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Productivity of Wheat (*Triticum aestivum* L) varieties as influenced by Seed rate and plant population density in the Nigerian Sahel savanna

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ABSTRACT

Wheat (Triticum aestivum L.) production in the Nigerian Sahel Savanna remains limited by suboptimal seed rate and plant spacing practices that constrain yield potential. This study evaluated the effects of variety, seed rate, and plant spacing on growth, yield components, and grain yield of wheat during the 2021 and 2022 cold dry seasons at the Flour Milling Association of Nigeria Research Farm, Ringim, Jigawa State. The experiment was arranged in a randomised complete block design with three replications, using two varieties (Borloug and Norman), three seed rates (100, 150, and 200 kg ha^{-1}), and three spacings (0, 15, and 30 cm). Results revealed significant ($p < 0.05$) main and interaction effects on most agronomic and yield traits. Borloug consistently outperformed Norman in 1000-grain weight and grain yield (up to 4.68 t ha^{-1}), while Norman produced more grains per spike, reflecting genotypic differences in assimilate partitioning. Moderate seed rate (150 kg ha^{-1}) and wider spacing (30 cm) enhanced spike length, spike density, and yield components, whereas excessive seeding reduced productivity due to competition stress. The three-way interaction showed that Borloug at 100 kg ha^{-1} with 30 cm spacing achieved the highest grain yield, while Norman at 200 kg ha^{-1} and 15 cm spacing exhibited superior spike fertility. These results emphasise the need for genotype-specific density and spacing management to optimise yield in semi-arid conditions. It is recommended that Borloug be cultivated at 100–150 kg ha^{-1} with 30 cm spacing for optimal performance under irrigated Sahelian wheat systems.

Keywords: *Wheat, seed rate, spacing, variety, yield components, Sahel Savanna.*

1.0 Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereal crops in the world and serves as a vital source of carbohydrates and proteins for human nutrition. Despite its global importance, wheat production in sub-Saharan Africa, particularly in Nigeria, remains significantly below the global average due to various agronomic and environmental challenges. In the Nigerian Sahel Savanna, where rainfall is erratic and temperatures are high, yield performance is constrained by inappropriate seed rate management, poor plant population density, and suboptimal varietal selection [16]. Studies have shown that inappropriate seed rates and plant densities can cause severe intra-specific competition among wheat plants, leading to reduced nutrient, light, and moisture availability, thereby lowering yield potential [17][8]. Understanding the interaction between seed rate, plant density, and wheat varietal performance under Sahelian conditions is therefore essential for improving productivity and ensuring sustainable cereal production in this agroecological zone [14][21].

The problem of low wheat yield in Nigeria is becoming increasingly urgent. While the global average yield of wheat exceeds 3.5 t/ha, the Nigerian average remains below 2.5 t/ha [22][23]. This persistent yield gap is largely attributed to the poor optimisation of seeding rates and plant population densities, which affect stand establishment and resource use efficiency [30]. Overly dense planting results in competition for limited soil moisture and nutrients, while sparse planting leaves large portions of land underutilised, reducing potential yield per hectare. The lack of locally validated data on optimal seed rates and plant populations for modern wheat varieties in the Nigerian Sahel has limited the development of precise agronomic guidelines and the achievement of the national target for wheat self-sufficiency.

This study is justified by the need to generate empirical data that can guide farmers, policymakers, and agricultural extension services in adopting efficient and sustainable wheat production practices in the Sahel Savanna. The Nigerian government's renewed drive toward achieving wheat self-sufficiency and reducing import dependence underscores the importance of improving productivity through agronomic optimisation [26]. Furthermore, optimising seed rate and plant density will enhance resource use efficiency, reduce production costs, and improve the resilience of wheat systems to climatic variability [29]. The outcomes of this research will contribute to sustainable agricultural intensification, improved livelihoods of farmers, and the overall enhancement of food security in northern Nigeria.

The overarching objective of this study is to evaluate the productivity of wheat varieties as influenced by seed rate and

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plant population density in the Nigerian Sahel Savanna. Specifically, the study aims to determine the effects of different seed rates on the growth and yield performance of selected wheat varieties, assess the influence of varying plant population densities on yield components, and identify the interaction effects between seed rate, plant population density, and varietal response. The ultimate goal is to recommend the optimal combination of these agronomic factors to achieve higher productivity under Sahelian environmental conditions.

The theoretical foundation of this study is based on the Resource Use Efficiency Theory and the Plant Competition Theory. According to the Resource Use Efficiency Theory, crop productivity is maximised when plants utilise available resources such as light, water, and nutrients with minimal waste and maximum conversion efficiency [26]. On the other hand, the Plant Competition Theory posits that excessive plant density intensifies competition among individuals for limited resources, resulting in reduced per-plant performance, while overly low density underutilises environmental inputs and potential yield [39]. Therefore, the balance between seed rate and population density represents a critical agronomic decision that determines the overall productivity and efficiency of wheat cultivation under the challenging climatic conditions of the Nigerian Sahel Savanna.

2.0 Materials and Methods

The field experiment was conducted during the 2021 and 2022 cold dry seasons at the Flour Milling Association of Nigeria Research Farm, Ringim Local Government Area, Jigawa State, located within the Sahel Savanna agro-ecological zone of Nigeria. The area is characterised by a semi-arid climate with low annual rainfall and high evapotranspiration, necessitating irrigation for wheat production.

Before planting each season, composite soil samples were collected from the experimental field at a depth of 0–30 cm and analysed for key physical and chemical properties such as pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium. These analyses provided baseline information for nutrient management and interpretation of crop performance.

The experiment was laid out in a 3-factor factorial arrangement (2 × 3 × 3) in a Randomised Complete Block Design (RCBD) with three replications. Treatments consisted of two wheat varieties (Borloug and Norman), three seed rates (100, 150, and 200 kg ha^{-1}), and three inter-row spacings (0, 15, and 30 cm). Each treatment combination was assigned to a plot measuring 5 m × 3 m, resulting in 18 treatment combinations and 54 experimental units in total. Land preparation involved ploughing, harrowing, and levelling to create a fine, uniform seedbed. Seeds of each variety were sown manually in rows at the designated spacing and seed rates. Fertiliser was applied based on regional recommendations for irrigated wheat, at a rate of 120 kg N, 40 kg P_2O_5, and 40 kg K_2O ha^{-1}. Half of the nitrogen and all of the phosphorus and potassium were applied at planting using NPK 15:15:15, while the remaining nitrogen was top-dressed as urea at the tillering stage.

Irrigation was provided through furrow irrigation to ensure adequate soil moisture throughout the growing period, especially at critical growth stages such as tillering, booting, and grain filling. Weed control was achieved through a combination of pre-emergence application of Pendimethalin (1.0 kg a.i. ha^{-1}) one day after sowing, followed by manual weeding at 40 days after planting.

Pest and disease management was carried out as needed through regular field scouting and timely application of recommended control measures.

Harvesting was done manually at physiological maturity when the spikes turned golden-yellow and grains hardened. Data were collected on key agronomic and yield parameters, including days to heading, plant height, number of spikes per square meter, spike length, number of grains per spike, 1000-grain weight, grain yield per plot, and grain yield per hectare.

All collected data were subjected to Analysis of Variance (ANOVA) using GenStat (17th Edition) to determine treatment effects. Where significant differences were detected ($P < 0.05$), means were separated using the Student-Newman-Keuls (SNK) test to compare treatment combinations for variety, seed rate, and spacing effects.

3.0 Results and Discussion

3.1 Growth characters

Table 1 presents plant height, days to heading, and physiological maturity of wheat as influenced by seed rate, spacing, and variety during the 2021 and 2022 cold dry seasons. Results show that both seed rate and spacing had significant ($p < 0.05$) effects on plant height and days to heading, while varietal differences were highly significant ($p < 0.001$) for all measured traits.

Variety had a profound effect on vegetative and phenological development across both seasons. *Norman* consistently produced taller plants (93.33 cm and 92.37 cm in 2021 and 2022, respectively) and exhibited longer durations to heading and physiological maturity compared to *Borloug*. This indicates that *Norman* is a late-maturing genotype with more vigorous vegetative growth and prolonged photosynthetic activity, possibly due to genetic differences in thermal time accumulation and photoperiod response. Similar varietal patterns have been documented under Sahelian and semi-arid conditions, where genotypes with longer growth duration accumulate greater biomass but risk exposure to terminal heat and moisture stress [34, 35] [40]. In contrast, *Borloug* showed shorter durations to heading (64.21 and 56.93 days) and maturity (104.89 and 105.19 days), confirming its early-maturing and potentially heat-escape characteristics advantageous in the Sahel Savanna environment [36].

Seed rate also significantly ($p < 0.001$) influenced plant height and phenology. Increasing the seed rate from 100 to 200 kg ha^{-1} led to a progressive increase in plant height (from 87.33 to 87.61 cm in 2021; 85.28 to 89.39 cm in 2022) and delayed days to heading (from 56.28 to 63.80 days in 2021; 61.83 to 63.11 days in 2022). This suggests that higher seed densities intensify interplant competition for light, nutrients, and moisture, promoting stem elongation but delaying reproductive transition [13][30]. However, excessively high seed rates can lead to resource competition and reduced tillering efficiency. The moderate seed rate (150 kg ha^{-1}) produced balanced growth and timely heading, indicating optimal stand density for Sahelian wheat cultivation. These findings agree with those of [17], who reported that intermediate seeding densities maximise yield components by balancing competition and resource utilisation.

Spacing significantly ($p < 0.001$) affected plant height and days to heading but not physiological maturity. Wider spacing (30 cm) resulted in taller plants (89.44 cm in 2021 and 89.39 cm in 2022) and delayed heading, whereas narrower spacing (0-15 cm) produced shorter plants with earlier heading.

This trend reflects reduced interplant competition at wider spacing, allowing greater canopy expansion and delayed transition to the reproductive stage [29]. The non-significant effect of spacing on physiological maturity suggests that final crop duration may depend more on genotypic traits than spatial arrangement. These results corroborate findings from similar semi-arid studies where optimal plant spacing (20–30 cm) improved photosynthetic efficiency and reduced competition stress [15].

Table 1: Plant height, Days to Heading and Physiological maturity of Wheat varieties as affected by Seed rate and spacing during 2021 and 2022 Cold dry seasons

Treatment	2021			2022		
	Plant Height (cm)	Days to Heading	Days to Physiological Maturity	Plant Height (cm)	Days to Heading	Days to Physiological Maturity
Variety (V)						
Borloug	82.33b	64.21a	104.89a	81.30b	56.93b	105.19b
Norman	93.33a	56.08b	117.93b	92.37a	67.82a	114.89a
p.value	<.0001	<.0001	<.0001	<.0001	<.0001	0.0127
SE±	0.3009	0.0692	0.3694	0.4955	0.1309	2.6169
Seed rate (Sr)						
100	87.33	56.28c	110.28b	85.28b	61.83b	105.61
150	88.56	60.36b	111.78a	85.83b	62.17b	112.17
200	87.61	63.80a	112.17a	89.39a	63.11a	112.33
p.value	0.0612	<.0001	0.0135	0.0058	<.0001	0.2523
SE±	0.3685	0.0847	0.4525	0.6069	0.1604	3.2047
Spacing (S)						
0	86.89b	56.24c	111.33	85.28b	62.22	112.50
15	87.17b	60.18b	111.72	85.83b	62.67	111.94
30	89.44a	64.01a	111.17	89.39a	62.22	105.67
p.value	<.0001	<.0001	0.6753	<.0001	0.0913	0.2592
SE±	0.3651	0.0847	0.4524	0.6069	0.1604	3.2048
Interaction						
V x Sr	0.0308	<.0001	0.1776	0.0169	<.0001	0.3993
V x S	<.0001	<.0001	0.1467	<.0001	0.0047	0.3697
Sr x S	0.0417	<.0001	0.2324	0.0033	0.0007	0.3734
V x Sr x S	<.0001	<.0001	0.1185	0.0083	<.0001	0.3768

Means in a column sharing the same letter are not significantly different at 5 % level of probability using SNK

Interaction Effects on Plant Height of Wheat

The interactive effects of variety, seed rate, and spacing significantly influenced the plant height of wheat across both seasons, reflecting strong varietal adaptability and management-dependent growth responses. The Variety × Seed Rate interaction (Figure 1) showed that Norman consistently produced taller plants (up to 94.44 cm in 2021 and 94.33 cm in 2022) compared to Borloug (81–83 cm), especially at moderate seed rates (150-200 kg ha^{-1}). This suggests that Norman, being late-maturing, responds more positively to higher plant density, while Borloug's height declined slightly under crowding due to earlier reproductive transition and competition stress. Similar genotype-dependent density responses were reported by [3] [5], who observed that tall, late-maturing cultivars-maintained elongation under denser stands.

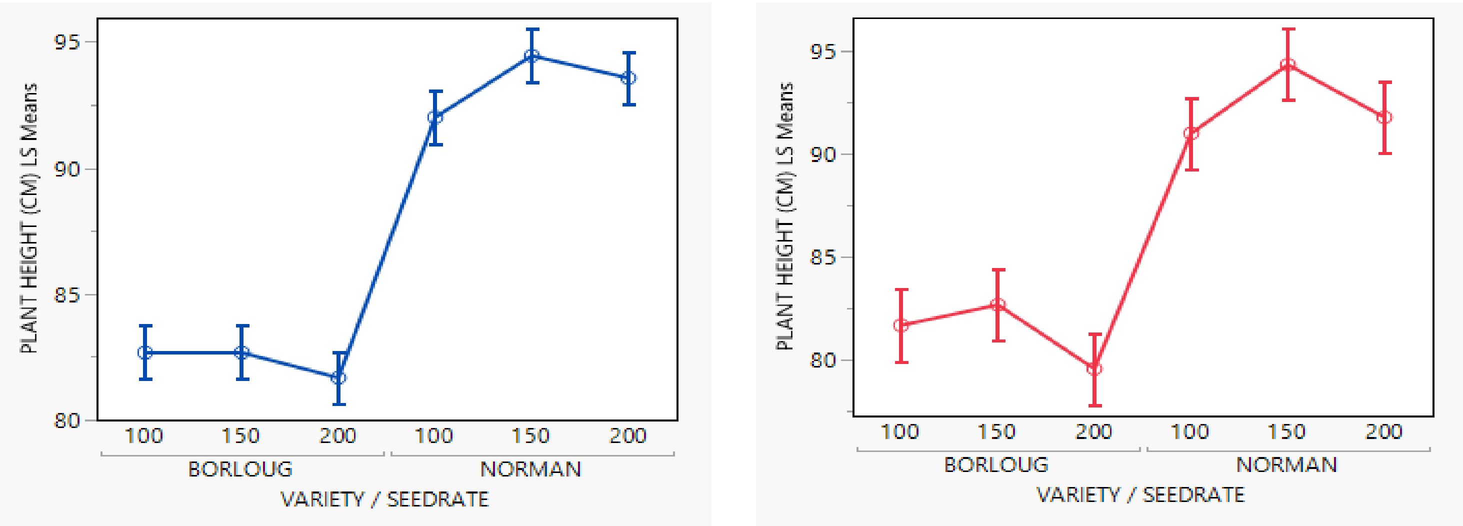


Figure 1: Interaction of Variety and Seed rate on Plant height of wheat during the 2021 and 2022 Cold dry season

The Variety × Spacing interaction indicated that plant height increased with wider spacing for both varieties (Figure 2), but the response was more pronounced in Norman (94.88 cm at 0 cm spacing vs. 93.33 cm at 30 cm) than Borloug (78.88-85.55 cm). Norman maintained greater height across all spacing levels, implying stronger canopy plasticity and better resource-use efficiency under crowding. Wider spacing likely reduced interplant competition, enhancing photosynthetic efficiency and nutrient uptake, as noted by [32].

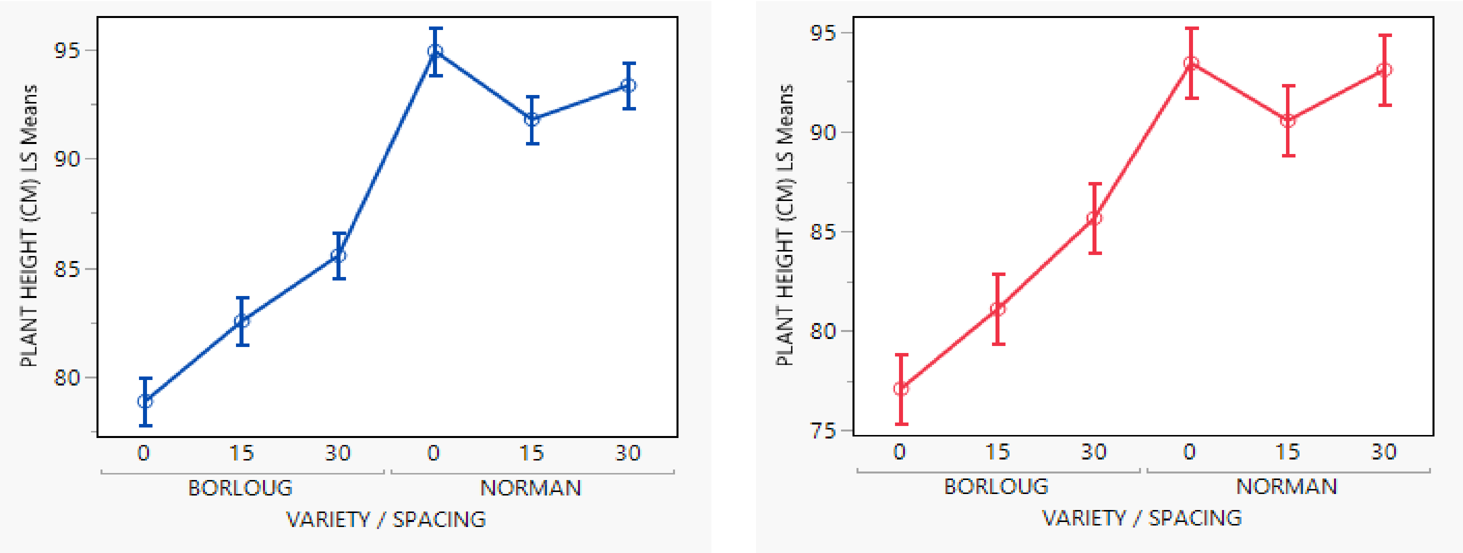


Figure 2: Interaction of Variety and Spacing on Plant height of wheat during the 2021 and 2022 Cold dry season

Similarly, the Seed Rate × Spacing interaction (Figure 3) revealed that plant height increased with both higher seed rates and wider spacing, reaching 90–92 cm under 150 kg ha^{-1} and 30 cm spacing in both years. This balance between density and space optimized light interception and nutrient availability per plant. Comparable findings by [1] and [37] confirm that moderate density combined with adequate spacing promotes better canopy development under Sahelian conditions.

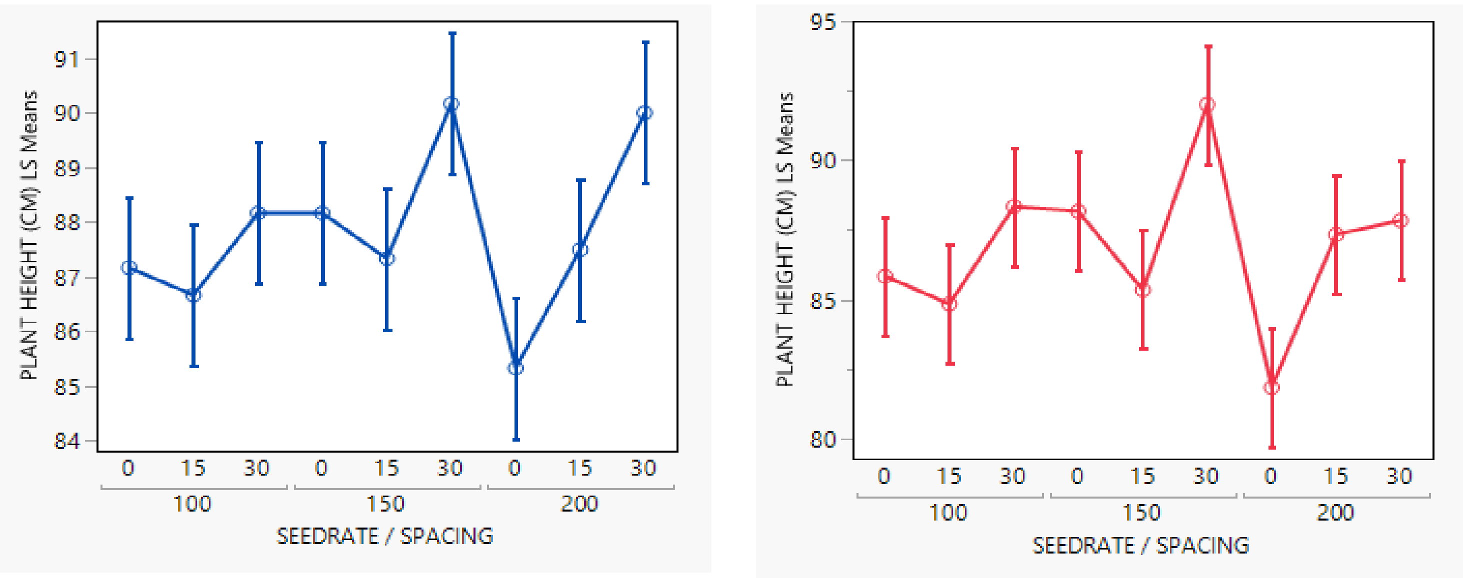


Figure 3: Effect of Seed rate and spacing on Plant height of wheat during the 2021 and 2022 Cold dry season

Figure 4 a & b shows the three-way interaction (Variety × Seed Rate × Spacing) which further demonstrated that Norman exhibited superior plant height (up to 99 cm in 2021 and 68.66 cm in 2022) under moderate to high seed rates (150–200 kg ha^{-1}) and moderate spacing (15–30 cm), while Borloug remained shorter (77–85 cm, 54–59 cm respectively) across most treatments. This indicates that Norman's tall structure and delayed phenology favor vegetative growth under optimal density, whereas Borloug's early maturity and reduced internode elongation limit height under crowding. Similar varietal-specific interactions under semi-arid conditions were reported by [11] and [9].

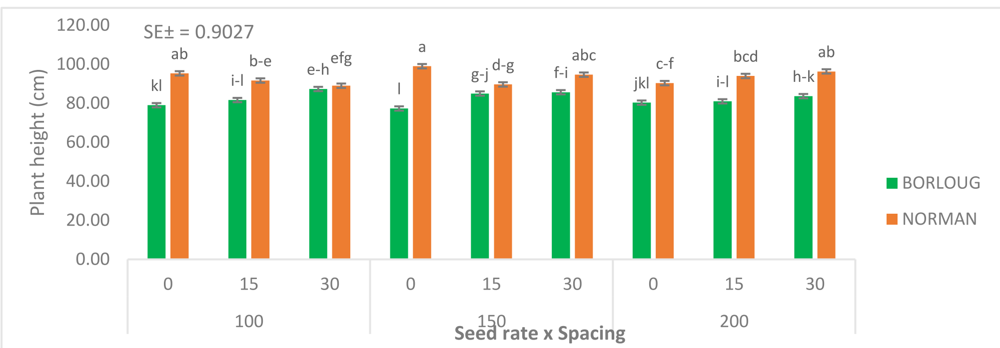


Figure 4a: Interaction of Variety, Seed rate and Spacing on plant height of wheat during the 2021 cold dry season

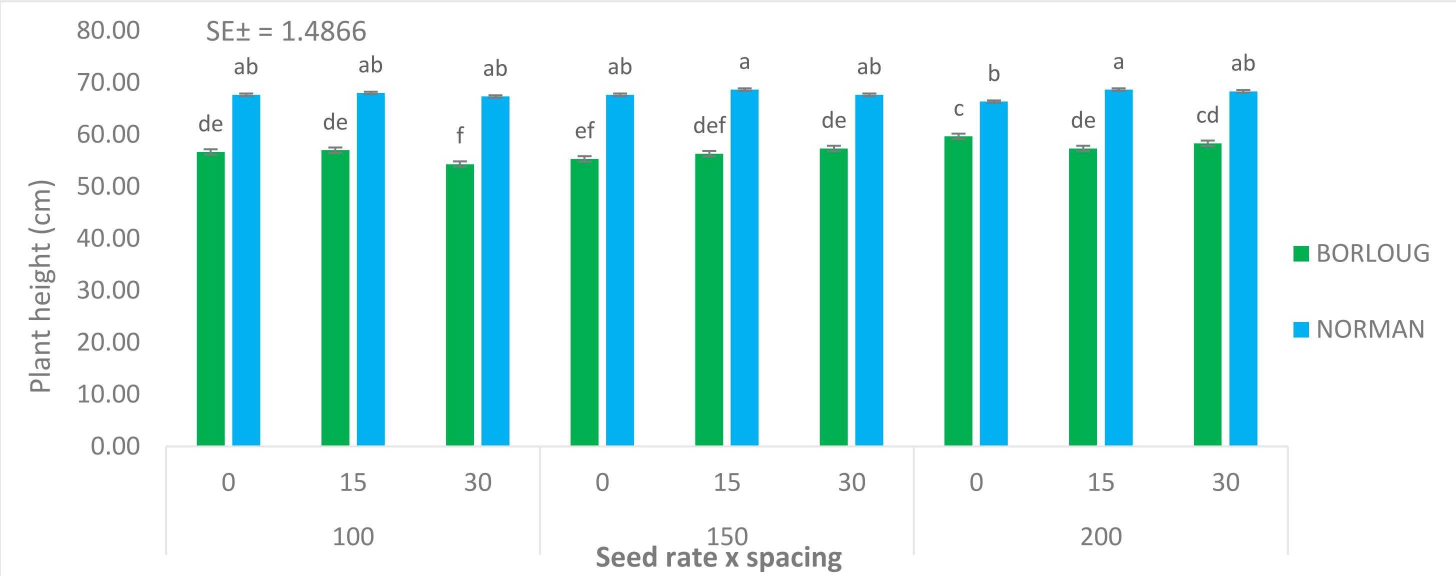
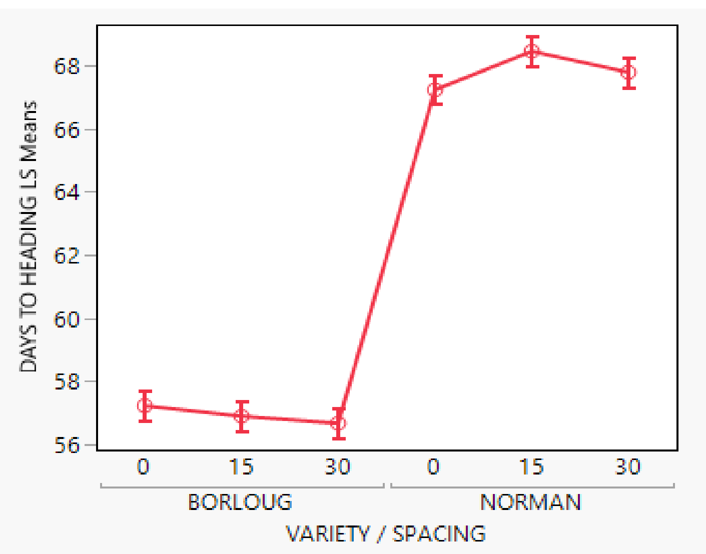


Figure 4b: Interaction of Variety, Seed rate and Spacing on plant height of wheat during the 2022 cold dry season

The Variety × Seed rate interaction is shown in Figure 5 and revealed that Norman consistently headed later (up to 68 days) than Borloug (56–58 days), particularly at higher seed rates (150–200 kg ha^{-1}), indicating that Norman's longer vegetative phase is enhanced under denser canopies, while Borloug's earlier heading reflects its rapid development and adaptability to short-season environments.

Similarly, the Variety × Spacing interaction (Figure 6) demonstrated that Norman maintained delayed heading across all spacings (67–68 days), whereas Borloug's heading was progressively delayed with wider spacing (59–68 days), suggesting that reduced interplant competition prolongs vegetative growth through improved light and nutrient availability. The Seed Rate × Spacing interaction (Figure 7) further revealed that heading was delayed at higher seed rates and wider spacing (up to 67 days in 2021), reflecting enhanced resource use and slower canopy closure. Overall, moderate seed rates (150 kg ha^{-1}) and intermediate spacing (15 cm) produced balanced phenology, optimizing thermal use efficiency under Sahelian conditions. These patterns agree with reports by [5], [19] and [33], which emphasize that genotype and planting geometry jointly determine wheat's developmental timing under semi-arid environments.



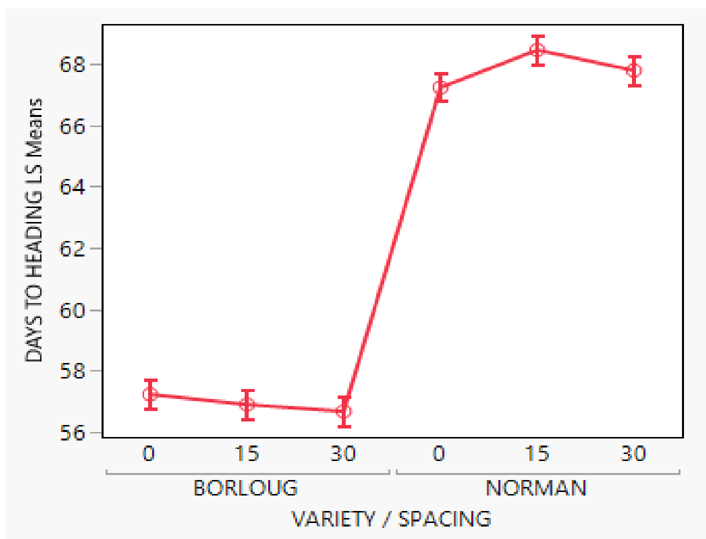


Figure 5: Interaction of Variety and Seed rate on Days to Heading of wheat during 2021 and 2022 the 2022 cold dry season

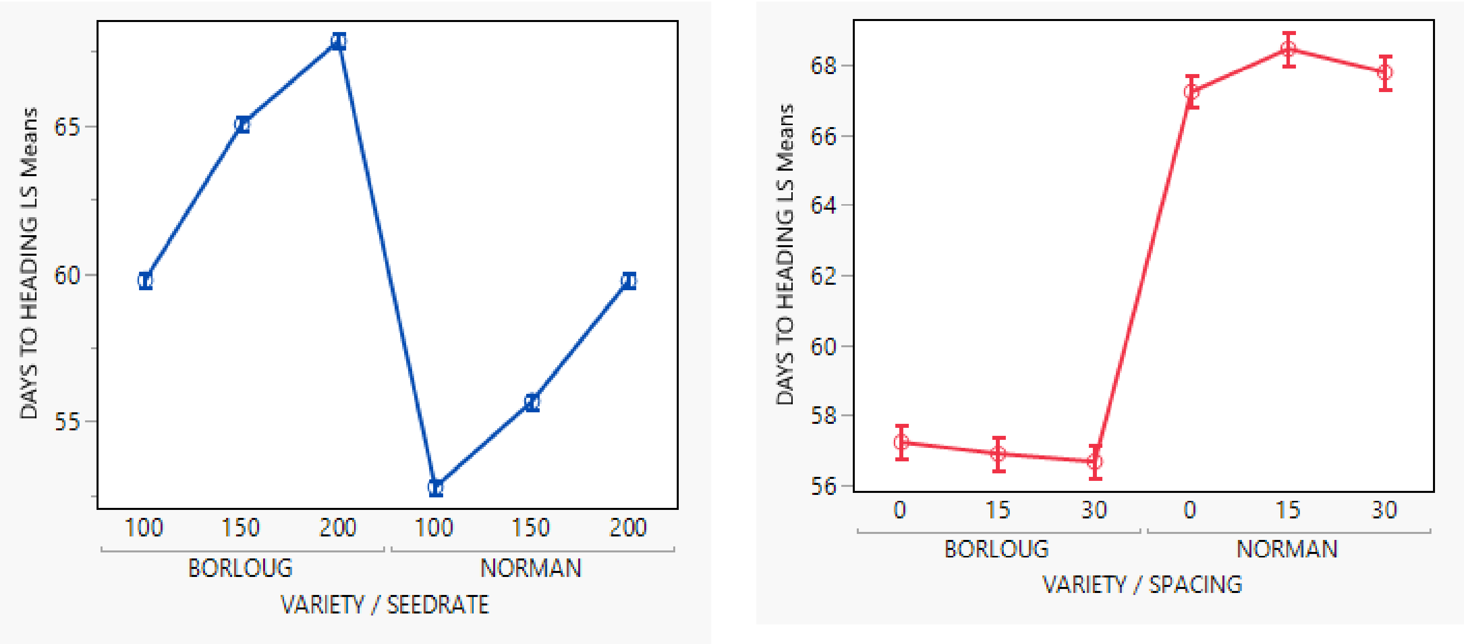


Figure 6: Interaction of Variety and spacing on Days to Heading of wheat during the 2022 cold dry seasons

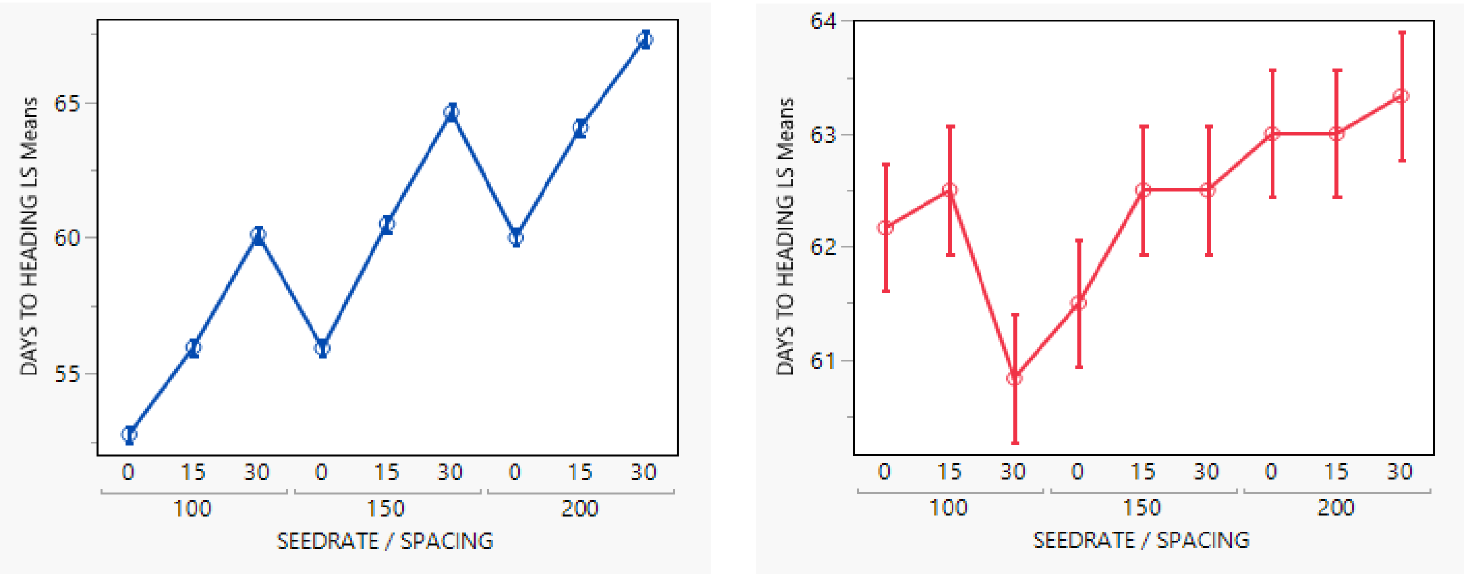


Figure 7: Interaction of Seed rate and spacing on Days to Heading of wheat during the 2022 cold dry seasons

The three-way interaction of variety, seed rate, and spacing on days to heading revealed distinct genotype-specific and management-dependent responses across both seasons. In 2021 (Figure 8a), Norman consistently exhibited delayed heading (52–66 days) compared to Borloug (53–69 days), with the delay most pronounced under higher seed rates (150–200 kg ha^{-1}) and wider spacing (30 cm). This indicates that Norman's late-maturing nature allows it to maintain a prolonged vegetative phase even under dense stands, while Borloug's heading was more responsive to spacing and seed rate, showing the longest delay (69 days) at 150–200 kg ha^{-1} and 30 cm spacing due to reduced interplant stress and improved assimilate accumulation.

In 2022 (Figure 8b), similar trends were observed. Norman maintained significantly later heading (67–69 days) across all treatments, while Borloug headed earlier (54–59 days). The consistency of Norman's phenological delay under all density and spacing combinations highlights its strong genotypic control of developmental timing and better adaptation to extended cool periods. In contrast, Borloug's earlier heading at higher density and narrow spacing suggests a stress-escape mechanism typical of early-maturing cultivars under Sahelian heat conditions.

In general, the interaction demonstrates that Norman's phenology is largely genotype-driven, while Borloug's is more sensitive to management variables such as spacing and seed rate. These findings agree with reports by [24] [20] and [7], who found that the combined effects of genotype, seed rate, and spacing regulate wheat's transition to heading through altered canopy structure, thermal accumulation, and light interception efficiency in semi-arid environments.

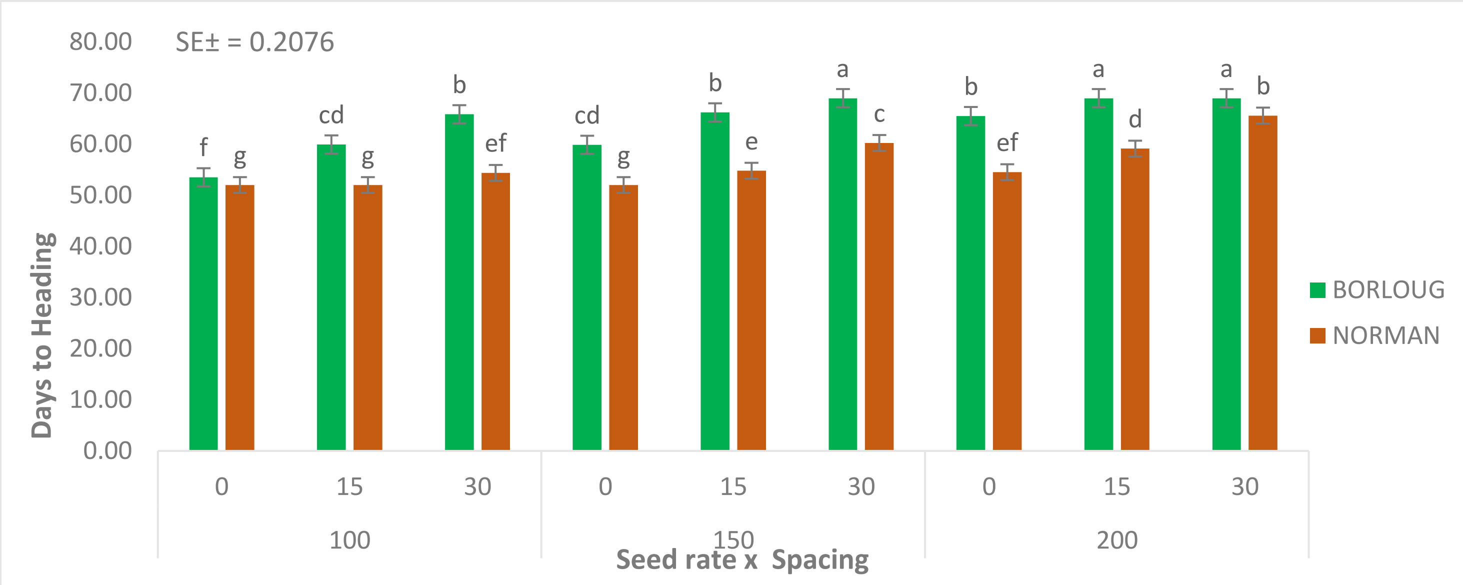


Figure 8a: Interaction of Variety, Seed rate and Spacing on Days to Heading of wheat during the 2021 cold dry season

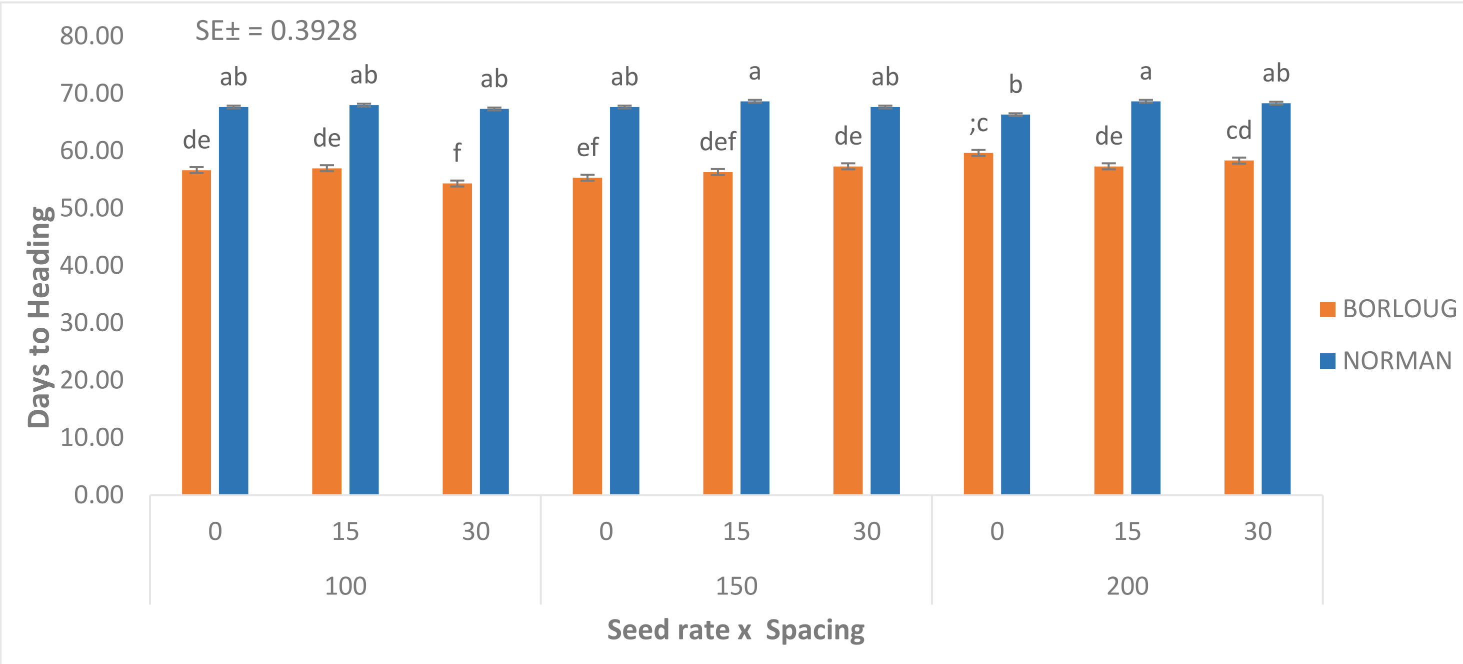


Figure 8b: Interaction of Variety, Seed rate and Spacing on Days to Heading of wheat during the 2022 cold dry season

3.2 Yield and yield-related components of wheat

Table 2 presents the effects of seed rate and spacing on yield components (number of spikes per square meter, spike length, and number of grains per spike) of two wheat varieties during the 2021 and 2022 cold dry seasons. Results revealed significant influences of variety, seed rate, and spacing, with notable interactions across seasons. Varieties differed significantly in the number of grains per spike but not in spike density or spike length during 2021. Norman produced more grains per spike (52.04) than Borloug (48.04), indicating superior reproductive efficiency, a trend consistent in 2022, though Borloug recorded slightly higher spike density. This reflects genotypic differences in assimilate partitioning and spike fertility, key determinants of final grain yield, as supported by [2] Alqudah et al. (2020). The stability of spike length across varieties further suggests this trait is more genetically controlled [18].

Seed rates significantly ($p < 0.001$) affected spike length and grains per spike but not spike density. The highest seed rate (200 kg ha^{-1}) produced shorter spikes and fewer grains, implying excessive intra-plant competition limited spike development [39]. In contrast, 100 kg ha^{-1} resulted in longer spikes (9.25 cm) and more grains (51.44), reflecting efficient resource use under moderate density, consistent with [27], who noted optimal seeding rates maximise spike fertility and spike length by reducing competition.

Plant spacing strongly ($p < 0.001$) influenced all spike traits in both years. Wider spacing (30 cm) produced the highest spike density (354.78 m^{-2}) and spike length (9.72 cm), while closer spacing (0 cm) reduced these values. This suggests that adequate spacing enhances photosynthetic efficiency and assimilate supply per plant, promoting reproductive growth as reported by [20]. Similarly, increased grains per spike under wider spacing align with [12], who reported that reduced interplant competition enhances spikelet fertility and grain formation. The interaction between experimental factors were significant across the two seasons and are presented below.

Table 2: Number of spikes per square meter, Spike length and Number of grains per spike of Wheat varieties as affected by Seed rate and spacing during 2021 and 2022 Cold dry seasons

Treatment	2021				2022		
	Number of spike m^{-2}	Spike length (Cm)	Number of grains $Spike^{-1}$		Number of spike m^{-2}	Spike length (Cm)	Number of grains $Spike^{-1}$
Variety (V)							
Borloug	332.00	9.04	48.04b		336.78a	9.26	49.67
Norman	332.74	8.95	52.04a		316.30b	9.01	51.70
p-value	0.9104	0.6654	<.0001		0.0061	0.1475	0.0639
SE±	4.6197	0.1441	0.2400		4.9754	0.1184	0.7536
Seed rate (Sr)							
100	341.44	9.25a	51.44a		333.17	9.28a	51.94
150	328.28	9.22a	48.55c		321.06	9.39a	50.50
200	327.39	8.51b	50.11b		325.39	8.74b	49.61
p-value	0.1591	0.0070	<.0001		0.3728	0.0069	0.2104
SE±	5.6579	0.1765	0.2940		6.0936	0.1452	0.9230
Spacing (S)							
0	317.67	8.47b	45.11c		311.67b	8.53c	46.83b
15	321.50	8.98b	51.94b		313.17b	9.16b	52.33a
30	357.94	9.53a	53.06a		354.78a	9.72a	52.89a
p-value	<.0001	0.0007	<.0001		<.0001	<.0001	<.0001
SE±	5.6579	0.1765	0.2940		6.0936	0.1451	0.9230
Interaction							
V x Sr	0.0303	0.0001	<.0001		0.0060	0.0002	0.0045
V x S	0.0139	0.0006	<.0001		0.0028	0.0002	0.0059
Sr x S	<.0001	0.0060	<.0001		0.0035	0.0092	0.0245
V x Sr x S	0.6288	0.0713	<.0001		0.1429	0.0013	0.0159

Means in a column sharing the same letter are not significantly different at 5 % level of probability using SNK

The Variety × Seed Rate interaction significantly influenced yield components of wheat across both seasons, highlighting genotype-specific responses to plant density. For spike number per square meter (Figure 9), Borloug consistently produced more spikes (up to 349.88 m^{-2} in 2022) than Norman, particularly at lower seed rates (100-150 kg ha^{-1}). Spike number declined at the highest seed rate (200 kg ha^{-1}) in both varieties, suggesting that excessive plant density increased intra-specific competition, reducing tiller survival. This agrees with findings by [2] and [27], who observed that moderate seeding rates optimize tillering and spike formation under semi-arid conditions.

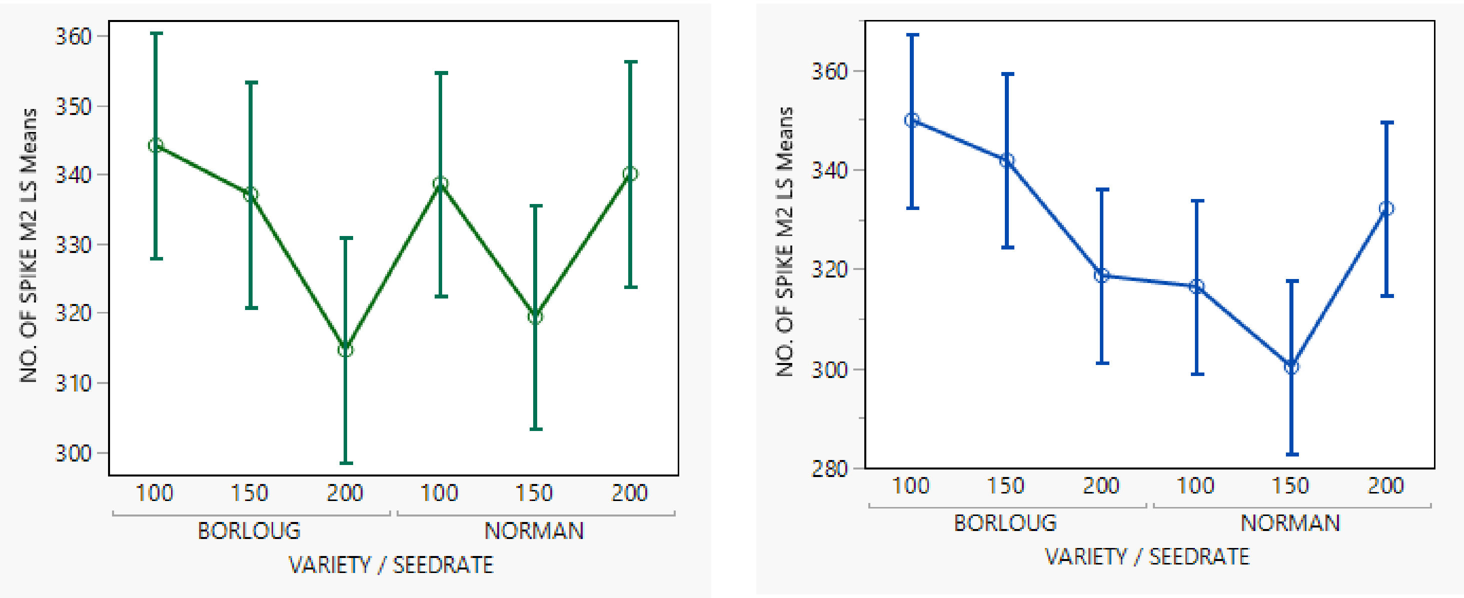


Figure 9: Interaction of Variety and Seed rate on Number of spikes per square meter of wheat during the 2022 cold dry seasons

Spike length also responded to the interaction between variety and seed rate (Figure 10). In 2021, Borloug recorded the longest spikes (9.94 cm) at 100 kg ha^{-1}, while Norman achieved comparable lengths (9.72 cm) at 150 kg ha^{-1}, indicating differential resource use efficiency between genotypes. In 2022, spike length increased slightly with higher seed rates for both varieties, reflecting compensatory growth under moderate competition. Similar patterns were reported by [12], who noted that moderate plant density enhances spike elongation by balancing assimilate supply and demand.

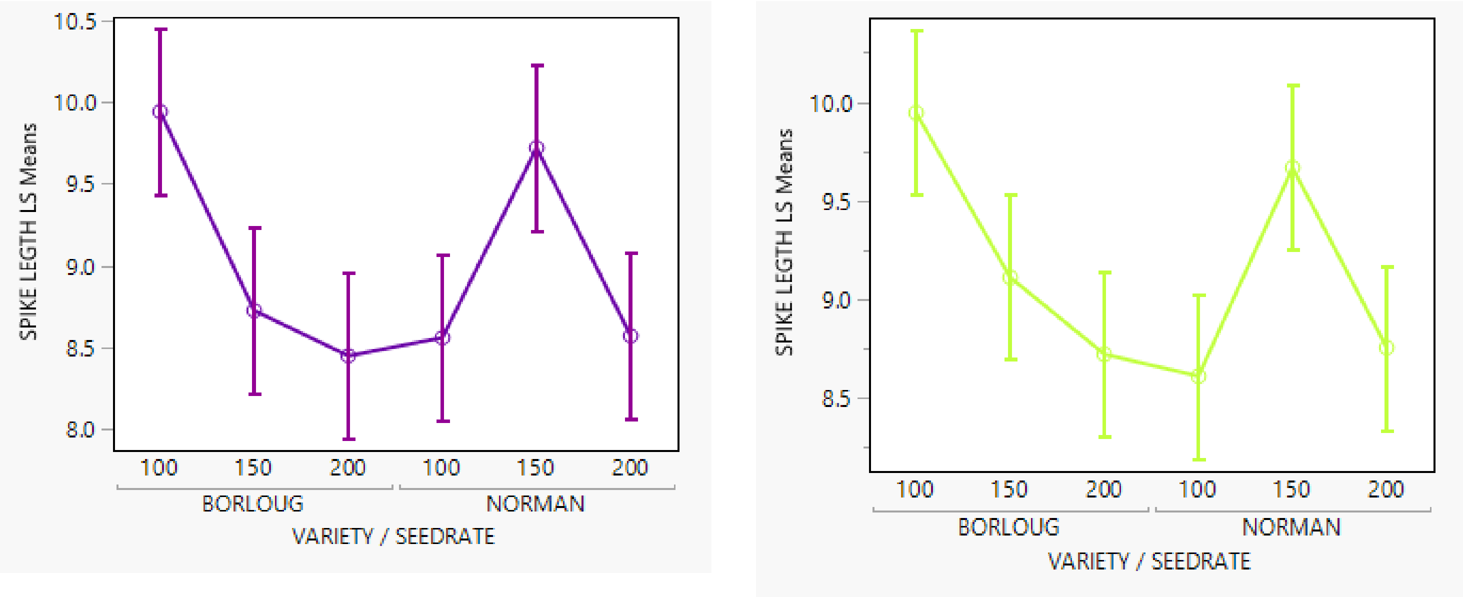


Figure 10: Interaction of Variety and seed rate on Spike length of wheat during 2021 and 2022 cold dry seasons

Figure 11 presents the interaction of variety and seed rate on number of grains per spike where Norman consistently ($p < 0.001$) produced more grains (up to 53.55) than Borloug (47-53), particularly at 150 kg ha^{-1} seed rate, indicating superior spike fertility and assimilate partitioning. Borloug's grain number declined sharply at intermediate densities, suggesting greater sensitivity to crowding stress. These results align with studies by [28] and [32], which emphasize genotype-dependent plasticity in spike fertility under varying plant densities in Sahelian wheat production.

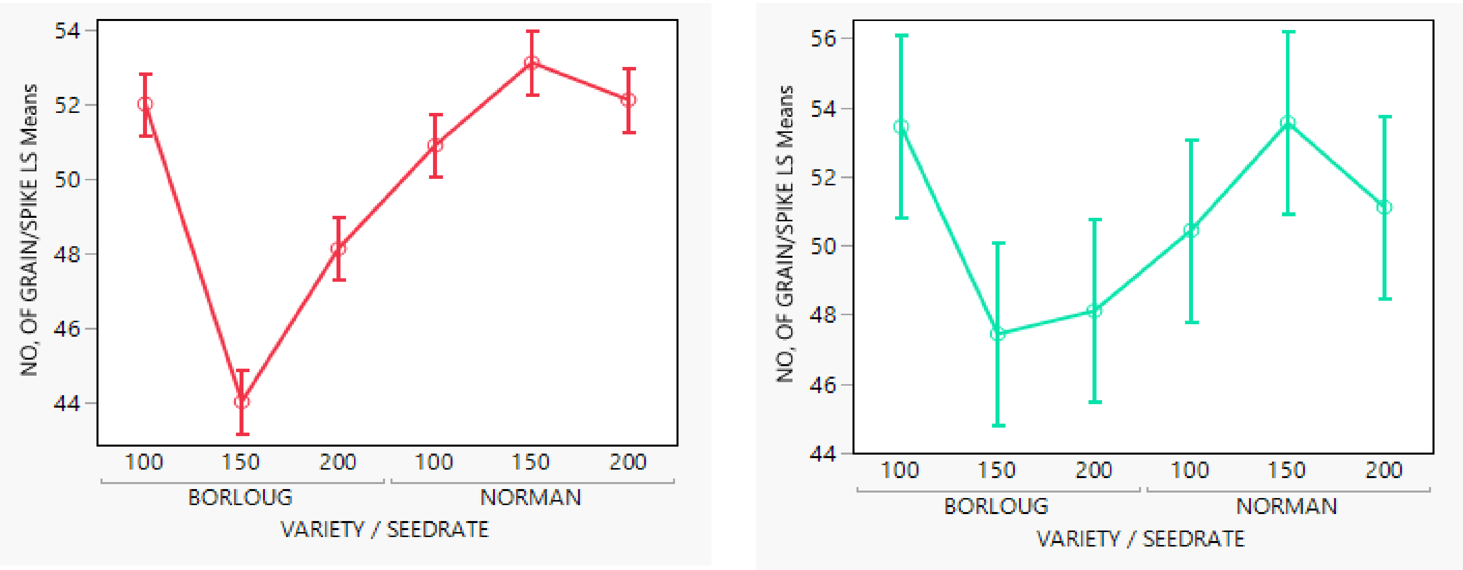


Figure 11: Interaction of Variety and seed rate on Number of Grain per Spike of wheat during 2021 and 2022 cold dry seasons

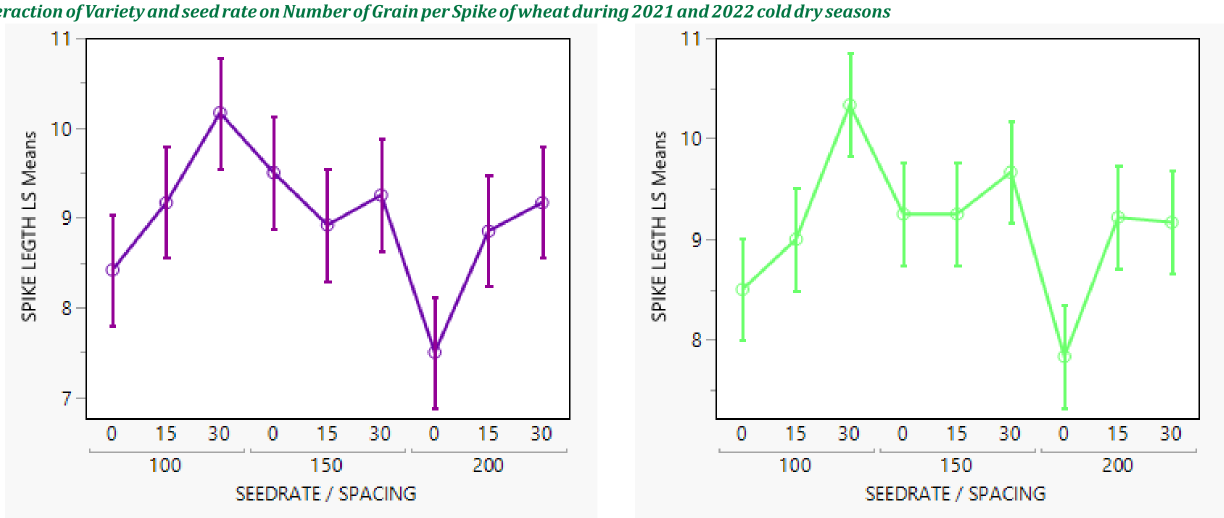


Figure 10: Interaction of Seed rate and Spacing on Spike length (cm) of wheat during 2021 and 2022 seasons

Interaction of Variety and spacing on number of spikes, spike length and number of grains per spikes

The observed Variety × Spacing interaction revealed that Borloug at 30 cm spacing achieved the highest spike density across both years (Figure 11), whereas Borloug at 0 cm spacing recorded the lowest. This indicates that wider spacing favored tillering and spike emergence due to reduced interplant competition and better access to light, nutrients, and moisture. Similar findings were reported by [28] and [20], who noted that wider row spacing enhances spike formation and overall yield components in wheat by improving canopy architecture and photosynthetic efficiency.

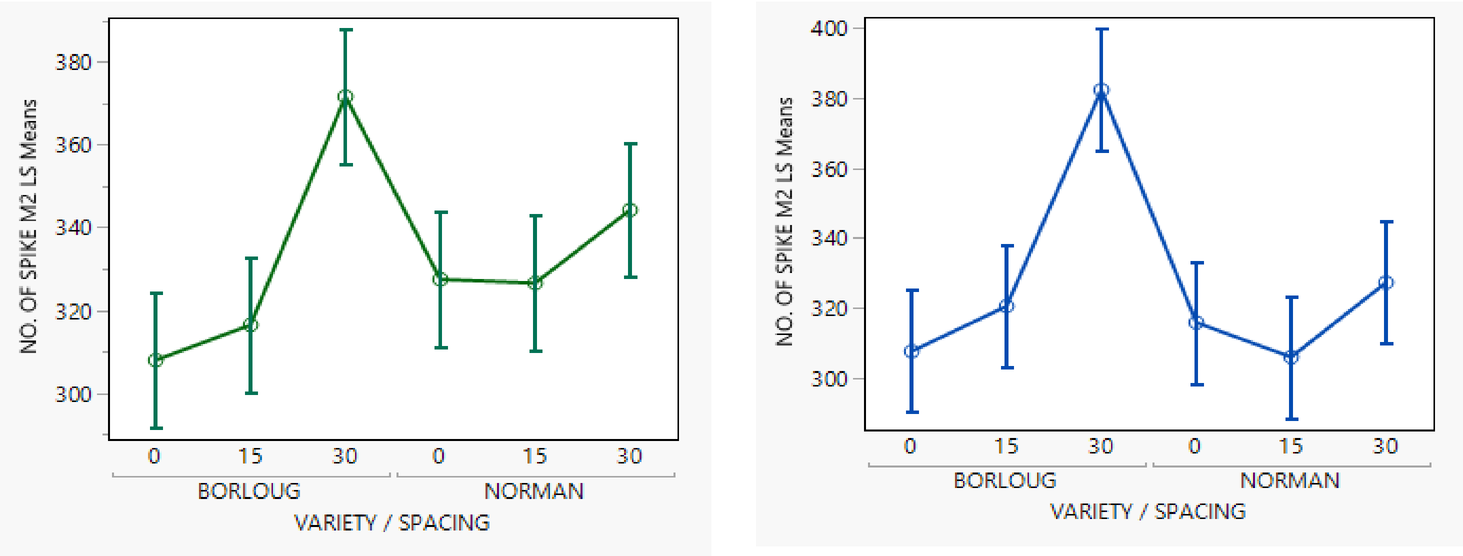


Figure 11: Interaction of Variety and Spacing on Number of spikes m-2 of wheat during 2021 and 2022 cold dry seasons

In contrast, Norman at 15 cm spacing produced the highest number of grains per spike as shown in Figure 12, suggesting that moderate spacing provided optimal resource balance for spikelet development and grain filling. [12] and [27] also reported that moderate plant spacing maintains sufficient photosynthetic surface area while minimizing competition, thereby enhancing spike fertility and kernel set. The poor performance of Borloug at 0 cm spacing further confirms that excessive crowding limits reproductive growth through shading and nutrient stress

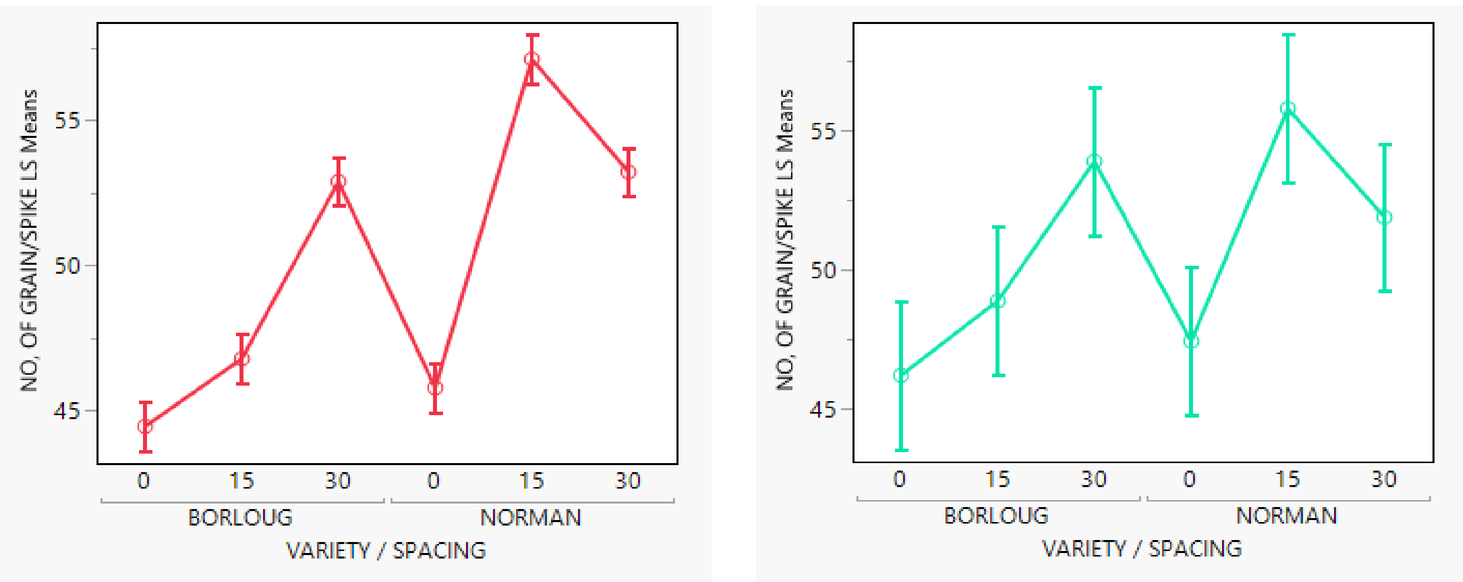


Figure 12: Interaction of Variety and spacing on Number of Grain per Spike of wheat during 2021 and 2022 cold dry seasons

Interaction of Seed rate and spacing on number of spikes, spike length and number of grains per spikes

The Seed Rate × Spacing interaction revealed clear and consistent effects on wheat yield components across both seasons (Figure 13-15). The combination of 100 kg ha^{-1} seed rate and 30 cm spacing produced the highest spike density (401.83 and 389.16 m^{-2}), longest spikes (10.1 cm and 10.3 cm), and most grains per spike (53.66 and 55.16), indicating that moderate seeding and wider spacing optimized both tiller formation and spike development. This superior performance likely resulted from reduced intra-plant competition, better light interception, and efficient resource use per plant [4] [27]. Conversely, the highest seed rate (200 kg ha^{-1}) at narrow spacing (0 cm) produced the lowest values for all yield components, reflecting the adverse impact of crowding on tiller survival and spikelet fertility. High plant density increases competition for light, nutrients, and moisture, leading to fewer productive tillers and reduced assimilate allocation to reproductive organs [6][20].

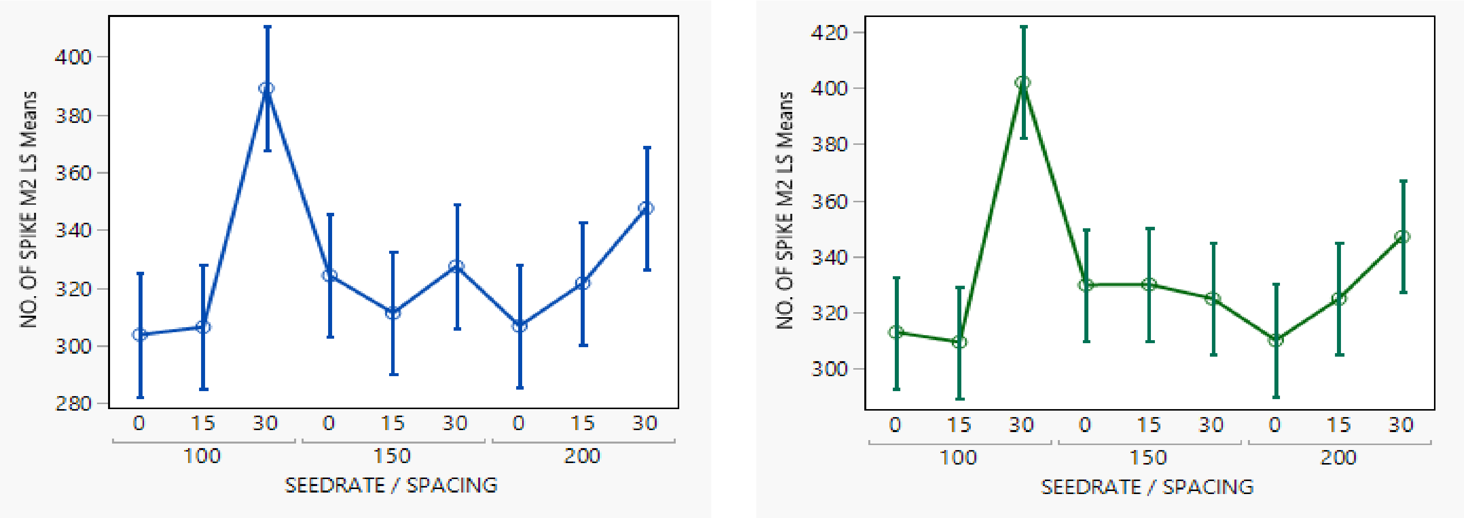


Figure 13: Interaction of Seed rate and Spacing on Number of spikes m-2 of wheat during 2021 and 2022 cold dry seasons

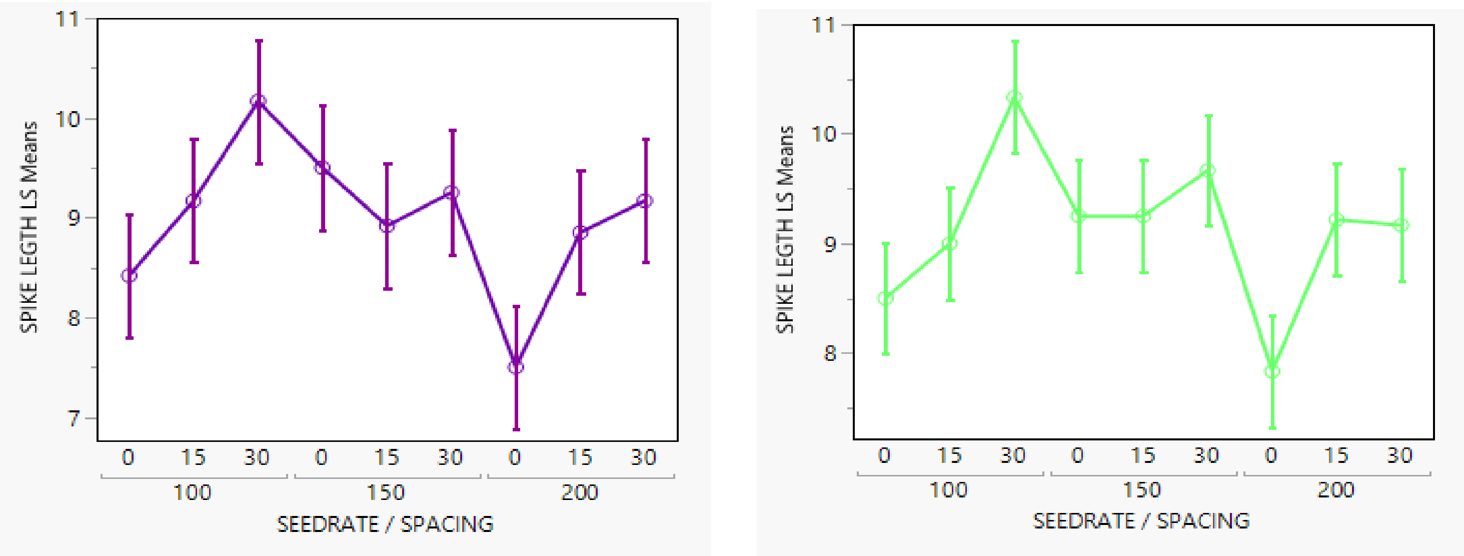


Figure 14: Interaction of Seed rate and Spacing on Spike length (cm) of wheat during 2021 and 2022 cold dry seasons

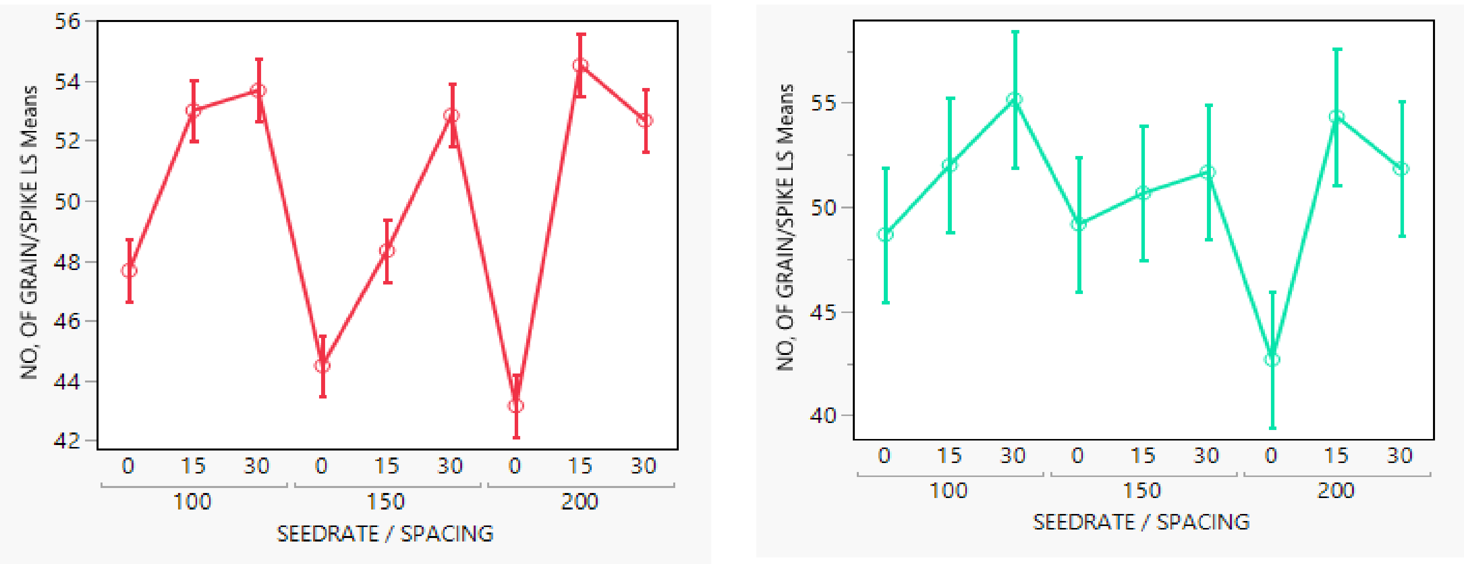


Figure 15: Interaction of Seed rate and spacing on Number of Grains per Spike of wheat during 2021 and 2022 seasons

Interaction of Variety x Seed rate x spacing on spike length and number of grains per spikes

The Variety × Seed Rate × Spacing interaction showed a clear differential response of wheat yield components across genotypes, with significant variation in both the number of grains per spike and spike length (Figure 16-18). Figure 16 shows longest spike length were obtained when the Borloug 100 kg ha^{-1} × 30 cm spacing combination gave the longest spikes (12.0 cm), while Norman at 200 kg ha^{-1} × 0 cm spacing recorded the shortest (7.66 cm). This pattern emphasizes that moderate seeding with wider spacing maximizes spike elongation through better nutrient availability and photosynthetic efficiency, while high density restricts spike growth due to competition stress [2][20].

Similarly, for number of grains per spike, the combination of Norman at 200 kg ha^{-1} seed rate and 15 cm spacing recorded the highest grain count (59.33 and 58.66), followed closely by Borloug at 100 kg ha^{-1} and 30 cm spacing (59.33 and 61.33). These combinations demonstrate the complementary influence of optimal density and spacing on spike fertility and grain set. Wider spacing likely enhanced light penetration and reduced competition, while moderate to high seed rates promoted uniform spike development [27]. Conversely, Borloug at 150 kg ha^{-1} and 0 cm spacing produced the lowest grain number (40.66 and 45), indicating the suppressive effect of excessive crowding on reproductive potential due to limited assimilate partitioning to the spikes.

Overall, the results indicate that Borloug under 100 kg ha^{-1} seed rate and 30 cm spacing achieved the best structural performance (long spikes and high grains per spike), while Norman under 200 kg ha^{-1} and 15 cm spacing expressed superior spike fertility. Thus, optimal performance depends on genotype-specific responses to planting density and spacing, reflecting inherent differences in tillering capacity and assimilate

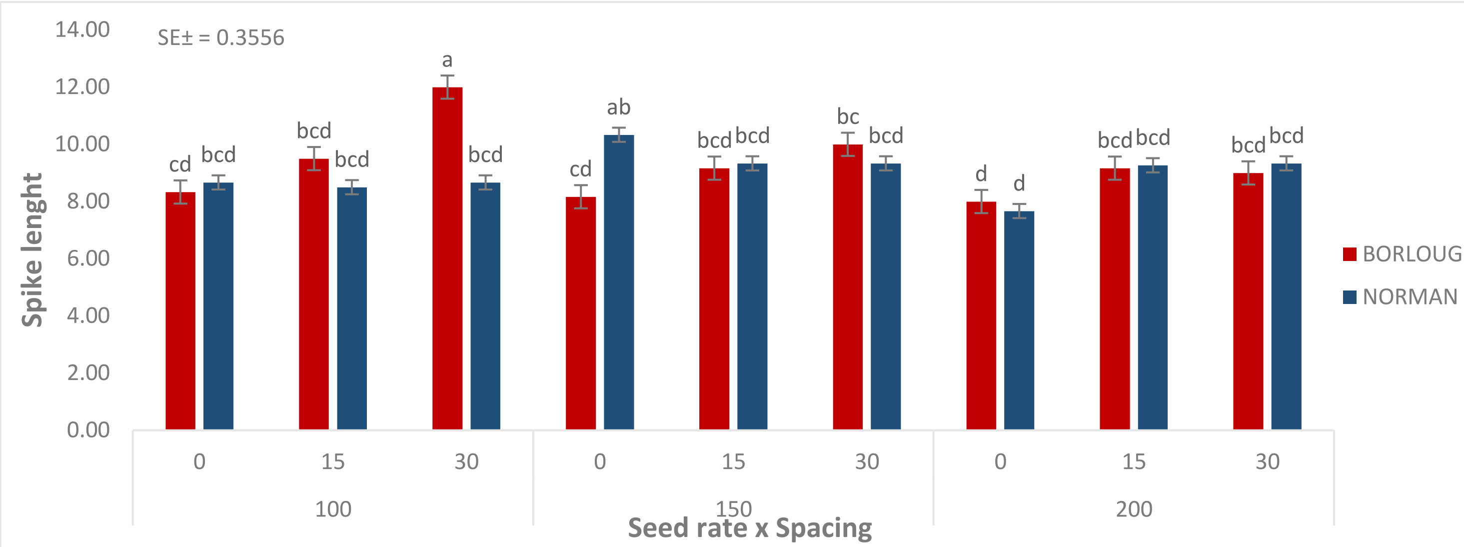


Figure 16: Variety x seed rate x spacing interactions on spike length of wheat during the 2022 cold dry season

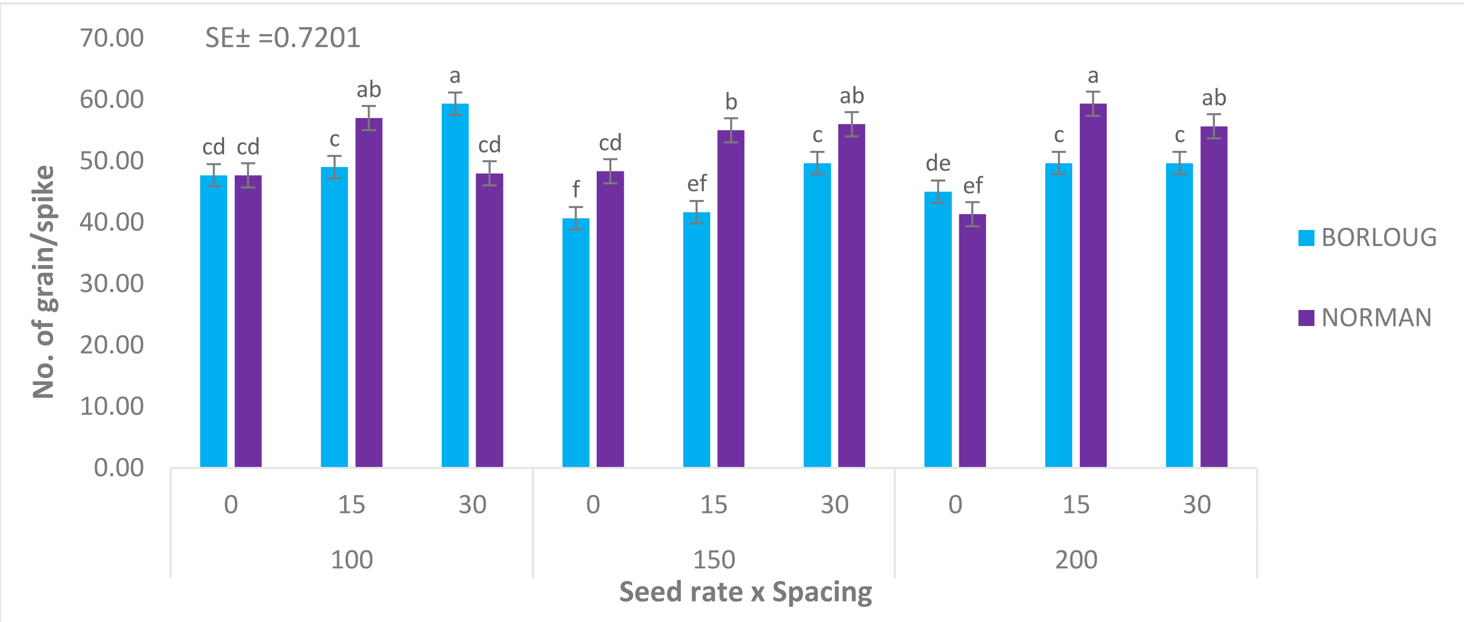


Figure 17: Variety x seed rate x spacing interaction on number of grains per spikes of wheat during the 2021 cold dry season

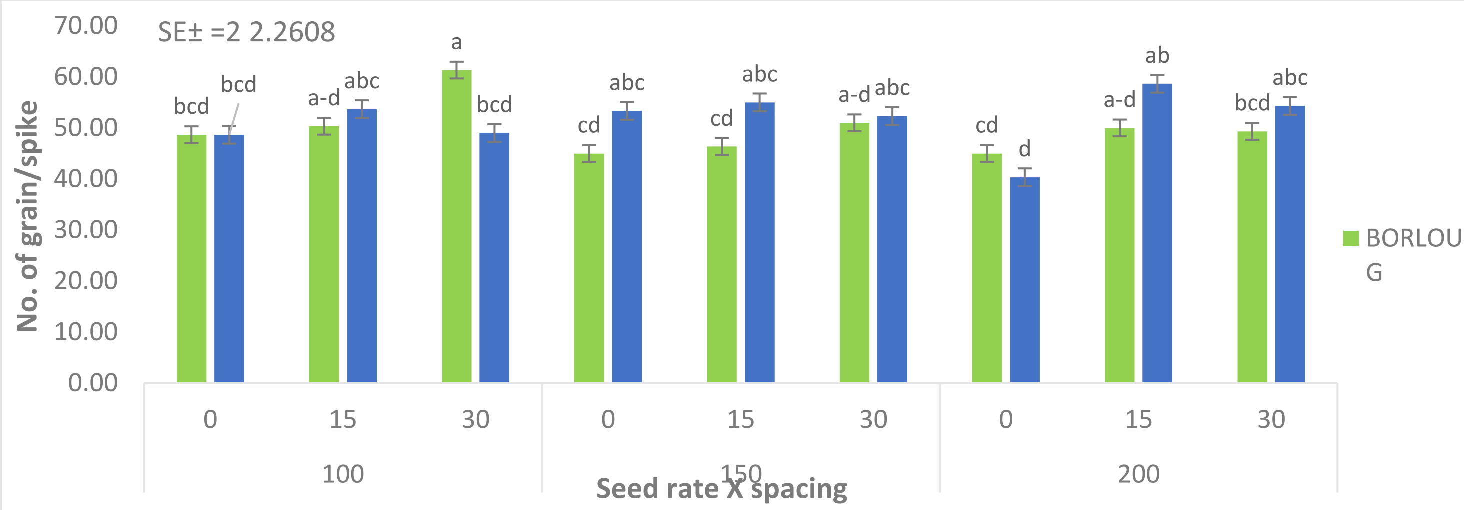


Figure 18: Variety x seed rate x spacing interaction on number of grains per spike of wheat during the 2022 cold dry season

Grain yield and 1000 seed weight

The results in Table 3 reveal that both variety, seed rate, and spacing significantly influenced the 1000-grain weight, grain yield per plot, and grain yield per hectare of wheat during the 2021 and 2022 cold dry seasons. Borloug consistently outperformed Norman, producing significantly ($p < 0.001$) the heaviest grains (49.36 g in 2021 and 47.41 g in 2022) and the highest grain yields (5.10 plots^{-1}; 3868.09 kg ha^{-1} in 2021 and 5.07 plots^{-1}; 3377.65 kg ha^{-1} in 2022). This indicates Borloug's superior assimilate partitioning to the grains and better adaptation to the Sahelian environment. In contrast, Norman produced lighter grains and lower yields, reflecting its longer growth duration and possible susceptibility to late-season heat stress. These findings align with [38]and [10], who reported that genotypic differences in grain filling efficiency and thermal tolerance largely determine yield performance in wheat under semi-arid conditions. This confirms that Borloug's morphological traits favor denser spike formation and efficient dry matter utilization under wider spacing and higher seed rates typical of the Nigerian Sahel.

The use of 200 kg ha^{-1} seed rate significantly ($p < 0.001$) produced the highest 1000-grain weight (48.97 g) and yield (3868.09 kg ha^{-1}) in 2021, though the yield advantage slightly declined in 2022, possibly due to interplant competition at excessive density. Moderate seed rate (150 kg ha^{-1}) consistently maintained good balance between spike fertility and resource use efficiency. Similar density-related yield trends were reported by [4] and [27], who found that optimal seeding rates (between 120-160 kg ha^{-1}) maximize grain yield by reducing intra-specific competition.

Spacing also exerted a significant ($p < 0.001$) effect on yield traits. Wider spacing (30 cm) produced the heaviest grains (49.17-50.56 g) and the highest grain yields (3868.04 and 3589.56 kg ha^{-1}) across seasons, while the narrowest spacing (0 cm) resulted in the lowest performance. Wider spacing improved photosynthetic efficiency and allowed for better canopy aeration and nutrient uptake, thereby enhancing grain filling and weight accumulation. These results corroborate the findings of [12] and [20], who reported that moderate to wide spacing enhances wheat productivity by improving light interception and reducing interplant competition.

Table 3: 1000 grain weight, Grain yield per plot and Grain yield per hectare of Wheat varieties as affected by Seed rate and spacing during 2021 and 2022 Cold dry seasons

Treatment	2021			2022		
	1000 Grain weight (g)	Grain yield plots^{-1}	Grain yield (kg ha^{-1})	1000 Grain Weight (g)	Grain yield plots^{-1}	Grain yield (kg ha^{-1})
Variety (V)						
Borloug	49.36a	5.10a	3868.09a	47.41a	5.07a	3377.65a
Norman	42.93b	4.36b	3164.83b	45.56b	4.48b	2989.02b
p-value	<.0001	0.0002	<.0001	0.0248	0.0007	0.0007
SE±	0.0822	0.1244	0.0873	0.5589	0.1115	74.3489
Seed rate (Sr)						
100	43.10c	4.25b	3164.96c	46.47	4.76	3174.19
150	46.37b	4.82a	3516.34b	46.75	4.97	3311.64
200	48.97a	5.12a	3868.09a	46.22	4.60	3064.17
p-value	<.0001	0.0011	<.0001	0.8623	0.1712	0.1712
SE±	0.1007	0.1524	0.1070	0.6846	0.1366	91.0585
Spacing (S)						
0	43.07c	4.30b	3164.83c	43.14c	4.44b	2958.08b
15	46.19b	4.82a	3516.52b	45.75b	4.50b	3002.36b
30	49.17a	5.07a	3868.04a	50.56a	5.38a	3589.56a
p-value	<.0001	0.0034	<.0001	<.0001	<.0001	<.0001
SE±	0.1007	0.1524	0.1070	0.6846	0.1366	91.0585
Interaction						
V x Sr	<.0001	0.8103	<.0001	0.0062	0.0691	0.0691
V x S	<.0001	0.3122	<.0001	0.6219	<.0001	<.0001
Sr x S	0.0023	0.4777	<.0001	0.2947	0.0138	0.0138
V x Sr x S	<.0001	0.4042	<.0001	0.0076	0.0002	0.0002

Means in a column sharing the same letter are not significantly different at 5 % level of probability using SNK

Interaction of Variety x Seed rate x spacing on 1000 seed weight and grains yield (kg ha-1)

The Variety × Seed Rate × Spacing interaction showed distinct genotype-specific responses in 1000-grain weight and grain yield (Figure 19-22). The best performance occurred with Borloug at 200 kg ha^{-1} seed rate and 30 cm spacing, producing the highest 1000-grain weight (53.0 and 46.5 g) and grain yield (4680.43 and 3580 kg ha^{-1} in 2021 and 2022) compared with rest of the interaction combination. This reflects efficient assimilate partitioning and reduced competition under wider spacing [31][11]. In contrast, Norman at 100 kg ha^{-1} and 0 cm spacing recorded the lowest grain weight (40.0 and 41.66 g) and yield (3133.53 and 2400 kg ha^{-1}), indicating limited resource-use efficiency and competition stress. Overall, Borloug responded better to higher seed rates and wider spacing, while Norman performed optimally under moderate density. These results confirm that balanced plant population and spacing enhance rain filling and yield stability under Sahelian conditions [38][12].

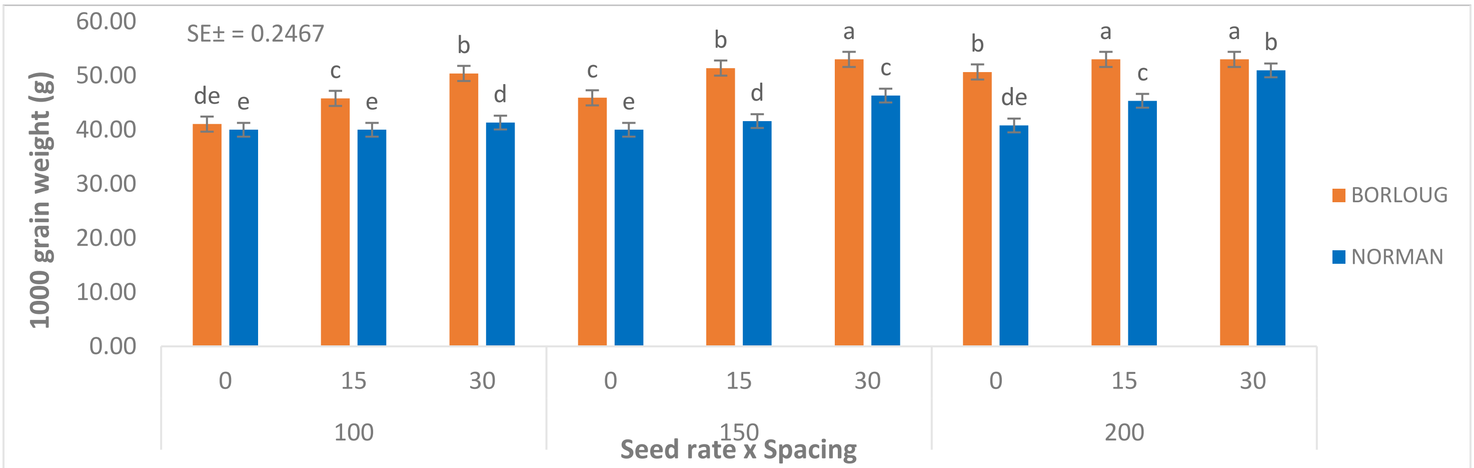


Figure 19: Variety x seed rate x spacing interaction on 1000 grain weight of wheat during the 2021 cold dry season

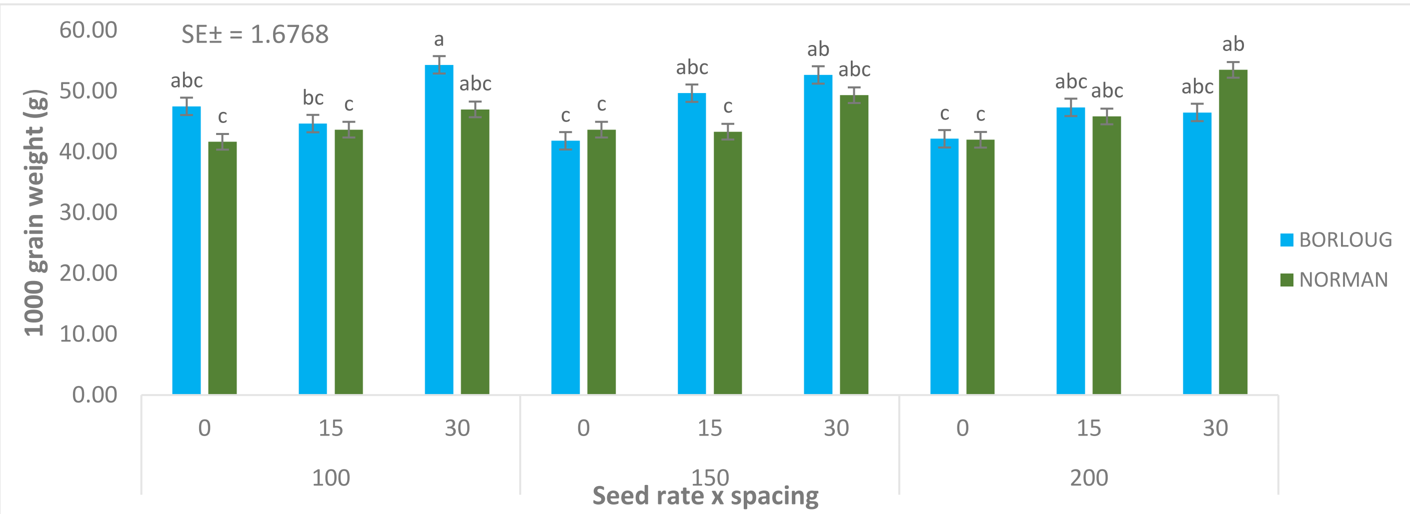


Figure 20: Variety x seed rate x spacing interaction on 1000 grain weight of wheat during the 2022 cold dry season

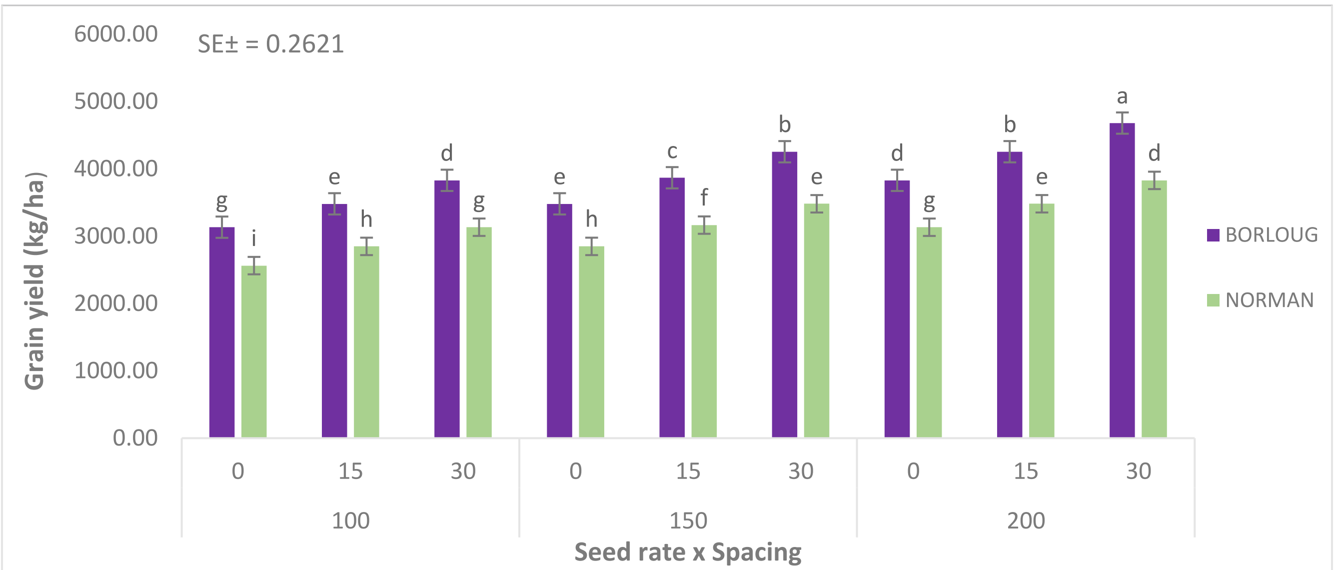


Figure 21: Variety x seed rate x spacing interaction on grain yield of wheat during the 2021 cold dry season

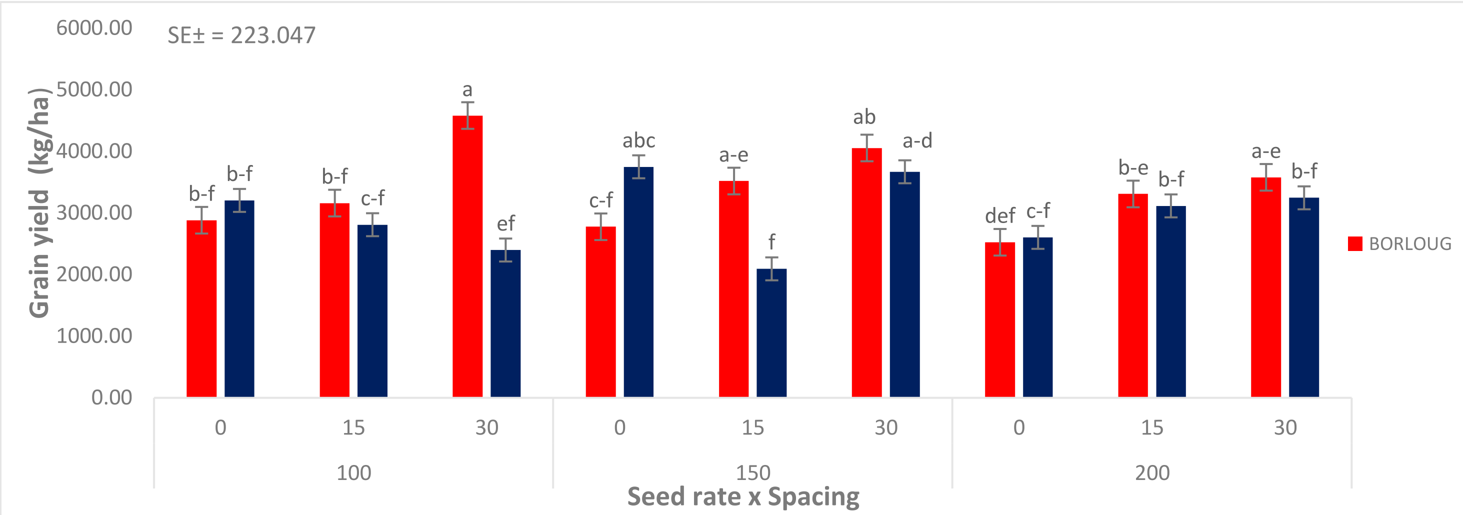


Figure 22: Variety x seed rate x spacing interaction on grain weight of wheat during the 2022 cold dry season

Conclusion and Recommendation

This study established that wheat productivity in the Nigerian Sahel Savanna is strongly determined by the interaction among variety, seed rate, and spacing. Across both seasons, Borloug outperformed Norman in grain yield and 1000-grain weight, while Norman produced more grains per spike, reflecting varietal differences in assimilate partitioning and reproductive efficiency. A moderate seed rate (150 kg ha^{-1}) and wider spacing (30 cm) consistently improved spike density, spike length, and grain yield, whereas excessive seeding (200 kg ha^{-1}) reduced yield components due to competition stress.

The Borloug × 100 kg ha^{-1} × 30 cm combination achieved the highest grain yield and 1000-grain weight, while Norman × 200 kg ha^{-1} × 15 cm excelled in spike fertility. These findings highlight the need for genotype-specific agronomic optimisation to balance plant density and spacing for maximum productivity.

It is therefore recommended that Borloug be cultivated at 100–150 kg ha^{-1} seed rate with 30 cm spacing under irrigated Sahelian conditions to achieve superior yield performance. Further studies should integrate these agronomic practices with nutrient and water management strategies to enhance wheat resilience and productivity under the evolving climatic conditions of the Sahel.

Competing Interests

Authors have declared that no competing interests exist.

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