



Interactive Effects of Plant Geometry and NPK Management on Growth, Yield, and Productivity of Wheat (*Triticum aestivum* L.)

Asif Ali Kaleri

Department of Agronomy, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Email: asifalikaleri2013@gmail.com

Rahim Bux Vistro

Department of Irrigation and Drainage, Faculty of Agricultural Engineering & Technology, Sindh Agriculture University, Tando Jam, Sindh, Pakistan 70060

Nighat Seema Soomro

Department of Agronomy, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Shahzad Ali Tunio

Department of Agronomy, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Naseeruddin

Department of Agronomy, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Gulnaz Talpur

Department of Agronomy, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Mehtab Ali

Department of Plant Breeding and Genetics, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Ali Raza Soomro

Department of Plant Breeding and Genetics, Faculty of Crop Production, Sindh Agriculture University, Tando Jam, Pakistan 70060.

Bina Khanzada

Plant Protection Research Institute, Agriculture Research Center, Tandojam, Sindh, Pakistan 70060.

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ABSTRACT

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Corresponding Author:

Asif Ali Kaleri

Email:

asifalikaleri2013@gmail.com

Plant geometry and (NPK) management significantly ($P \leq 0.05$) influenced all wheat growth parameters. Cross sowing consistently produced the tallest plants, recording 24.31, 66.74, 95.68, and 98.74 cm at 30 DAS, 60 DAS, 90 DAS, and harvest, respectively, while border sowing resulted in the greatest dry matter accumulation (20.12 g plant⁻¹ at harvest). Cross sowing also produced the highest number of tillers (62.81 tillers m⁻¹ row length at 60 DAS) and leaves (23.36 leaves plant⁻¹ at 60 DAS), outperforming traditional sowing by 36.2% and 10.8%, respectively. Increasing NP application significantly enhanced all growth attributes, with the NPK 120:90:60 kg ha⁻¹ treatment producing the maximum plant height (107.68 cm), tillers (74.26 m⁻¹ row length), leaves (26.42 plant⁻¹), and dry matter accumulation (20.98 g plant⁻¹) at their respective peak growth stages. Compared with the control, the highest NPK level increased plant height by 23.0%, tiller number by 110.5%, leaf number by 51.3%, and dry matter accumulation by 32.4% at harvest or peak vegetative growth. Overall, the findings demonstrate that optimizing plant geometry through cross sowing, together with balanced NPK fertilization, substantially improves vegetative growth, biomass accumulation, and crop establishment, while border sowing combined with NPK 120:90:60 ha⁻¹ maximized dry matter production, indicating its potential for enhancing wheat productivity under field conditions.

Introduction

Wheat (*Triticum aestivum* L.) is one of the world's most important cereal crops, serving as a staple food for more than one-third of the global population and contributing approximately 20% of the calories and protein consumed by humans. Increasing wheat productivity is essential to meet the food demands of a rapidly growing population while ensuring sustainable use of natural resources under changing climatic conditions (Manzoor et al., 2024; Ahmed et al., 2023). However, wheat production in many developing countries, including Pakistan, remains below its genetic yield potential due to poor crop management practices, suboptimal plant population, and imbalanced nutrient application (Kaleri et al., 2024(a); Erenstein et al., 2022). Plant geometry is a critical agronomic factor that determines crop growth through its influence on light interception, canopy architecture, photosynthetic efficiency, and resource utilization. Appropriate row spacing and planting arrangement reduce inter-plant competition for light, water, and nutrients while improving aeration and root development (Belete et al., 2018; Gadahi et al., 2024; Kaleri et al., 2024(b)). Cross sowing and optimized planting geometry have been reported to enhance tiller production, leaf area development, dry matter accumulation, and grain yield compared with conventional planting methods (Kaleri et al., 2026; Li et al., 2020). Balanced nutrient management is equally important for maximizing wheat productivity. Nitrogen (N), phosphorus (P), and potassium (K) are the primary macronutrients required in large quantities throughout the wheat growth cycle. Nitrogen promotes vegetative growth, chlorophyll formation, and protein synthesis; phosphorus stimulates root development, energy transfer, and early crop establishment; whereas potassium regulates enzyme activation, water relations, photosynthesis, and tolerance to environmental stresses (Hayyawi et al., 2018; Kubar et al., 2025a; Kaleri et al., 2023). Deficiency of any of these nutrients adversely affects plant growth, biomass accumulation, and final grain yield. Several studies have demonstrated that increasing NPK application within the optimum range significantly improves plant height, tillering, leaf production, dry matter accumulation, spike development, grain number, and grain yield in wheat (Li et al., 2022; Umrani et al., 2024 and Naqeebullah et al., 2024). Nevertheless, excessive fertilizer application may reduce nutrient use efficiency, increase production costs, and contribute to environmental degradation through nutrient losses. Therefore, identifying optimum fertilizer rates in combination with efficient crop management practices has become a major objective of sustainable wheat production. Recent research has emphasized that the interaction between plant geometry and nutrient management plays a vital role in determining crop performance. Optimum plant spacing improves fertilizer utilization by reducing competition among plants and enhancing root exploration of soil nutrients, while balanced fertilization supports vigorous canopy development and efficient interception of solar radiation (Chen et al., 2020; Duan et al., 2019). Consequently, integrating appropriate planting geometry with balanced NPK fertilization can improve growth, nutrient use efficiency, and productivity compared with adopting either practice independently. Although numerous studies have evaluated plant geometry and fertilizer management separately, information regarding their combined effects on wheat growth attributes under local agro-climatic conditions remains limited. Therefore, the present study was conducted to evaluate the influence of different plant geometries and NPK fertilizer levels on plant height, tiller production, leaf development, dry matter accumulation, and overall wheat productivity. The findings are expected to provide a scientific basis for developing integrated agronomic practices that enhance wheat growth, optimize nutrient use efficiency, and improve sustainable wheat production.

Materials and Methods

Field Experiment

A field experiment was conducted during the Rabi season of 2025 at Kaleri Agriculture Farm, located near Sindh Agriculture University (SAU), Tando Jam, Sindh, Pakistan. The experimental site lies in the semi-arid agro ecological zone of Sindh, characterized by mild winters and warm, dry conditions that are favorable for wheat cultivation. The soil of the experimental field was prepared through conventional tillage practices before sowing to ensure a fine seedbed for uniform crop establishment.

Experimental Design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with a factorial arrangement consisting of 12 treatment combinations, replicated three times. Each experimental plot measured 15 m² (5 m × 3 m). The treatments comprised the combination of three planting methods and four nitrogen-phosphorus-potassium (NPK) fertilizer levels.

Planting methods

- P₁:** Traditional sowing
- P₂:** Border sowing

P₃: Cross sowing

Fertilizer levels

F₀: Control (no fertilizer)

F₁: 60:30:15 kg ha⁻¹

F₂: 90:60:30 kg ha⁻¹

F₃: 120:90:60 kg ha⁻¹

The combination of the three planting methods and four fertilizer levels resulted in a total of 12 treatment combinations.

Crop Establishment and Fertilizer Application

The wheat crop was sown according to the designated planting methods using recommended agronomic practices for the region. Nitrogen, phosphorus, and potassium fertilizers were applied according to the respective treatment levels. Phosphorus and potassium were applied as basal doses at sowing, whereas nitrogen was applied in split applications following the recommended fertilizer management practices for wheat to improve nitrogen use efficiency and minimize nutrient losses. All other crop management practices, including irrigation, weed control, and plant protection measures, were kept uniform across all experimental plots throughout the growing season.

Data Collection

Growth observations were recorded from five randomly selected plants from the central rows of each plot to avoid border effects. The selected plants were tagged and used throughout the experiment for recording observations.

The following growth parameters were recorded at different growth stages:

- Plant height (cm)
- Number of tillers per meter row length
- Number of leaves per plant
- Dry matter accumulation (g plant⁻¹)

At crop maturity, yield and yield-related traits were recorded following standard agronomic procedures.

Statistical Analysis

The recorded data were subjected to analysis of variance (ANOVA) appropriate for the Randomized Complete Block Design using Statistix 8.1 statistical software. The significance of treatment effects was evaluated at the 5% probability level ($P \leq 0.05$). Whenever significant differences among treatments were observed, treatment means were separated using the Least Significant Difference (LSD) test following the procedure described by Steel, Torrie, and Dickey (1997).

Results

Effect of Plant Geometry on Plant Height

Table 01 and Graph 01. Plant geometry significantly ($P \leq 0.05$) influenced wheat plant height at all growth stages (Table 1). At 30 DAS, cross sowing produced the tallest plants (24.31 cm), followed by border sowing (23.57 cm), whereas traditional sowing recorded the shortest plants (22.84 cm). A similar trend was observed at 60 DAS, where cross sowing attained the greatest plant height (66.74 cm), followed by border sowing (64.26 cm) and traditional sowing (61.92 cm). At 90 DAS, plant height further increased, reaching 95.68 cm under cross sowing compared with 93.21 cm and 90.14 cm under border and traditional sowing, respectively. At harvest, cross sowing maintained the highest plant height (98.74 cm), which were 2.69% greater than border sowing and 5.96% greater than traditional sowing. These findings indicate that improved plant geometry enhanced crop growth by providing better light interception, aeration, and efficient utilization of soil resources.

Effect of Plant Geometry on Number of Tillers m⁻¹ Row Length

Plant geometry significantly ($P \leq 0.05$) influenced the number of tillers m⁻¹ row length throughout the crop growth period (Table 1 and Graph 01). The number of tillers increased from 30 DAS to 60 DAS, corresponding to the active tillering stage, and declined slightly at 90 DAS due to natural mortality of weaker tillers. Cross sowing produced significantly more tillers than the other planting geometries at all growth stages. At 30 DAS, cross sowing recorded 58.94 tillers m⁻¹, which increased to 62.81 tillers m⁻¹ at 60 DAS before declining slightly to 59.86 tillers m⁻¹ at 90 DAS. Border sowing ranked second with 45.36, 49.18, and 46.74 tillers m⁻¹, while traditional sowing produced the fewest tillers (41.28, 46.12, and 43.58 tillers m⁻¹) at the respective growth stages. Compared with traditional sowing, cross sowing increased tiller production by approximately 42.8%, 36.2%, and 37.4% at 30, 60, and 90 DAS, respectively.

Effect of Plant Geometry on Number of Leaves per Plant

Plant geometry significantly ($P \leq 0.05$) affected the number of leaves per plant throughout the crop growth period (Table 01 and Graph 01). The number of leaves increased from 30 DAS to 60 DAS, reflecting active vegetative growth, and declined slightly at 90 DAS due to the natural senescence of lower leaves. Among the planting geometries, cross sowing produced the highest number of leaves per plant at all growth stages, recording 17.65, 23.36, and 20.71 leaves plant⁻¹ at 30, 60, and 90 DAS, respectively. Border sowing ranked second with 16.22, 22.14, and 19.42 leaves plant⁻¹, while traditional sowing produced the lowest values (14.84, 21.08, and 18.34 leaves plant⁻¹). Compared with traditional sowing, cross sowing increased the number of leaves by 19.0%, 10.8%, and 12.9% at 30, 60, and 90 DAS, respectively. The greater leaf production under cross sowing may be attributed to improved plant spacing, better solar radiation interception, and reduced inter-plant competition.

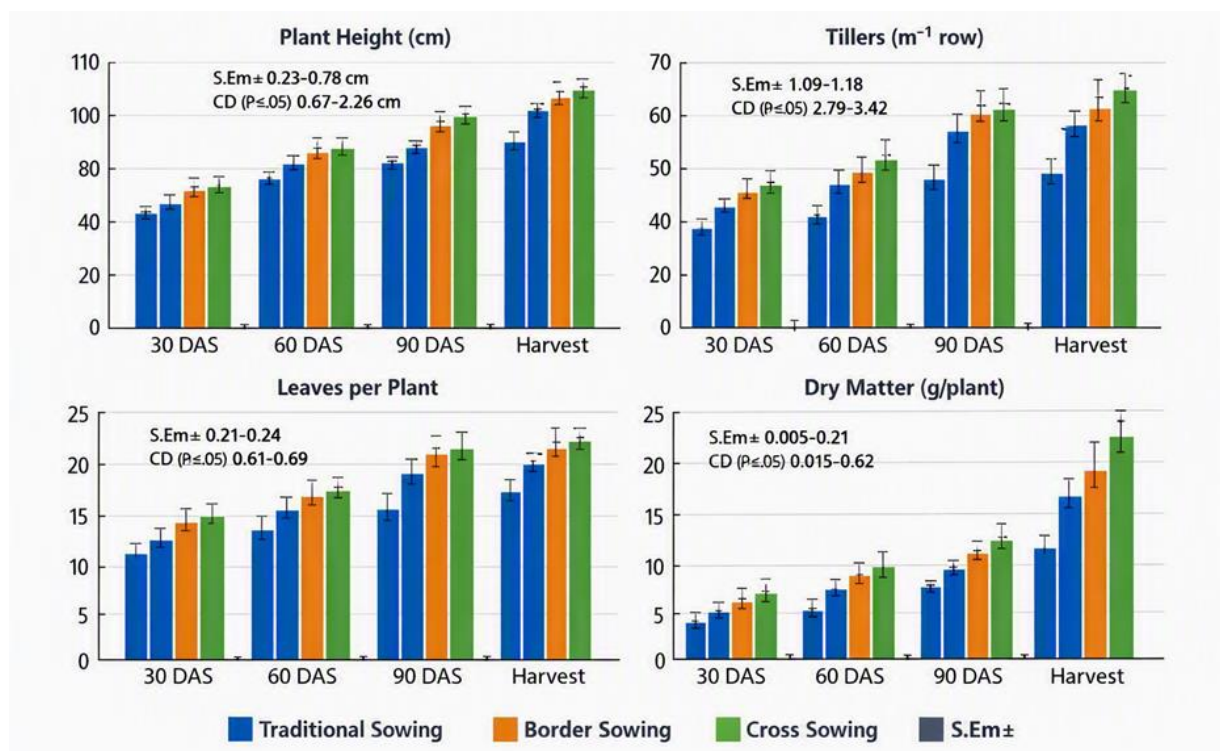
Effect of Plant Geometry on Dry Matter Accumulation

Plant geometry significantly ($P \leq 0.05$) affected dry matter accumulation throughout the crop growth period (Table 01 and Graph 01). Dry matter increased progressively from 30 DAS to harvest under all planting geometries. Among the treatments, border sowing produced the highest dry matter accumulation at every growth stage, recording 0.341, 1.96, 10.74, and 20.12 g plant⁻¹ at 30 DAS, 60 DAS, 90 DAS, and harvest, respectively. Cross sowing ranked second with 0.296, 1.83, 10.08, and 18.46 g plant⁻¹, whereas traditional sowing recorded the lowest dry matter accumulation (0.228, 1.58, 9.42, and 16.24 g plant⁻¹). At harvest, border sowing increased dry matter accumulation by approximately 23.9% compared with traditional sowing. The superior biomass production under border sowing may be attributed to improved canopy architecture, greater interception of solar radiation, and more efficient utilization of soil moisture and nutrients.

Table 1. Interactive Effects of Plant Geometry and NPK Management on Growth, Yield, and Productivity of Wheat.

Growth Attribute	Growth Stage	Traditional Sowing	Border Sowing	Cross Sowing	S.Em±	CD ($P \leq 0.05$)
Plant height (cm)	30 DAS	22.84	23.57	24.31	0.23	0.67
	60 DAS	61.92	64.26	66.74	0.61	1.78
	90 DAS	90.14	93.21	95.68	0.72	2.09
	Harvest	93.18	96.05	98.74	0.78	2.26
Tillers (m ⁻¹ row)	30 DAS	41.28	45.36	58.94	1.18	3.42
	60 DAS	46.12	49.18	62.81	1.09	3.16
	90 DAS	43.58	46.74	59.86	0.96	2.79
Leaves plant ⁻¹	30 DAS	14.84	16.22	17.65	0.21	0.61
	60 DAS	21.08	22.14	23.36	0.24	0.69
	90 DAS	18.34	19.42	20.71	0.22	0.64
Dry matter (g plant ⁻¹)	30 DAS	0.228	0.341	0.296	0.005	0.015
	60 DAS	1.58	1.96	1.83	0.047	0.136
	90 DAS	9.42	10.74	10.08	0.18	0.53
	Harvest	16.24	20.12	18.46	0.21	0.62

(Graph 01) Interactive Effects of Plant Geometry and NPK Management on Growth, Yield, and Productivity of Wheat.



Effect of NPK Management on Wheat Growth Attributes

Effect of (NPK) Management on Plant Height

Table 2 and Graph 02. Shows that NPK management significantly ($P \leq 0.05$) influenced all wheat growth attributes at different growth stages. Plant height increased progressively with increasing NPK levels throughout the crop growth period. At 30 DAS, the tallest plants were recorded with NPK 120:90:60 kg ha⁻¹ (27.82 cm), followed by NPK 90:60:30 kg ha⁻¹ (24.68 cm) and NPK 60:30:15 kg ha⁻¹ (22.56 cm), while the control produced the shortest plants (20.38 cm). A similar trend was observed at 60 DAS (74.26 cm), 90 DAS (103.41 cm), and at harvest (107.68 cm), where the highest NPK level consistently resulted in significantly greater plant height than the lower fertilizer treatments and the control.

Effect of (NPK) Management on Number of Tillers m⁻¹ Row Length

Table 2 and Graph 02. The number of tillers per metre row length also responded significantly to increasing NPK application. At 30 DAS, the maximum tillers (69.50 m⁻¹ row) were recorded under NPK 120:90:60 kg ha⁻¹, compared with 52.38, 41.56, and 32.14 m⁻¹ row under NPK 90:60:30, NPK 60:30:15, and the control, respectively. The same trend continued at 60 DAS and 90 DAS, with the highest NPK treatment producing 74.26 and 70.43 tillers m⁻¹ row, respectively, indicating superior tiller development under adequate nutrient supply.

Effect of (NPK) Management on Number of Leaves per Plant

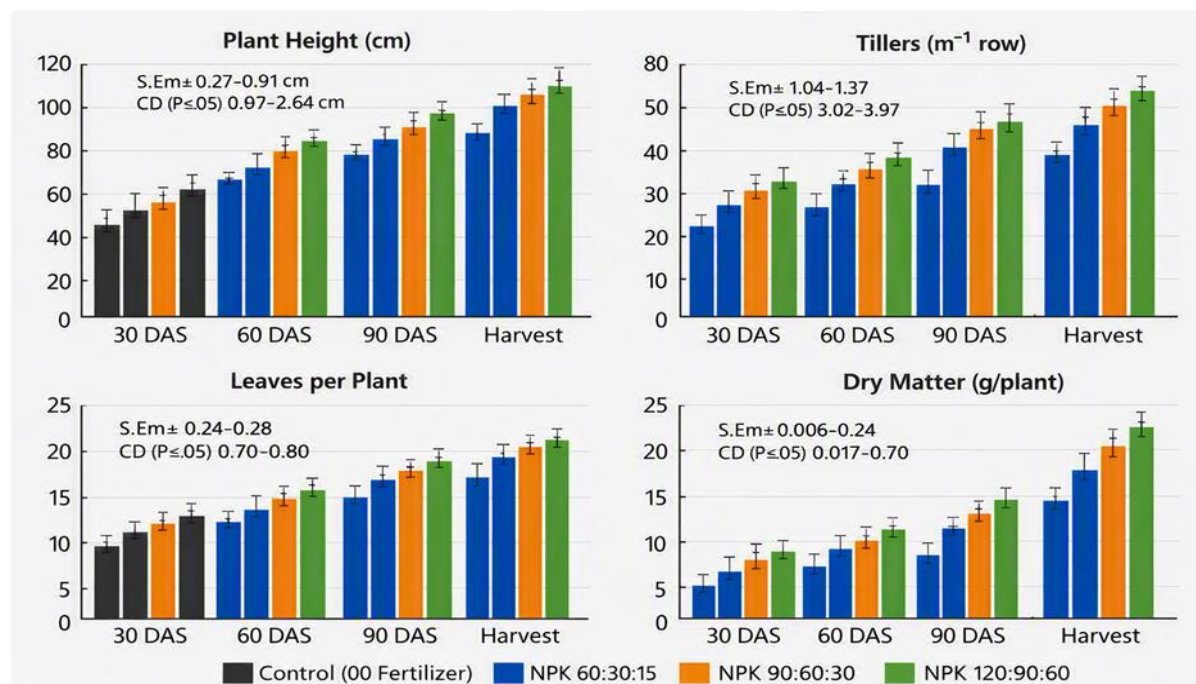
Table 2 and Graph 02. Leaf production was significantly enhanced by increasing fertilizer application. At 30 DAS, plants receiving NPK 120:90:60 kg ha⁻¹ produced the highest number of leaves (22.14 plant⁻¹), whereas the control recorded only 10.86 leaves plant⁻¹. Similar increases were observed at 60 DAS (26.42 leaves plant⁻¹) and 90 DAS (22.86 leaves plant⁻¹), demonstrating that balanced NPK fertilization promoted greater vegetative growth compared with the lower fertilizer levels and the unfertilized control.

Effect of (NPK) Management on Dry Matter Accumulation

Table 2 and Graph 02. Dry matter accumulation increased significantly with increasing NPK application throughout the growing season. At 30 DAS, dry matter ranged from 0.194 g plant⁻¹ in the control to 0.408 g plant⁻¹ under NPK 120:90:60 kg ha⁻¹. At 60 DAS, 90 DAS, and harvest, the highest NPK level produced the greatest dry matter accumulation (2.36, 12.08, and 20.98 g plant⁻¹, respectively), whereas the control consistently recorded the lowest values (1.46, 8.42, and 15.84 g plant⁻¹, respectively). Overall, the application of NPK 120:90:60 kg ha⁻¹ consistently outperformed the lower fertilizer levels and the control, indicating that balanced and higher nutrient supply substantially improved wheat vegetative growth and biomass production.

Table 2. Interactive Effects of Plant Geometry and NPK Management on Growth, Yield, and Productivity of Wheat

Growth Attribute	Growth Stage	Control 00 Fertilizer	NPK 60:30:15	NPK 90:60:30	NPK 120:90:60	S.Em±	CD (P≤0.05)
Plant height (cm)	30 DAS	20.38	22.56	24.68	27.82	0.27	0.79
	60 DAS	54.63	61.85	68.54	74.26	0.71	2.06
	90 DAS	84.72	91.63	96.82	103.41	0.84	2.44
	Harvest	87.54	94.62	100.14	107.68	0.91	2.64
Tillers (m ⁻¹ row)	30 DAS	32.14	41.56	52.38	69.50	1.37	3.97
	60 DAS	35.27	45.02	56.41	74.26	1.25	3.63
	90 DAS	33.18	42.86	53.97	70.43	1.04	3.02
Leaves plant ⁻¹	30 DAS	10.86	14.48	18.36	22.14	0.24	0.70
	60 DAS	17.46	20.84	23.54	26.42	0.28	0.80
	90 DAS	15.38	18.21	20.32	22.86	0.26	0.75
Dry matter (g plant ⁻¹)	30 DAS	0.194	0.236	0.317	0.408	0.006	0.017
	60 DAS	1.46	1.62	1.86	2.36	0.054	0.156
	90 DAS	8.42	9.36	10.34	12.08	0.20	0.59
	Harvest	15.84	17.18	18.76	20.98	0.24	0.70

Graph 02. Interactive Effects of Plant Geometry and NPK Management on Growth, Yield, and Productivity of Wheat.

Discussion

Effect of Plant Geometry on Wheat Growth Attributes

Plant geometry significantly influenced wheat growth throughout the growing season. Cross sowing produced taller plants, more tillers, and a greater number of leaves, while border sowing recorded the highest dry matter accumulation. These improvements can be attributed to better plant distribution, enhanced light interception, reduced inter-plant competition, and more efficient utilization of soil moisture and nutrients. Similar findings were reported by Mohammadi et al., 2015 and Zhang et al., 2013) who concluded that optimum planting geometry improves canopy architecture, photosynthetic efficiency, and crop growth. Likewise, (Chauhan et al., 2014; Rathod et al., 2026), and (Sharma et al., 2022) observed that improved spacing enhanced tiller production and productive tiller survival. The greater dry matter accumulation under border sowing agrees with the findings of (Haque et al., 2015) and (Hussain et al., 2012), who reported that improved canopy structure enhances radiation use efficiency, assimilate partitioning, and biomass production. Overall, these results demonstrate that optimized plant geometry enhances wheat growth by improving resource-use efficiency and creating favorable conditions for vegetative development. Overall, the findings suggest that optimizing plant geometry enhances wheat growth by improving canopy architecture, increasing radiation interception, reducing inter-plant competition, and facilitating efficient utilization of available soil resources.

Effect of NPK Management on Wheat Growth Attributes

Balanced NPK management significantly improved plant height, tiller production, leaf number, and dry matter accumulation, with the highest values consistently recorded under NPK 120:90:60 kg ha⁻¹. These improvements are attributed to the complementary roles of nitrogen in promoting vegetative growth and chlorophyll synthesis, phosphorus in enhancing root development and energy transfer, and potassium in regulating photosynthesis, enzyme activity, and assimilate translocation. Similar findings have been reported by (Ghimire et al., 2021). Wan et al., 2022), Sharma et al., 2017), Irshad et al., 2018), and Chen et al. (2020), who observed significant increases in wheat growth under balanced NPK fertilization. Likewise, Ullah et al., 2024), Shah et al., 2015), and Rashid et al., 2014) reported that adequate nutrient supply enhances tillering, leaf development, photosynthetic efficiency, and biomass accumulation, ultimately leading to improved wheat productivity. Overall, the results indicate that balanced application of NPK 120:90:60 kg ha⁻¹ is an effective nutrient management strategy for promoting vigorous growth and maximizing wheat biomass production. Overall, the findings demonstrate that integrating optimized plant geometry with balanced NPK fertilization significantly enhances wheat growth and productivity. Improved planting geometry promotes better canopy architecture, greater light interception, reduced inter-plant competition, and more efficient utilization of soil

moisture and nutrients, while balanced NPK application enhances plant height, tiller production, leaf development, and dry matter accumulation through improved physiological and metabolic processes. Among the fertilizer treatments, NPK 120:90:60 kg ha⁻¹ consistently produced the best growth performance, indicating that adequate nutrient availability, combined with efficient crop spatial arrangement, maximizes nutrient use efficiency, biomass production, and overall wheat productivity. These findings highlight the importance of integrating appropriate plant geometry with balanced nutrient management as a sustainable agronomic strategy for improving wheat performance under field conditions.

Conclusion

Plant geometry and (NPK) management significantly ($P \leq 0.05$) influenced all wheat growth parameters. Cross sowing consistently produced the tallest plants, recording 24.31, 66.74, 95.68, and 98.74 cm at 30, 60, 90 DAS and harvest, respectively, while border sowing resulted in the greatest dry-matter accumulation (20.12 g plant⁻¹ at harvest). Cross sowing also produced the highest number of tillers (62.81 m⁻¹ row length at 60 DAS) and leaves (23.36 plant⁻¹ at 60 DAS), outperforming traditional sowing by 36.2 % and 10.8 %, respectively. Increasing NPK application significantly enhanced all growth attributes, with the NPK 120:90:60 kg ha⁻¹ treatment producing the maximum plant height (107.68 cm), tillers (74.26 m⁻¹ row length), leaves (26.42 plant⁻¹), and dry-matter accumulation (20.98 g plant⁻¹) at their respective peak growth stages. Compared with the control, the highest NPK level increased plant height by 23.0 %, tiller number by 110.5 %, leaf number by 51.3 %, and dry-matter accumulation by 32.4 % at harvest or peak vegetative growth.

Overall, the findings demonstrate that optimizing plant geometry through cross sowing, together with balanced NPK fertilization, substantially improves vegetative growth, biomass accumulation, and crop establishment. Meanwhile, border sowing combined with NPK 120:90:60 kg ha⁻¹ maximized dry-matter production, indicating its potential for enhancing wheat productivity under field conditions.

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