) and water use efficiency (WUE), while the interaction between N rates and planting patterns was significant only for ET (Table 3).

ET (367 mm) and WUE (7.86 kg ha⁻¹ mm⁻¹) was substantially higher when 120 kg N ha⁻¹ was applied as

compared to control. M-planting pattern recorded more ET (352 mm) as compared to broadcasting, W-planting pattern recorded improved WUE (6.98 kg ha⁻¹ mm⁻¹), which was statistically not different from the M-planting pattern as compared to other planting patterns. The interaction of N rates and planting pattern showed that ET and WUE were increased with N application at the rate of 120 kg ha⁻¹ in the M and W-planting patterns as compared to other treatments (Fig. 7). The lowest ET and WUE were observed in broadcasting sowing method without N application.

Principal component analysis (PCA)

Principal component analysis was performed to determine the effect of various nitrogen levels in different planting patterns on agronomic traits, grain nitrogen

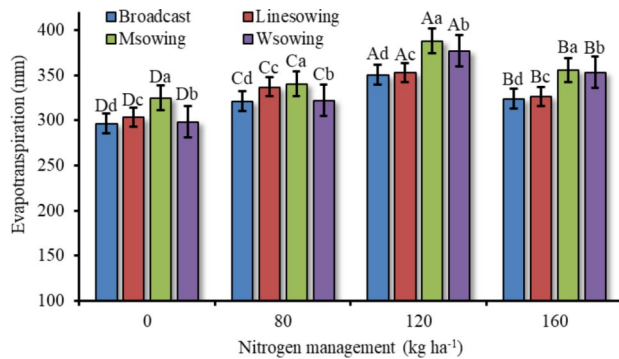


Fig. 7 Interactive effect of nitrogen rates and planting patterns on crop evapotranspiration (mm). Error bars indicate the standard error of the mean. The uppercase letters are used for nitrogen rates interactions within each planting patterns, whereas lowercase letters are used for the planting pattern within each nitrogen rates. The identical alphabetic letters do not differ from each other, as analyzed by LSD (nitrogen rates; $p < 0.05$) and (planting pattern; $p < 0.05$) test for both years. ($n = 4$ replications)

content and uptake as well as ET and WUE of wheat. The effect of these parameters of wheat against combined treatments are presented as PC1 (principal component 1) and PC2 (principal component 2). The variables explained 88.45% of the variations in the first two axes (PC1 and PC2). PC1 and PC2 explained 81.72% and 6.73% of the total variance. The results clarified that all parameters did not show any association with N0 when combine with all planting patterns. Chlorophyll *b* and carotenoids were associated with N3 in W planting. Biological yield and chlorophyll *a* were highly associated with N3 when applied in line and W planting pattern. Parameters such as tillers m^{-2} , spikelets $spikes^{-1}$, grains

$spike^{-1}$, 1000 grain weight, WUE and ET of wheat was positive correlated with N2 when applied in line, M and W planting patterns (Fig. 8).

Association between grain yield and grain N content with nitrogen levels at different planting patterns

Significant difference was noted when relationship was plotted between grain yield and grain nitrogen content at different nitrogen levels in different planting conditions (Fig. 9).

N0 showed no significant effect of grain yield on grain content. However, it grains N slightly improved with increasing grain yield in line planting (b). Similarly, nitrogen dose of N1 showed weak positive interaction between yield and grain N in W planting as compared to other planting patterns that showed no association. Application of N2 and N3 reported no significant correlation except for N3 in line planting pattern that showed moderate correlation.

Association between grain yield and evapotranspiration with nitrogen levels at different planting patterns

Variability was observed when relationship was plotted between grain yield and evapotranspiration (ET) at different nitrogen levels in different planting conditions (Fig. 10).

N0 showed negative correlation of grain yield with ET in broadcast, line and W planting patterns (a, b and d) except in M planting, where it showed small positive correlation (c). More evapotranspiration occurred in response to increasing grain yield with N1 as indicated by

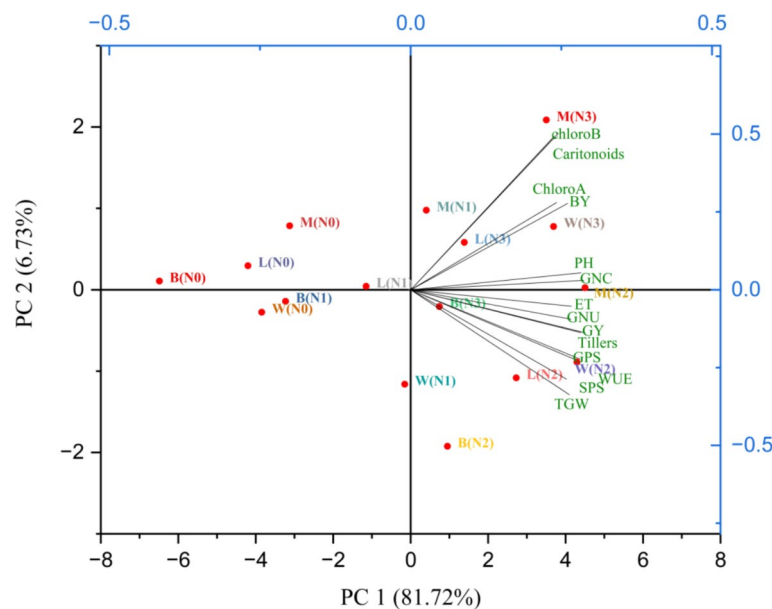


Fig. 8 Principal component analysis (PCA) for studied traits of wheat against different combinations of nitrogen rates and various planting patterns during 2020-21 and 2021-22. N0 = control, N1 = 80 kg N ha^{-1} , N2 = 120 kg N ha^{-1} and N3 = 160 kg N ha^{-1} while B = broadcasting, L = line planting, M = M planting and W = W planting pattern

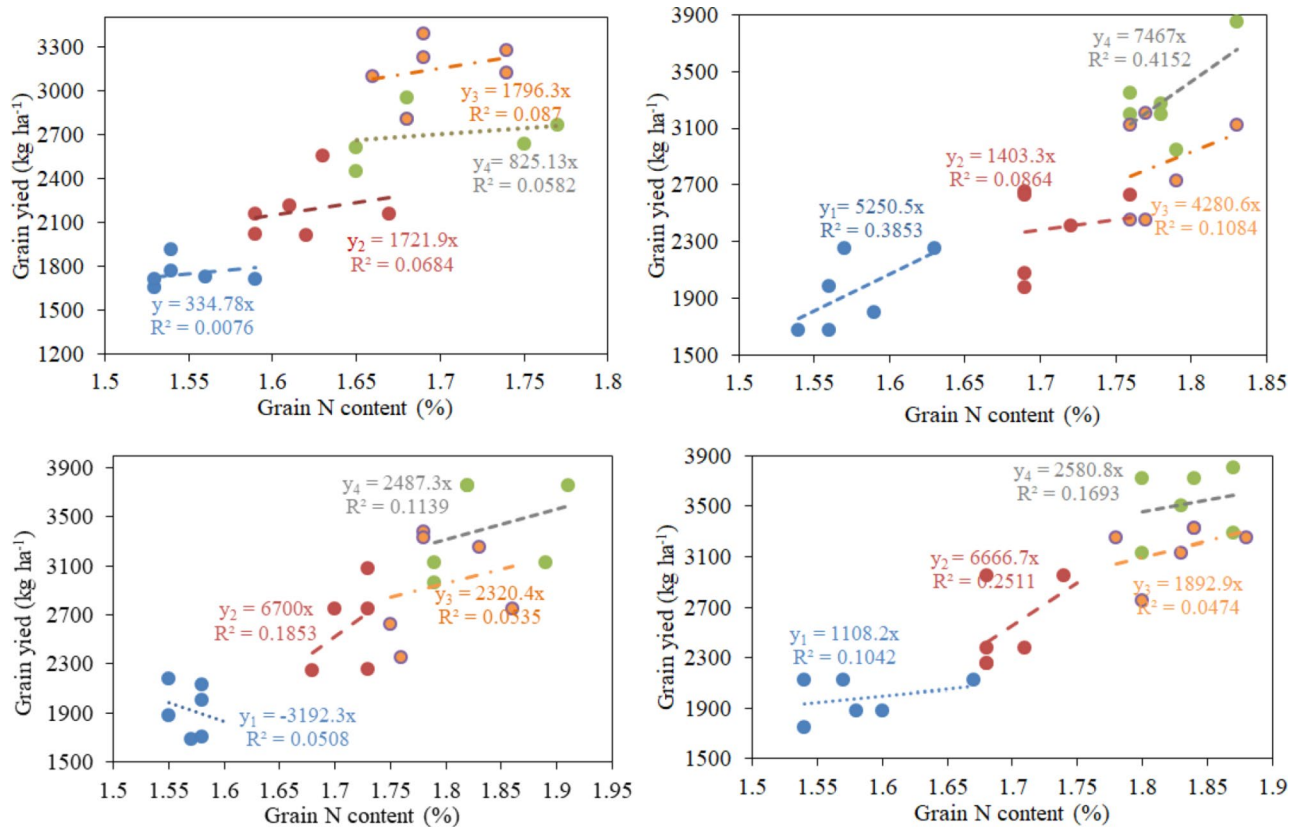


Fig. 9 Correlation between grain yield and grain N content (%) at different nitrogen rates ($y_1=N_0$, $y_2=N_1$, $y_3=N_2$ and $y_4=N_3$) at broadcasting (a), line planting (b), M planting (c) and W planting pattern (d)

linear correlation at broadcast planting (a) whereas this correlation became weaker at M planting and got highly negative at W planting (d) indicating significant effect of planting patterns. There was no prominent relationship discovered between grain yield and ET when N₂ was applied except for M planting, where moderate to high correlation was noted. Lastly, N₃ level showed positive correlation between grain yield and ET in broadcast and M planting. However, the relationship was negative in line planting and very weak in W planting (d).

Discussion

The study demonstrated significant benefits of optimized planting patterns and nitrogen (N) management strategies on wheat growth and yield (Figs. 3 and 9). Effective implementation of these strategies has the potential to enhance plant growth, yield components, and productivity, thereby contributing to sustainable agricultural practices (Supply Table 1). A linear increase in chlorophyll a, chlorophyll b, and carotenoids was observed with increasing N rates (Table 1). This is because wheat exposed to higher N levels can capture more sunlight and uptake more nutrients from the soil, leading to an enhanced rate of photosynthesis and greater leaf area index, which resulted in greater production of

photopigments [21, 22]. It has also reported that higher N rates could increase transportation of photosynthetic N that consequently improve plant photosystem [23]. The present study also indicated that W and M planting patterns had improved plant pigment as compared to traditional planting pattern (Table 1), as exposing plant canopy and leaf orientation to light from a better angle can enhance photosynthesis and photosynthetic pigments.

The current results noticed that higher rates of N and planting patterns were observed with taller plants compared to lower rate of N and broadcasting (Table 2). It has previously reported that N fertilization stimulates shoot elongation that could help the plants to reach to maximum plant height [24]. Liu et al. [25] also verified that high N levels have substantial impact on plant growth and consequently boosted plant height. Previous study indicated that W planting induced a correlation with some important agronomic traits, which enhance plant height [26]. The present results recorded that high N rates and planting patterns improved productive tillers m⁻² (Table 2), probably due to the efficient use of nutrient resources, enhanced biomass and prolonged green leaf retention, which increase tiller m⁻² and plant height [27]. It has observed that high N application can improve chlorophyll content and translocation of assimilates to

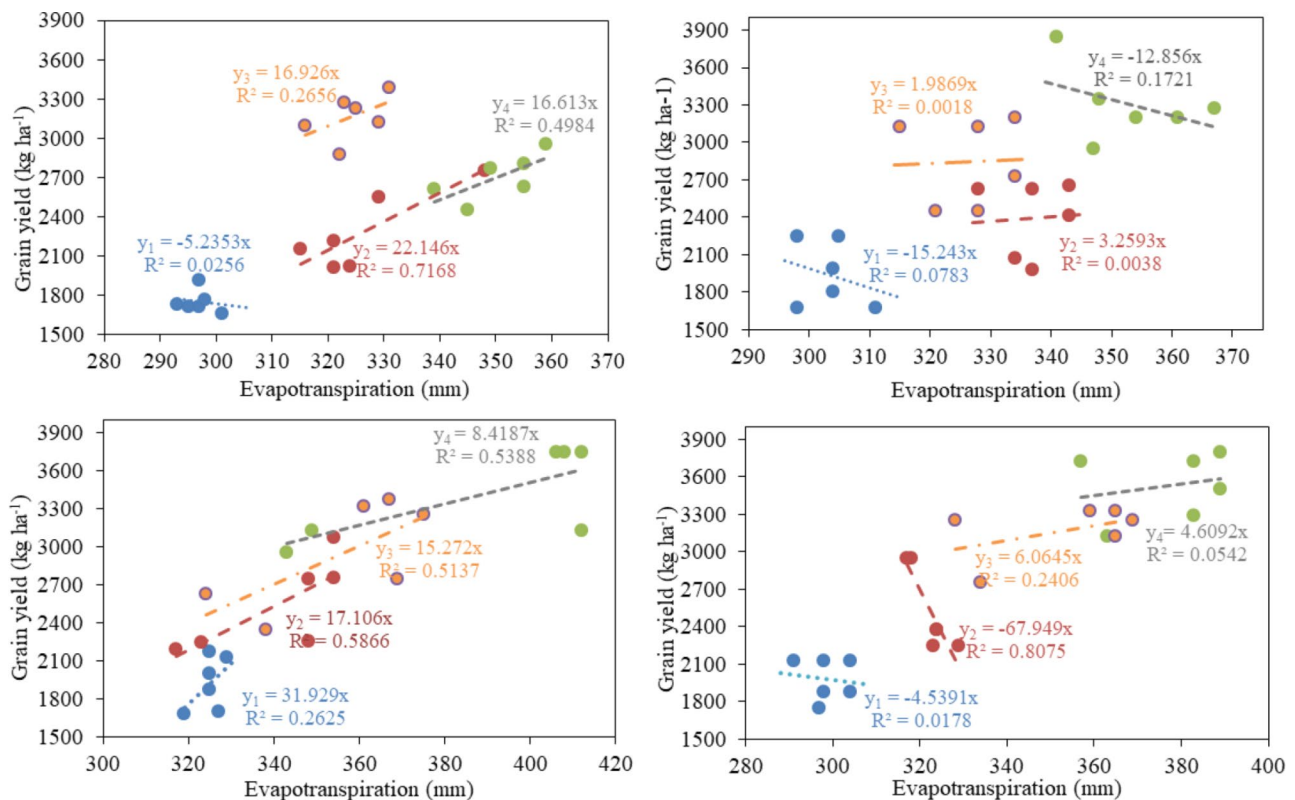


Fig. 10 Correlation between evapotranspiration (mm) and nitrogen levels ($y_1=N_0$, $y_2=N_1$, $y_3=N_2$ and $y_4=N_3$). (a) Evapotranspiration with broadcast planting, (b) Evapotranspiration with line planting, (c) Evapotranspiration with M planting and (d) Evapotranspiration with W planting

sink, thus increasing number of productive tillers [28]. The W pattern provide more space between plants and less competition for the utilization of the resources and light, which can be the possible reason for more tillering and dry matter of wheat [29, 30].

Number of grains and spikelets spike⁻¹ are the key yield components that significantly contribute to greater crop yield [31]. Spikelets and grains spike⁻¹ were increased with N₂ application (Fig. 4), supported by Hussain et al. [32] who reported that N deficiency decreases the rate of primordium initiation, resulting in reduced spikelets [33]. Higher number of spikelets and grains spike⁻¹ were recorded with W and M planting patterns (Table 2). The optimal arrangement of plants creating a favorable microenvironment that balances competition and use of resource, although the spacing in M pattern may not be as wide as in the W pattern but could still reduce competition for similar benefits. Similarly, Xin et al. [30] stated that numbers of spikelets spike⁻¹ were increased in wider planting pattern than in the conventional cultivation.

Furthermore, maximum thousand grains weight was observed with the higher N rates as compared to other treatments (Table 2). Kubar et al. [34] explained that there is a direct correlation of N rates and thousand grains weight [35]. The present study observed greater thousand grains weight within W and M planting

patterns (Table 2). Bian et al. [29] recorded greater thousand grains weight in W planting pattern compared to others.

Our results reported that application of N at a rate of 160 kg ha⁻¹ and improved planting pattern were observed with greater biological yield (Supply Table 2; Fig. 5a). The reason could be the effectiveness of N application in increasing number of tillers that could reflect in plant population and consequently greater biomass [36, 37]. The W planting pattern due to its spatial arrangement, enhances photosynthetic capacity, increases chlorophyll levels, and prolonged the growth stage, leading to higher photosynthetic production and ultimately resulting in greater biomass. [38]. Moreover, grain yield was greatly improved with higher rates of N and planting patterns as compared with lower rates of N and broadcasting (Supply Table 2; Fig. 5b). The relationship of N to grain yield obeys the law of diminishing returns that means yield increases with increasing N consumption but at higher rates of N, yield gradually reduce [39]. The W-planting pattern might have enhanced canopy structure, leading to more effective transpiration rate and nutrient uptake including N, which is vital for grain development [30]. Likewise, observations were also observed by Bain et al. [29] that grain yield was significantly higher (4% in

2013–2014 and 10% in 2014–2015) in W planting pattern than in conventional.

Nitrogen application is widely recognized as an important factor in promoting protein storage and wheat grain quality [40, 41]. Improved N concentration observed in wheat grains under the highest N application rate (Supply Table 2; Fig. 6a), facilitating N translocation during the grain-filling phase [42]. Similarly, Arduini et al. [43] reported higher grain N concentration in bread wheat from 1.52 to 2.28% with the N application from 60 to 120 kg ha⁻¹. Our results verified that N2 (120 kg ha⁻¹) improved grains N uptake in wheat while further improvement to N3 (160 kg N ha⁻¹) reduced grain N uptake (Fig. 6b). Several previous studies documented that increasing N rates beyond certain thresholds in prevailing environmental conditions does not enhance N uptake and exerts negligible influence on grain yield [44, 45]. Moreover, surplus N application has been associated with a phenomenon known as luxury absorption that led to a reduction in yield [46]. Higher grain N uptake was associated with M and W planting patterns as compared to line and broadcasting (Fig. 6b). The change in spatial arrangement of plant could increase N use efficiency that led to higher N gain in wheat grains [30]. Consistent with our findings, Yang et al. [47] recorded higher N uptake and utilization in improved wheat planting methods.

Evapotranspiration (ET) peaked at 120 kg N ha⁻¹ and showed no further increase at higher N concentrations (Table 3), aligning with findings from previous studies [48–50]. This phenomenon can be attributed to the higher N rates, fostering biomass accumulation and substantial canopy development, resulting in greater above-ground shading [48]. Higher N rates, such as N3 (160 kg ha⁻¹) promote vigorous plant growth and a denser canopy, which increases shading, reduces soil evaporation, and alters the microclimate by raising humidity and lowering wind speed at the soil surface. These factors contribute to lower ET compared to the treatments with less canopy cover. Application of N fertilizers can significantly increase water use efficiency (WUE) of wheat [51]. In our study, WUE was improved with application of N2 and N3 rates (Table 4), primarily because higher nitrogen concentrations enhanced photosynthesis more effectively than they increase transpiration (Fig. 10). As emphasized by Ashraf et al. [52] that appropriate N fertilizer application (100–200 kg N ha⁻¹) could efficiently increase crop yield, ET and WUE. ET was higher at M planting followed by W planting whereas both M and W planting patterns showed improved WUE (Table 4). These two new planting patterns that has wider rows at one end and narrower at other end, might have contributed effectively to factors like canopy development, microclimate modification, soil cover, and root distribution, led to improved parameters like ET and WUE. Previous study by Noor et

al. [31], who stated that wide-space sowing (WS) and furrow sowing (FS) improved ET and WUE of wheat compared to traditional planting.

Conclusions

The findings of the study indicated that optimal application of nitrogen, specifically at a rate of 120 kg ha⁻¹ (N2–2/3rd during sowing time and 1/3rd applied two weeks after emergence) resulted in greater yield and yield components of wheat. Additionally, among different planting patterns, W and M patterns showed superior performance, yielding maximum output in terms of both yield and yield components, when compared to broadcast and line planting methods. These results highlight the critical role of precise nitrogen management and effective planting patterns in enhancing wheat production efficiency which is essential for addressing future food security needs. Further research could explore these practices in different climatic conditions and refine recommendations for various wheat-growing regions. This would ensure that the benefits observed in this study can be realized more broadly, contributing to sustainable wheat production on a global scale in the future.

Supplementary Information

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Supplementary Material 1

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Author contributions

M.F.A: Investigation; Conceptualization; writing - original draft; J.B and N.A: Investigation; Methodology, writing - original draft; B.I: Investigation; methodology, review & editing; U.A: Investigation; M.K.O: writing - review & editing; N.A: Writing - review & editing, methodology; I.A. A: Investigation; methodology; H.A: Conceptualization; A.J: Project administration; writing - review & editing. All authors have read and agreed to the published version of the manuscript.

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Data availability

The data was used for the research described in the article and will be made available on request.

Declarations

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