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RESEARCH ARTICLE

Influence of planting pattern and nitrogen requirement on quality and nitrogen uptake of wheat (*Triticum aestivum* L.)

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Abstract

Stagnating wheat yields and dropping of grain protein content pose a significant challenge to the nation's food and nutritional security. Hence, optimising resource-use efficiency through synchronised nutrient management and precise spatial arrangements is necessary to provide a balance between productivity and quality. This study evaluates how the synergy of planting geometry, soil nitrogen application and strategic foliar application can enhance nitrogen uptake and improve the end-use quality of wheat (*Triticum aestivum* L.) under Indian conditions. The research was designed as a split-split plot experiment with three replications. The primary factor, constituting the main plot treatments, involved three distinct planting patterns: M_1 being conventional flat sowing, M_2 and M_3 being bed sowing with two rows per bed and three rows per bed, respectively. Within these planting patterns, the sub-plot treatments were three different levels of soil-applied nitrogen (N), where compared, i.e. N_1(0 kg/ha N), N_2 and N_3 being 50 and 100 % of the recommended dose of nitrogen. Finally, the sub-sub plot treatments introduced three different timings for a 2 % foliar nitrogen application at the crown root initiation stage (F_1), tillering stage (F_2) and boot stage (F_3). The outcome revealed significant synergistic effects between different planting geometries, soil nitrogen application and strategic foliar application of nitrogen, with M_2 yielding the best results among planting geometries, N_3 being the best treatment for soil applications and F_2 showing the best results among strategic foliar application of nitrogen. These findings highlight the potential of the interactive effect of these factors to mitigate the inherent trade-off between productivity and nutritional quality of the wheat crop.

Keywords: foliar nitrogen application; nitrogen levels; nitrogen uptake; nitrogen use efficiency; planting patterns; split application; wheat

Introduction

Wheat (*Triticum aestivum* L.) is commonly referred to as the King of Cereals. It is a grass species cultivated worldwide for its seed and commercially classified as an essential cereal grain and staple food across the globe. Its most economically important species belong to the genus and these are bread wheat (*T. aestivum*) and durum wheat (*T. turgidum*) (1). Since wheat has been cultivated since prehistoric times, it is the most widespread staple crop, fulfilling the food requirements of more than a billion people in various forms. Nutritionally, wheat is an excellent vegetative protein source, reflecting superior quality when compared to other major cereals like maize and rice. Commonly, wheat possesses a sound nutritional profile with contents of 12.1 % protein, 1.8 % lipids, 59 % starch and significant amounts of several vitamins, minerals and nicotinic acid (2).

Wheat is produced in about 120 countries, with the two largest producers being China and India. The total area occupied by the crop globally stands at approximately 219 M ha, yielding an annual global production of about 760.92 million tonnes, with a global average productivity of 3,474 kg/ha (3). In the context of the Indian economy, agriculture remains pivotal, accounting for approximately 16 % of the Gross Domestic Product (GDP) and engaging 54.60 % of the total workforce (Census 2011). The country's geographical area of 328.70 million hectares includes a gross cropped area of 200.20 million hectares and a net cultivable area of 139.4 M ha. Being the staple diet of one-third of the nation's population, wheat holds especially strategic status among Indian crops, mainly grown across northern India. Of the total cultivated area, Uttar Pradesh has the largest share (30.19 %), followed by Madhya Pradesh (20.83 %), Punjab (11.15 %), Haryana (9.91 %) and Rajasthan (8.06 %). Punjab is the state with the highest per capita production per unit area (4).

High returns and improved crop yield are intrinsically linked with the planting geometry, where the raised beds have consistently performed better as compared to the conventional flat sowing method in enhancing growth, yield and quality of the crop (5). While the two methods have their unique benefits and shortcomings, the advantage of bed sowing lies in its capability to enhance wheat plants' mechanical strength and to promote the conservation of water, significantly improve fertiliser use efficiency and reduce crop-weed competition (6). Further, the bed-sowing is an important strategy for reducing the adverse impacts of waterlogging, especially in heavy-textured soils, highly effective in optimising the distribution of irrigation water within high-yield cropping systems. This would make the technique pivotal for optimising overall wheat performance across varied planting densities and nitrogen fertilisation regimes (7).

Nitrogen is essential for plant health and contributes to the synthesis of amino acids, the production of chlorophyll and general plant health, which is vital for optimum growth and production(8). Therefore, effective N management is crucial for sustainable improvement in both crop quality and yield. On the contrary, excessive use of N degrades soil and groundwater, enhances the susceptibility of crops to lodging, insects and diseases and reduces grain quality due to associated risks to human and environmental health (9). A deficiency in nitrogen, on the other hand, leads to stunted growth and low productivity. Precise application timing should be done to coincide with the critical growth stages in an effort to maximise its uptake and assimilation for sustainable and high-quality wheat production (10). As one of the most important approaches to increasing grain yield and protein content, the use of N in split doses is more effective than application in a single dose. Maximising the N split and optimum timing of application, considering the crop demand optimizes N uptake and utilisation, leading to higher biomass and grain yield (11). In addition, foliar application of N during the critical growth stages has been considered one of the most efficient and convenient approaches, as it enables the nutrient to be absorbed directly through the foliage, thereby greatly improving the nitrogen use efficiency (NUE) (12). It is, therefore, one of the promising approaches to optimising wheat N management coupled with improving yield and grain quality for sustainable resource use and environmental health. The objective of this study is to evaluate the synergistic influence of different planting geometries, graded soil nitrogen levels and strategic foliar application timings of nitrogen on nitrogen uptake and grain quality in wheat (*Triticum aestivum* L.) under Indian subtropical conditions.

Materials and Methods

Experimental site and soil properties

The field experiment was carried out during the Rabi season of 2023–2024 at the agricultural research farm facility, Lovely Professional University, Phagwara, India. Geographically, Lovely Professional University is situated at 31° 13' 28'' North latitude and 75° 46' 25'' East longitude, with an elevation of 245 m Above Mean Sea Level (AMSL), having a subtropical climate. The soil in the experimental field can be texturally classified as sandy loam according to the triangle method of soil classification approved by the International Society of Soil Science (ISSS), with a slightly acidic pH of 6.03. The initial available nitrogen content in the topsoil was 298.4 kg/ha.

Experimental design and treatment details

The experiment was designed as a split-split plot with three replications, laying out in detail the effects of planting methods and nitrogen application on wheat growth and final yield. As the main plot treatments, the primary factor consisted of three distinct planting patterns: M_1- flat sowing with rows spaced 22.5 cm apart, M_2- bed sowing with two rows per 67.5 cm bed (37.5 cm bed top + 30 cm furrow) and M_3- bed sowing with three rows per 90 cm bed (60 cm flat top + 30 cm furrow).

Within these planting patterns, three levels of soil-applied nitrogen (N) constituted the subplot treatments, with the recommended dose of nitrogen (RDN) being 125 kg/ha (along with 60 kg/ha P_2O_5 and 40 kg/ha K_2O). N_1- 0 kg/ha N, N_2- 50 % of RDN, N_3 - 100 % of RDN. Finally, the sub-sub plot treatments consisted of three different timings for a 2 % foliar nitrogen application. F_1- 2 % foliar nitrogen applied at the Crown Root Initiation (CRI) stage, F_2 - 2 % foliar nitrogen applied at the tillering stage, F_3- 2 % foliar nitrogen applied at the boot stage.

The wheat sown was PBW 824, a high-yielding variety developed by Punjab Agricultural University, Ludhiana.

Field preparation and sowing

Thorough preparation of the experimental field was carried out by first ploughing with a mould board plough and finishing with fine harrowing to attain a proper seedbed. The layout of the experiment was then done using the Split-Split Plot Design with three replications. Sowing was done manually by skilled labourers on November 19, 2023. Planting methods adhered strictly to the main plot treatments:

M_1 (Flat sowing): Seeds were sown across the entire plot, maintaining a uniform row-to-row spacing of 22.5 cm.

M_2 (Two-row bed sowing): Raised beds were constructed with a 37.5 cm bed top and a 30 cm furrow. Two rows of wheat were sown on the surface of each bed top.

M_3 (Three-row bed sowing): Raised beds were constructed with a 60 cm bed top and a 30 cm furrow. Three rows of wheat were sown on the surface of each bed top.

Fertilizer and weed management

Soil nitrogen application

Nitrogen dosages corresponding to the sub-plot treatments (T_1, T_2, T_3) were given in two equal splits: one-half at the time of planting and the second half thirty days after sowing (DAS). The full dose of phosphorus and potassium was given as a basal dose during the final seedbed preparation.

Foliar nitrogen application

The 2 % foliar nitrogen solution, representing the sub-sub plot factor (F_1, F_2, F_3), was applied precisely according to the specified crop growth stage for each treatment.

Weed control

Uniform weed control was achieved across the entire experimental area by applying the post-emergence herbicide ACM -9 (a pre-mix of Metribuzin + Clodinafop), which was sprayed 35 days after sowing.

Irrigation and pest control

Prevailing rainfall and crop water demand determined the application of three to four irrigations to the wheat crop. Irrigation was scheduled according to critical physiological growth stages; the first irrigation was provided at 21 DAS, corresponding to CRI. Subsequent irrigations were given at tillering, booting and dough stages. To control sucking pests, especially aphids and jassids, the entire experimental area was uniformly sprayed with Malathion 50 EC at the rate of 1.0 L/ha.

Harvesting and yield measurement

The grain hardened at approximately 145 to 150 DAS, when the colour of the plant had changed due to senescence and the crop attained physiological maturity. Harvesting was done manually with the help of a sickle. Soon after cutting, the produce from each net plot was carefully bundled and spread in the sun for proper field drying to reduce moisture content. After this, the dried bundles were threshed manually with sticks. The grain was cleaned and weighed immediately by a calibrated electronic balance to measure the plot-wise grain yield and later converted to standard measurement (kg/ha).

Lab analysis

Nitrogen content was determined using the Kjeldahl method and protein content using the conversion factor multiplied by the nitrogen content in grains (%)

Field attributes analysis

Chlorophyll index was measured using a SPAD meter and Canopy temperature (°C) was measured using infra-red thermometer.

Nitrogen uptake analysis

Nitrogen Uptake in Grain -The formula determines the total mass of nitrogen accumulated in the economic yield (grain) and is usually expressed in kg N/ha:

Nitrogen uptake in grain (kg N/ha) = Grain yield (kg/ha) × N content in grain (%) /100 (Eqn. 1)

Nitrogen uptake in straw -This formula determines the total mass of nitrogen accumulated in the vegetative biomass (straw):

Nitrogen uptake in straw (kg N/ha) =Straw yield (kg/ha) × N content in straw (%)/100 (Eqn. 2)

Statistical analysis

All collected experimental data were subjected to statistical analysis of variance (3-way ANOVA) at 95 % confidence level (5 % level of significance; $p \leq 0.05$) using the OPSTAT software package to evaluate the significance of the main and interaction effects of the planting patterns, soil nitrogen levels and foliar application timings.

Results

Physiological traits

The physiological parameters analysed include chlorophyll content (SPAD), canopy temperature (°C), protein content in grains (%), nitrogen content in grains and straw (%). Interactive effects of planting geometry, soil nitrogen and foliar timing significantly influenced all traits ($p<0.05$) exhibited in the tables below. Chlorophyll content showed an upward trend in bed planting compared to flat sowing. Chlorophyll content, being a measure of the relative amount of chlorophyll present in leaves, a higher chlorophyll content indicates proficient ability of the plant to perform photosynthesis.$M_2$and M_3 were found to be on par at 45 and 90 days after sowing. Chlorophyll index showed significantly higher results in M_3at 135 days after sowing, with 6.25 % increase compared to M_1 (Table 1). Chlorophyll content was also significantly higher in N_3at all different stages, with 20.10 % increase at 45 DAS, 18.4 % and 17 % at 90 DAS and 135 DAS compared to N_1. Optimum rates of nitrogen are directly associate to improved photosynthetic capacity and total growth of the plant, hence showing this result. Furthermore, chlorophyll index was found to be significantly higher in F_2at 90 and 135 days after sowing compared to other treatments, whereas all treatments were found to be at par at 45 days after sowing (Table 2). During the tillering stage, wheat plants undergo rapid leaf development and hence proper nitrogen supplementation at this stage can have a positive effect on the leaf development, thereby increasing photosynthetic activity, leading to higher chlorophyll content, maximising light absorption and energy production(13). This research established a pronounced three-way statistical interaction involving the planting method (A), the level of nitrogen applied to the soil (B) and the schedule of supplemental foliar spray of nitrogen (C) on chlorophyll index recorded at both 45 and

Table 1. Influence of planting methods, nitrogen levels and foliar application of nitrogen on the periodic chlorophyll Index (SPAD) of wheat crop

Treatments	Chlorophyll index (SPAD) 45 DAS	Chlorophyll index (SPAD) 90 DAS	Chlorophyll index (SPAD) 135 DAS
Main plots (Methods of planting)			
Flat sowing (22.5 row to row planting)	41.9	41.5	36.8
Bed sowing with two rows per bed of 90 cm (37.5 cm flat top + 30 cm furrow)	41.5	41.9	37.4
Bed sowing with three rows per bed of 90 cm (60 cm flat top + 30 cm furrow)	41.2	42.5	39.1
S.E(m)	0.11	0.13	0.28
C.D. (5 %)	0.44	0.51	1.13
Sub plots (Nitrogen levels- soil application)			
N_1- 0 kg N/ha	37.3	38	34.30
N_2 -50 % of RDN	42.0	42.4	38.6
N_3- 100 % of RDN	44.8	45.5	40.5
S.E(m)	0.15	0.13	0.19
C.D. (5 %)	0.46	0.40	0.60
Sub-Sub plot (Foliar application of Nitrogen)			
2 % foliar nitrogen application at the CRI stage	41.7	41.6	37.04
2 % foliar nitrogen application at the tillering stage	41.2	42.6	38.5
2 % foliar nitrogen application at Boot stage	41.1	41.7	37.8
S.E(m)	0.15	0.14	0.26
C.D. (5 %)	0.45	0.42	0.77
C.D. (<5 %) Interaction			
A × B	0.80	0.69	NS
A × C	NS	NS	NS
B × C	NS	NS	NS
A × B × C	1.37	1.26	NS

C.D. – critical difference, S.E(m) – standard error of mean, NS – non-significant

Table 2. Interactive effect of planting methods, nitrogen levels and foliar application of nitrogen on chlorophyll (SPAD) at 45 DAS

45 DAS	Flat sowing			Two rows/bed			Three rows/bed			Mean
	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	
CRI	36.3	41.0	45.5	36.4	42.3	45.7	38.3	41.8	42.6	41.1
Tillering	37.5	40.6	45.6	37.5	43.5	43.5	38.1	43.4	45.7	41.7
Boot	36.7	40.6	44.4	37.8	41.9	44.4	37.0	42.4	45.8	41.2
Mean	36.8	40.7	45.2	37.2	42.6	44.5	37.8	42.5	44.7	
SE(m±)						0.47				
C.D (<5 %)						1.37				

90 days after sowing (DAS) (Table 3). The treatment regimen that was deemed most productive, resulting in the highest chlorophyll readings (45.7 at 45 DAS and 48.5 at 90 DAS), was found in the interaction of M_3, N_3 and F_2. This superior photosynthetic potential is attributed to enhanced nutrient utilisation efficiency achieved by this specific management strategy compared to other treatments. Conversely, the lowest chlorophyll index was observed under the interaction of M_1, N_1 and F_1. Furthermore, notable synergistic effects on the chlorophyll index were also detected in the two-way interaction between the main planting method (A) and the soil nitrogen rate (B) at both 45 and 90 DAS.

Canopy temperature was observed to be significantly highest in M_1 at 45 (14.7 °C), 90(13.2 °C) and 135 (25 °C) days after sowing and at harvest (33.6 °C) (Table 4). Canopy temperature was highest in N_1 at 45 (15.02°C), 90 days after sowing (13.95°C) and at harvest (34.10°C) (Table 4). Canopy temperature was highest in 0 kg N/ha due to insufficient vegetative growth and canopy cover due to a lack of nitrogen, hence showed increase in canopy temperature. Canopy temperature at 2 % Nitrogen foliar application at different stages did not exhibit any major influence and hence was deemed insignificant (Table 4). Main plot and subplot interactions were found to be significant in canopy temperature at 45 and 90 days after sowing.

Grain quality traits

Protein content can be referred to as a direct measure of the nitrogen (N) accumulated in the grains of the crop and is a direct indicator of the grain's quality and sustainability. In wheat, planting geometry and levels of nitrogen had a crucial effect on seed quality. Protein content (%) showed high results in M_1 compared to M_2 and M_3. The protein content recorded in M_1 showed 7.1 % increase in comparison to M_3 and 4.7 % compared to M_2(Table 5). Reduced tillering and lower yield potential allow more nitrogen to be allocated per grain, enhancing protein content in flat sowing. Whereas in bed sowing, nitrogen is distributed among a larger number of grains, slightly reducing protein concentration (Fig. 1).

Furthermore, the nitrogen content in grains and straw (%) was significantly greater in M_1 compared to M_2 and M_3 (Table 5). Nitrogen content in grain and straw (%) showed 7.1 % and 14 %

Table 3. Interactive effect of planting methods, nitrogen levels and foliar application of nitrogen on Chlorophyll (SPAD) at 90 DAS

90 DAS	Flat sowing			Two rows/bed			Three rows/bed			Mean
	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	
CRI	37.6	41.6	44.8	37.4	42.4	45.2	38.7	42.1	44.2	41.5
Tillering	38.3	41.6	45.2	37.5	44.0	46.2	38.3	43.9	48.5	42.6
Boot	37.8	41.7	44.7	38.1	42.3	44.3	37.9	42.2	46.7	41.7
Mean	37.9	41.6	44.9	37.6	42.9	45.2	38.8	42.7	46.5	
SE(m±)						0.44				
C.D (<5 %)						1.26				

Table 4. Influence of planting methods, nitrogen levels and foliar application of nitrogen on canopy temperature.

Treatments	Canopy temperature (°C) at 45 DAS	Canopy temperature (°C) at 90 DAS	Canopy temperature (°C) at 135 DAS	Canopy temperature (°C) at harvest
Main plots (methods of planting)				
Flat sowing (22.5 row to row planting)	14.3	13.2	24.2	33.6
Bed sowing with two rows per bed of 90 cm (37.5 cm flat top + 30 cm furrow)	14.4	12.6	24.6	33.4
Bed sowing with three rows per bed of 90 cm (60 cm flat top + 30 cm furrow)	14.7	12.6	25	32.9
S.E(m)	0.19	0.03	0.14	0.03
C.D. (5 %)	0.05	0.14	0.55	0.12
Sub plots (Nitrogen levels- soil application)				
N_1- 0 kg N/ha	15.02	13.95	25.93	34.10
N_2 -50 % of RDN	14.40	12.65	23.37	33.38
N_3- 100 % of RDN	14.07	11.96	24.64	32.56
S.E(m)	0.03	0.04	0.20	0.05
C.D. (5 %)	0.11	0.14	0.63	0.17
Sub-Sub plot (Foliar application of Nitrogen)				
2 % foliar nitrogen application at the CRI stage	14.47	12.87	24.46	33.39
2 % foliar nitrogen application at the tillering stage	14.51	12.84	24.79	33.33
2 % foliar nitrogen application at Boot stage	14.50	12.84	24.68	33.32
S.E(m)	0.03	0.07	0.17	0.05
C.D. (5 %)	NS	NS	NS	NS
C.D (<5 %) Interaction				
A × B	0.20	0.24	NS	NS
A × C	NS	NS	NS	NS
B × C	NS	NS	NS	NS
A × B × C	NS	NS	NS	NS

NS – non-significant, RDN – recommended dose of nitrogen, DAS – days after sowing, CRI – crown root initiation

Table 5. Influence of planting methods, nitrogen levels and foliar application of nitrogen on protein content in grains, nitrogen content in grains and nitrogen content in straw

Treatments	Protein content in grains (%)	Nitrogen content in grains (%)	Nitrogen content in straw (%)
Main plots (Methods of planting)			
Flat sowing (22.5 row to row planting)	10.41	1.66	0.56
Bed sowing with two rows per bed of 90 cm (37.5 cm flat top + 30 cm furrow)	9.95	1.59	0.50
Bed sowing with three rows per bed of 90 cm (60 cm flat top + 30 cm furrow)	9.72	1.55	0.47
S.E(m)	0.01	0.002	0.003
C.D. (5 %)	0.05	0.008	0.013
Sub plots (Nitrogen levels- soil application)			
N_1- 0 kg N/ha	9.40	1.50	0.44
N_2 -50 % of RDN	9.96	1.59	0.52
N_3- 100 % of RDN	10.72	1.71	0.57
S.E(m)	0.01	0.002	0.003
C.D. (5 %)	0.04	0.007	0.010
Sub-Sub plot (Foliar application of nitrogen)			
2 % foliar nitrogen application at the CRI stage	9.96	1.59	0.50
2 % foliar nitrogen application at the tillering stage	10.03	1.60	0.51
2 % foliar nitrogen application at Boot stage	10.08	1.61	0.52
S.E(m)	0.01	0.003	0.002
C.D. (5 %)	0.05	0.009	0.006
C.D. (<5 %) Interaction			
A × B	NS	NS	NS
A × C	NS	NS	NS
B × C	NS	NS	NS
A × B × C	NS	NS	NS

NS—non-significant, RDN – recommended dose of nitrogen, DAS – days after sowing, CRI – crown root initiation

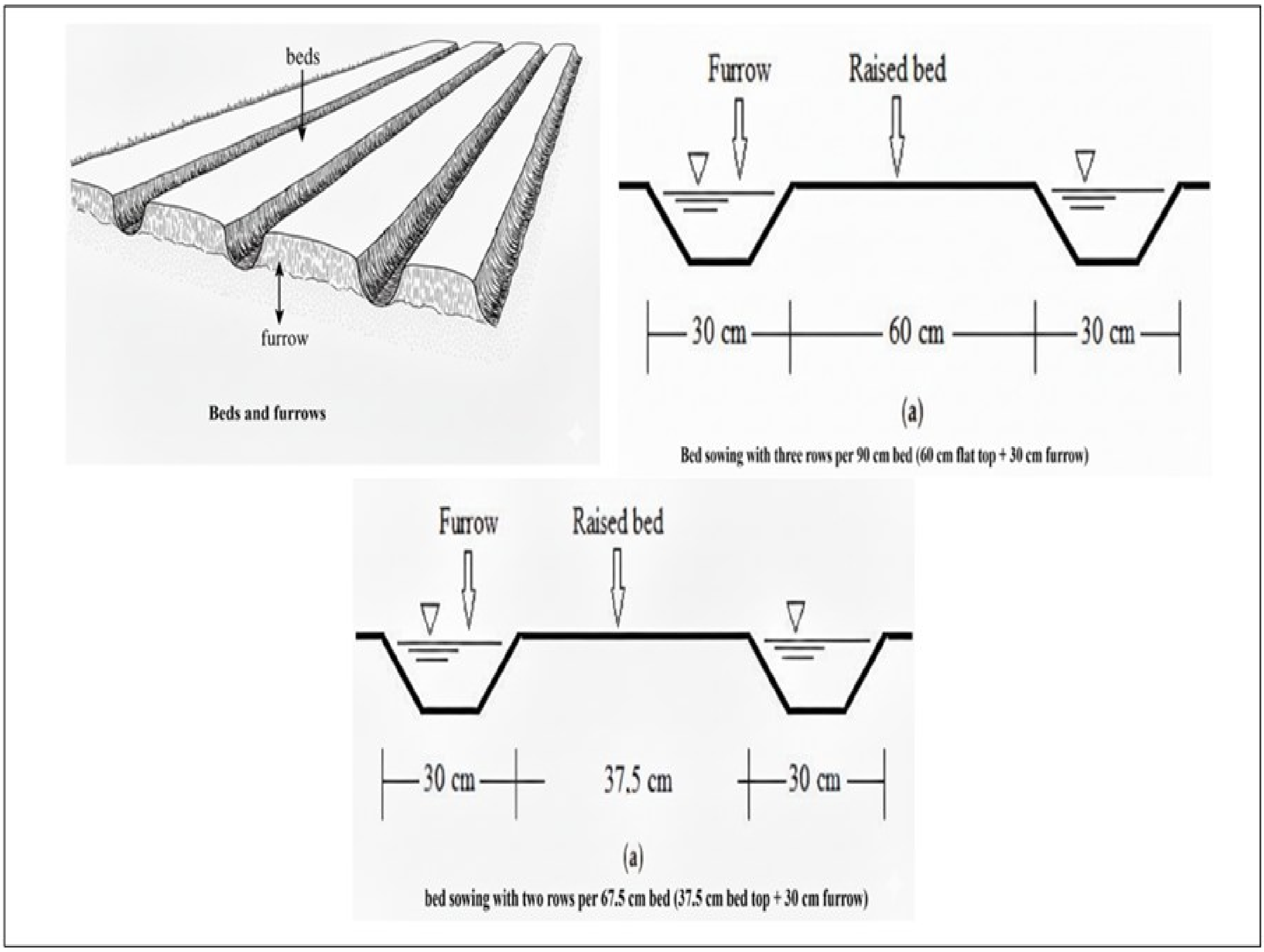

Fig. 1. Bed sowing with different bed sizes used in treatment.

growth compared to M_3(Table 5). Additionally, Protein content in grains (%), nitrogen content in grains and straw (%) were considerably greater in N_3compared to all other nitrogen levels, as optimum nitrogen supply leads to more photosynthetic capacity, improved vegetative growth and hence increased protein content. These results are similar to the investigations undertaken (14, 15). Protein content (%), nitrogen content in grains and straw (%) were found to be statistically at par in 2 % foliar nitrogen application at different stages (Table 5).

Uptake studies

In wheat, different planting geometries, graded soil nitrogen levels and strategic foliar application timings of nitrogen had a significant impact on the uptake of nitrogen in both grain and straw. M_3 and M_2 resulted in significantly better seed yields compared to M_1. In M_3, the nitrogen uptake in grain (kg/ha) was 65.7 kg/ha, which was significantly greater than M_1(61.6 kg/ha), increasing the uptake by 6.7 %, but was statistically comparable to M_2 (64.4 kg/ha) (Table 6). The improved nitrogen uptake in grain in M_2 and M_3 could be due to the loose soil structure and more consistent availability of nutrients, which supports improved crop growth (16). Furthermore, the uptake of nitrogen in straw (kg/ha) was greatly higher in the M_3 (25.3 kg/ha) than in M_2 (23.3 kg/ha) and M_1(21.2 kg/ha) (Table 6). M_3facilitated 18.7 % more Nitrogen uptake in straw compared to M_1. Additionally, Nitrogen uptake by grain (87 kg/ha) and nitrogen uptake by straw (31.9 kg/ha) were greatly higher in the N_3 compared to all other nitrogen levels because it precisely matches the plant's nutritional needs throughout its growth stages (Table 7). This ample nitrogen supply stimulates vigorous vegetative growth, enhances the plant's ability to perform photosynthesis and ensures the efficient movement of nitrogen from the leaves and stems to the maturing grain (17). Nitrogen uptake in grain and straw was statistically similar between the F_2 and F_3, while it was significantly lower in F_1 (Table 8). Research findings highlight a substantial three-way interaction among planting density (Main Plot A), nitrogen fertiliser rate (Sub-Plot B) and the strategic foliar supplementation of nitrogen (Sub-Sub-Plot C) concerning nitrogen absorption by both grain and straw. The most effective strategy for nitrogen accumulation in grain (95.6 kg/

Table 6. Influence of planting methods, nitrogen levels and foliar application of nitrogen on nitrogen uptake by grain and nitrogen uptake by straw

Treatments	Nitrogen uptake by grain (kg/ha)	Nitrogen uptake by straw (kg/ha)
Main plots (Methods of planting)		
Flat sowing (22.5 row to row planting)	61.6	21.2
Bed sowing with two rows per bed of 90 cm (37.5 cm flat top + 30 cm furrow)	64.4	23.3
Bed sowing with three rows per bed of 90 cm (60 cm flat top + 30 cm furrow)	65.7	25.3
S.E(m)	0.39	0.19
C.D. (5 %)	1.53	0.74
Sub plots (Nitrogen levels- soil application)		
N_1- 0 kg N/ha	40.9	13.9
N_2 -50 % of RDN	63.8	24
N_3- 100 % of RDN	87.0	31.9
S.E(m)	0.77	0.19
C.D. (5 %)	2.37	0.60
Sub-Sub plot (Foliar application of nitrogen)		
2 % foliar nitrogen application at the CRI stage	59.8	21.8
2 % foliar nitrogen application at the tillering stage	65.3	23.7
2 % foliar nitrogen application at Boot stage	66.7	24.3
S.E(m)	0.75	0.22
C.D. (5 %)	2.16	0.65
C.D. (<5 %) Interaction		
A × B	4.11	1.05
A × C	3.74	NS
B × C	NS	NS
A × B × C	6.48	1.95

NS—non-significant, RDN – recommended dose of nitrogen, DAS – days after sowing, CRI – crown root initiation

Table 7. Interactive effect of planting methods on nitrogen levels, foliar application of nitrogen and nitrogen uptake by grain

	Nitrogen uptake by grain (kg/ha)									
	Flat sowing			Two rows/bed			Three rows/bed			
	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	Mean
CRI	23.3	61.1	81.6	43.6	61.0	83.0	38.2	58.2	88	59.8
Tillering	40.6	66.4	82.3	43.3	61.5	90.8	41.9	65.6	95.6	65.3
Boot	48.3	69.4	82	44.7	65.6	86.5	44.7	65.4	93.6	66.7
Mean	37.4	65.6	82	43.8	62.7	86.8	41.6	63	92.4	63.9
SE(m±)						2.26				
C.D (<5 %)						6.48				

Table 8. Interactive effect of planting methods on nitrogen levels, foliar application of nitrogen and nitrogen uptake by straw

	Nitrogen uptake by straw (kg/ha)									
	Flat sowing			Two rows/bed			Three rows/bed			Mean
	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	0 % kg/ha	50 % N	100 % N	
CRI	8.3	21	28.4	13.7	22.4	30.7	15.5	24.2	32.5	21.9
Tillering	12.8	23.2	29.1	13.9	23.4	33.7	14.5	26.9	35.6	23.7
Boot	15.5	23.5	28.8	14.7	24.7	32.8	16.5	26.9	35.6	24.3
Mean	12.2	22.6	28.8	14.1	23.5	32.4	15.5	26	34.5	
SE(m±)						0.68				
C.D (<5 %)						1.95				

ha) and straw (35.6 kg/ha) was observed within the interaction of M_3, N_3 and F_2. This superior performance is attributed to the synergistic benefits of an optimal spatial arrangement, sufficient nutrient delivery and accurately timed supplementation of nutrients. A comparable, statistically similar outcome was also observed in an interaction of M_3, N_3 and F_3, yielding 93.6 kg/ha nitrogen in grain and 35.6 kg/ha in straw. Furthermore, significant synergistic effects on grain nitrogen uptake were evident in the two-way interactions between the planting layout and the fertiliser rate (A + B) and the planting layout and the foliar treatment (A + C). For nitrogen uptake in straw, only the interaction between the planting layout and the fertilizer rate (A + B) proved to be statistically significant.

Discussions

Physiological parameters

This study demonstrated the interactive effects of planting geometry, soil nitrogen and foliar timing on nitrogen uptake and grain quality in wheat. Efficient implementation of these interactions has the potential to improve the quality and nitrogen uptake of the crop, thereby having a positive effect on growth and yield, leading to sustainable agriculture. Wheat being exposed to higher N levels can absorb more sunlight and uptake more soil nutrients, leading to improved photosynthetic rate and chlorophyll content (18). It is reported that increased N rates can improve chlorophyll content and translocation of assimilates to the sink, improving yield (19). Bed planting usually provides more space between the plants, leading to less competition for the utilisation of sunlight and other resources. This spatial arrangement improves photosynthetic capacity, increases chlorophyll levels, resulting in higher photosynthetic production (20). This spatial arrangement of plants could increase N use efficiency, thereby resulting in higher N gains in wheat grains(21). Bed planting outperformed conventional flat sowing in terms of chlorophyll content, with M_3showing an increase of 6.25 % compared to M_1at 135 days after sowing, due to better light interception, nutrient access and root aeration by the plant. Full dose of nitrogen (N_3) improved the chlorophyll content by 17-20 % at various stages compared to 0 kg N/ha (N_1). Since nitrogen is essential for chlorophyll synthesis and leaf expansion during their peak demand, lack of nitrogen stunts photosynthesis (22). Tillering foliar spray (F_2) improved chlorophyll content at 90/135 DAS because it aligns with rapid tiller and leaf growth, directly promoting chlorophyll production. The superiority of the tillering-stage foliar spray (F_2) is likely due to the high metabolic demand for nitrogen during the rapid vegetative growth (23). The three way interaction of M_3, N_3 and F_2 yielding 48.5 SPAD at 90 DAS shows the synergy i.e. bed sowing optimizes the nitrogen absorption by the roots, 100 % recommended dose of nitrogen provides adequate baseline supply and foliar application at tillering stage tops up maximum photosynthesis which is in contrary to the interaction of conventional flat sowing with 0 kg/ha nitrogen and foliar application of nitrogen at crown root initiation stage (Fig. 2).

Canopy temperature was observed to be the highest in conventional flat sowing (F_1) and 0 kg N/ha (N_1) due to the less canopy cover exposing soil, reducing transpirational cooling. An increase in canopy temperature is an indication of physiological stress. A shallow canopy allows more solar radiation to reach the soil surface, increasing the micro-environmental heat absorption. Bed sowing and higher nitrogen improved canopy closure (24). Sufficient nitrogen promotes dense canopy and improves leaf area index (LAI), which increases the rate of transpirational cooling, leading to lower canopy temperature (25). Foliar timing's insignificance arises from its minimal role in early vegetative cooling compared to soil nitrogen's dominance in biomass (26).

Grain quality traits

Nitrogen accumulation is the primary driving factor of wheat protein development. During plant growth, it decomposes the vegetative nitrogen into amino acids, which are then transferred and converted into protein within the grain (27). Since there is a direct connection between nitrogen application and protein levels, farmers can improve the nutrient quality and volume of their yield. This kind of approach ensures modern wheat production with a focus on both quantity and dietary requirements. The interactions between planting geometry, soil nitrogen and foliar timing of nitrogen on protein content were found significantly ($P < 0.05$). Higher protein and Nitrogen content were found to be in M_1 compared to M_2 and M_3 (7.1 % and 14 % increase). This seems contradictory since bed sowing showed better yield compared to conventional flat sowing. This is mainly due to the dilution effect, i.e. bed sowing increases the number of tillers and grains,

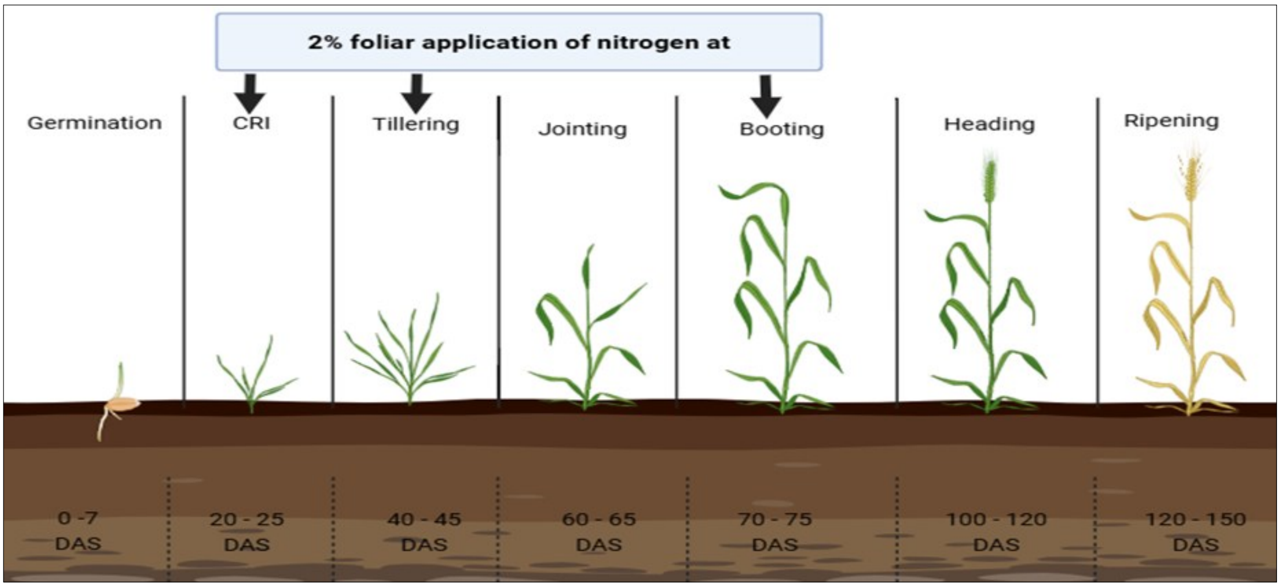

Fig. 2. Foliar application of nitrogen at critical growth stages, as in the sub-sub plot treatment.

partitioning the available nitrogen across a larger sink, leading to a slight reduction in protein concentration per grain (28). However adequate quantity of nitrogen treatment can effectively mitigate the effects by providing sufficient nitrogen to balance both higher yield and improved quality of the plant (29). Foliar timings were found to be statistically similar to each other, since 2 % foliar application of urea provides supplemental rather than primary nitrogen. It was insufficient to overcome soil nitrogen's role in terms of quality (30).

Uptake studies

The result of the study underlines the significant interactive effect between planting geometry, nitrogen application and strategic foliar supplementation of nitrogen in improving nitrogen (N) uptake in wheat crop. Bed sowing was observed to be superior to conventional flat sowing. Bed sowing improved the soil physical properties and minimized water logging; they also enhance root proliferation. They facilitate proper placement of nutrient improving the nutrient availability and use efficiency (31). Hence, M_3 showed 6.7 % increase in grain nitrogen uptake compared to M_1, confirming the significance of spatial arrangement in improving nutrient use efficiency. The optimum level of soil nitrogen is essential to provide the necessary substrates for an increase in photosynthesis and biomass production. The translocation of this nitrogen from vegetative structures to reproductive organs is essential for maintaining the quality of the grains (32). Hence, N_3 (100 % recommended dose of nitrogen) showed the best results in terms of nitrogen uptake. Foliar supplementation of nitrogen during late stages directly supply nitrogen required for protein synthesis, thereby bypassing potential soil immobilisation or leaching losses (33). Hence, foliar nitrogen application at tillering and booting stages showed higher nitrogen uptake compared to the crown root initiation stage. The peak nitrogen accumulation of 95.6 kg/ha in grain demonstrates that maximising wheat quality is not the result of a single factor, but rather the synchronisation of optimal plant spacing, robust soil fertilisation and precise supplemental timing. This synergy effectively mitigates the common biological trade-off between grain volume and nutritional concentration, offering a sustainable pathway for enhancing food security.

Conclusion

From results it is concluded that there is significant synergistic effects between different planting geometries, soil nitrogen application and strategic foliar application of nitrogen which can improve the psychological and uptake qualities of the crop like chlorophyll Index (SPAD), protein content in grains (%), nitrogen content in grains (%) and nitrogen content in straw (%), nitrogen uptake by grain(kg/ha) and nitrogen uptake by straw(kg/ha). The interaction of three-row bed sowing, 100 % recommended soil nitrogen and foliar application at the tillering stage emerged as the most effective strategy, maximising nitrogen uptake in both grain and straw. While bed planting improved the resource use efficiency, strategic foliar application was able to mitigate the soil limitations to improve chlorophyll retention and nitrogen assimilation. The future research should focus more on these interactions across different wheat genotypes and different moisture stress environments to develop site-specific nutrient management protocols for sustainable food security.

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Authors' contributions

MM conducted the field trial, laboratory work, technical analysis and developed the framework of the paper. NR provided guidance and supervision throughout the study. SM carried out the formal review and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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During the preparation of this work, the authors used Grammarly solely for grammar, spelling and punctuation correction at the final editing stage. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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