original scientific paper
Ratar. Povrt. 2026, 63(1): 22-36
doi: 10.5937/ratpov63-59214
Manuscript submitted: 31 May 2025
Manuscript accepted: 4 March 2026
Published online: 17 March 2026

Optimizing Seed Rate and NPSB Fertilizer for Enhanced Yield and Nutrient Use Efficiency of Bread Wheat (*Triticum aestivum* L.) in Kambeta Zone, Central Ethiopia

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Summary: Bread wheat is a vital staple crop in Ethiopia, yet yields remain critically low due to suboptimal agronomic practices. A significant problem persists in the Kambeta Zone, where low soil fertility, excessive seeding rates, and blanket fertilizer recommendations lead to poor plant stands and severe nutrient deficiencies (N, P, S, B), resulting in unacceptably low nutrient use efficiency (NUE <40%). While blended NPSB fertilizer offers a potential solution, the precise interaction between seed rates, NPSB levels, and modern wheat varieties remains unquantified, hindering the development of localized, efficient management strategies. This study therefore investigated these interactions on varieties Wane and Danda. A factorial experiment tested three seed rates (75, 100, 125 kg ha^{-1}) and four NPSB levels (0, 50, 100, 150 kg ha^{-1}). Results demonstrated that the variety Danda consistently outperformed Wane at grain yield and yield components. The optimal combination was a seed rate of 125 kg ha^{-1} with 150 kg ha^{-1} NPSB, which achieved the highest grain yield (5.2 t ha^{-1}) and superior NUE by significantly enhancing productive tillers, thousand-kernel weight, and harvest index. This research provides a definitive strategy to close the yield gap by synchronizing seeding density with adequate NPSB fertilization, offering farmers a precise recipe to enhance productivity and nutrient efficiency in wheat cultivation.

Key words: agronomic practices, bread wheat, Ethiopia, NPSB fertilizers, NUE, nutrient-use efficiency, seed rate

Introduction

Bread wheat (*Triticum aestivum* L.) is a major staple crop in Ethiopia, with average yields ranging from 2.94 to 3.58 t ha^{-1} (Alemu, 2024). However, productivity remains low due to suboptimal agronomic practices, such as inappropriate seed rates and insufficient fertilizer application (Tadesse et al., 2022). Although the government has promoted improved varieties and irrigation technologies, adoption challenges continue to hinder progress (Tolossa et al., 2024). The use of blended NPSB fertilizer (containing 19% N, 38% P_2O_5, 7% S, and 0.1% B) offers potential to alleviate nutrient deficiencies, yet its interaction with seed rates and varietal performance in Central Ethiopia requires further investigation (Teshome & Shifaraw, 2024).

In the Kambeta Zone, low soil fertility, excessive seeding rates (up to 200 kg ha^{-1}), and blanket fertilizer recommendations reduce yields. Nutrient deficiencies (N, P, S, B) and poor plant stands result in low nutrient use efficiency (NUE <40%) (Desta et al., 2023). Studies in similar agroecologies show that improper seed rates reduce tillering, while insufficient NPSB limits grain formation (Adare, 2024). Optimizing inputs could increase yields by up to 98.5% (Li et al., 2024) while improving NUE, aligning with Ethiopia's Climate-Resilient Green Economy strategy (Tesfaye et al., 2023). Adapted varieties (e.g., Wane and Danda) may enhance adoption and reduce wheat imports (Mohammed et al., 2021).

Therefore, the general objective of the study is to assess the effects of seed rate and NPSB fertilizer applications on bread wheat varieties for enhanced yield and nutrient use efficiency in the Kambeta Zone, Central Ethiopia. The specific objectives of this study are:

- To evaluate the effects of different seed rates on the yield and yield components of selected bread wheat varieties in the Kambeta Zone.
- To assess the impact of varying NPSB fertilizer application rates on the growth, yield, and nutrient use efficiency of these wheat varieties.
- To determine the interaction effects between seed rates and NPSB fertilizer levels on the performance of bread wheat.
- To identify strategies that enhance yield and optimize nutrient use efficiency in bread wheat cultivation within the Kambeta Zone.

Materials and Methods

Description of the Study Area

The experiment was conducted at the Farmers' Training Center in Hamencho Kebele, located in the Kambeta Zone of Central Ethiopia (7°15' N, 37°50' E) at an elevation of 2,100 meters above sea level. The soil in the experimental area has a pH ranging from 5.8 to 6.5 and is characterized by sandy loam. (Godebo et al., 2021), and the location of the experiment is shown in Figure 1.

Climatic Conditions of the Study Site

During the cropping seasons of 2021 and 2022, rainfall was highest between June and September, ranging from about 127 to 138 mm (Figure 2). This period provided sufficient moisture for wheat establishment and vegetative growth. From October onward, rainfall declined steadily, which is generally favorable for crop maturation and harvest. Temperatures followed a seasonal pattern. Minimum values were coolest in July (around 14°C), creating good conditions for tillering. Average temperatures during June–September stayed within the optimal range for wheat growth (20–23°C). However, from October to December, both minimum and average temperatures rose sharply, reaching nearly 29 °C by December (Figure 2). These warmer conditions can shorten the grain-filling period and reduce yield if planting is delayed.

Experimental Materials and Design

The two-year field experiment (2021 and 2022) evaluated two bread wheat (*Triticum aestivum* L.) varieties: Wane, released in 2016, and Danda, released in 2010. Wane is recommended for elevations between 2,100 and 2,700 m and areas receiving 700–1,000 mm of annual rainfall. It matures in approximately 125 days and has a potential yield of 6.0 t ha^{-1} (Mohammed et al., 2021). Danda is adapted to altitudes of 2,000–2,600 m and requires about 600 mm of annual rainfall. It reaches maturity within 110–145 days and can produce yields of up to 5.5 t ha^{-1} (Wakwaya et al., 2023).

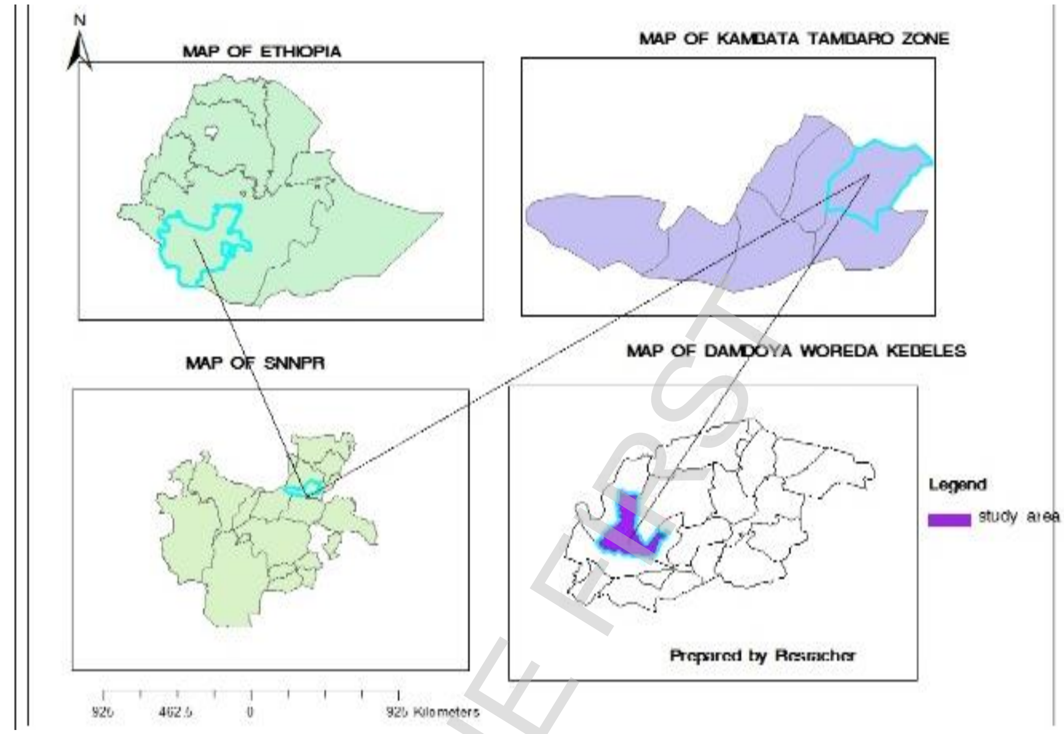

Figure 1. Study area map

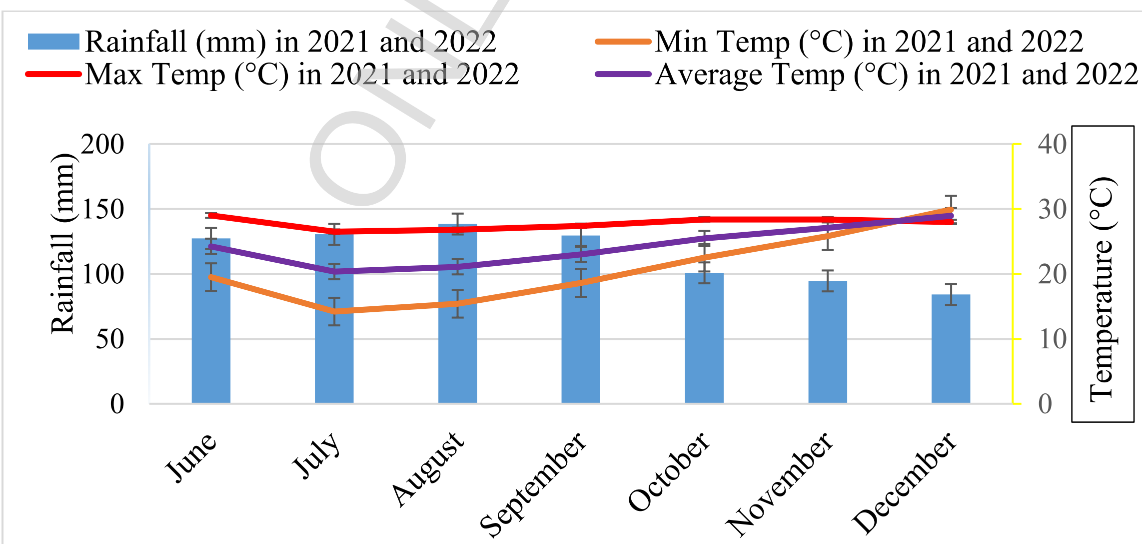

Figure 2. Average meteorological data for the cropping seasons of 2021 and 2022 are provided by the National Meteorology Agency, Hawassa Branch

The experiment followed a randomized complete block design (RCBD) with three replications conducted over two consecutive growing seasons. In total, 72 treatment combinations were tested, derived from a factorial arrangement of two wheat varieties (Danda and Wane), four NPSB fertilizer rates (0, 50, 100, and 150 kg ha^{-1}), and three seed rates (75, 100, and 125 kg ha^{-1}). Sowing took place on July 27–28 in both years, and seedling emergence occurred approximately one week later. Fertilizer was applied in two equal splits: at planting and at the mid-tillering stage. Each plot measured 5 m^2 and consisted of ten rows. Data were collected from an eight-row net plot (3.2 m^2), with border rows excluded to minimize edge effects (Wakwaya et al., 2023).

Soil Sampling and Analysis. Soil samples (0-30 cm depth) were collected from an experimental field before wheat sowing for both years. Composite samples were air-dried, ground, sieved, and analyzed at Wachemo University's lab for physicochemical properties: organic carbon (Walkley & Black method) (Melkani et al., 2023), total nitrogen (Kjeldahl), pH (potentiometrically, 1:2.5 soil-water) (Derebe et al., 2022), CEC (ammonium acetate), phosphorus (Olsen), sulfur (ammonium acetate), and boron (hot water).

Data Collection and Measurements. Days to 50% heading were recorded from sowing until half of the plants in each plot reached the heading stage. Days to 90% maturity were determined when 90% of the spikes had turned yellow. Plant height (measured from the soil surface to the spike tip, excluding awns) and spike length (measured from the base to the tip) were recorded from ten tagged plants per plot. Total and productive tillers were counted on ten plants per plot, while kernels per spike were averaged from ten main tillers. Thousand kernel weight was determined at 12.5% moisture content. Aboveground biomass was sun-dried and weighed, expressed in kg ha^{-1}. Grain yield was adjusted to 12.5% moisture content following Zeleke (2020), and harvest index was calculated as the ratio of grain yield to total biomass (%). Leaf area index at each interval was measured immediately after harvest using an automatic leaf area meter (Rahman et al., 2014).

Grain Tissue Nutrient Availability and Use Efficiency. In this study, the availability of key nutrients in wheat grain tissue was carefully assessed to understand their role in growth, yield, and efficiency. Nitrogen, which is indispensable for plant development, was analyzed using the Kjeldahl method and expressed as grams of nitrogen per kilogram of grain dry matter (g N kg^{-1} DM) following Lim (2021). Phosphorus concentration was determined according to the procedure outlined by DGT Research Ltd (2020) and reported as milligrams of phosphorus per kilogram of grain dry matter (mg P kg^{-1} DM). Sulfur, a nutrient that plays a central role in amino acid and enzyme synthesis and directly influences protein content and grain yield, was measured as milligrams of sulfur per kilogram of grain dry matter (mg S kg^{-1} DM), with reference to the findings of Zhang et al. (2024). Boron, which is essential for cell wall formation and reproductive processes and contributes significantly to seed set and grain development, was quantified as milligrams of boron per kilogram of grain dry matter (mg B kg^{-1} DM) following TC and Jones (2018).

Beyond nutrient concentrations, the study also examined nutrient use efficiency (NUE), which reflects the plant's ability to utilize applied nutrients effectively. NUE was evaluated both for individual nutrients and as an average across treatments. Several components were considered in this evaluation. Nutrient uptake was expressed as kilograms of nutrient per hectare (kg nutrient ha^{-1}), representing the total nutrient content accumulated in the grain yield. Nutrient recovery efficiency (NRE) was calculated as the percentage of applied nutrient absorbed by the crop, thereby indicating the effectiveness of nutrient capture (Godebo et al., 2021). Agronomic efficiency (AE) was defined as the increase in grain yield per unit of nutrient applied, expressed as kilograms of grain per kilogram of nutrient applied (kg grain kg^{-1} nutrient). Physiological efficiency (PE) was measured as the increase in grain yield per unit of nutrient absorbed, expressed as kilograms of grain per kilogram of nutrient absorbed (kg grain kg^{-1} nutrient). Finally, overall nutrient use efficiency (NUE) was presented as a percentage, integrating the plant's capacity to absorb, utilize, and convert nutrients into yield.

1. Nutrient Uptake

Nutrient uptake (kg ha^{-1}) = Grain yield (kg ha^{-1}) × Nutrient concentration (g kg^{-1}) × 0.001

2. Nutrient Recovery Efficiency (NRE or RE)

NRE (%) = [(Nutrient uptake in fertilized plot − Nutrient uptake in control plot) / Amount of nutrient applied] × 100

3. Agronomic Efficiency (AE)

AE = (Yield in fertilized plot − Yield in control plot) / Amount of nutrient applied

4. Physiological Efficiency (PE)

PE = (Yield in fertilized plot − Yield in control plot) / (Nutrient uptake in fertilized plot − Nutrient uptake in control plot)

5. Nutrient Use Efficiency (NUE)

The expression NUE (%) = PE × RE is mathematically equivalent to Agronomic Efficiency (AE).

Data Analysis

Prior to statistical analysis, the assumptions of multivariate normality, homogeneity, and linearity were verified using the Shapiro–Wilk test. Multivariate analysis of variance (MANOVA) was conducted for both combined and separate datasets where interaction effects were significant, using SAS version 9.34. Mean comparisons were performed with Fisher's Protected Least Significant Difference (PLSD) test at the 5% level of significance.

Results and Discussion

Effects of NPSB Fertilizer Applications on the Soil Composition

Figure 3 presents the soil characteristics of the experimental site, classified as sandy loam, a texture that strongly influences water retention, infiltration, aeration, root penetration, and fertility (Wang et al., 2021). The measured pH (5.63–6.0) was within the optimal range for crop productivity, supporting nutrient availability and microbial activity. Organic carbon (2.8–3.64%), total nitrogen (0.89–1.7%), and available phosphorus (27.25–30.7 mg kg^{-1}) were moderate, while sulfur was relatively high (18–20 mg kg^{-1}), potentially enhancing protein synthesis and crop quality. The cation exchange capacity (22–29 meq $100g^{-1}$) indicated strong nutrient retention and exchange capacity. Despite these favorable attributes, relatively low organic matter remains a limitation, and without practices such as organic amendments, residue recycling, or integrated nutrient management, nutrient availability may decline over time (Solly et al., 2020).

Nutrient dynamics across two cropping years revealed consistent improvements. In 2021, phosphorus increased from 27.25 mg kg^{-1} before planting to 29.92 mg kg^{-1} after harvest, sulfur rose from 18.25 to 20.49 ppm, and boron nearly doubled from 0.97 to 1.66 ppm. By the 2022 harvest, phosphorus reached 30.7 mg kg^{-1}, sulfur stabilized at 20.6 ppm, and boron rose slightly to 1.8 ppm. The rise in phosphorus supports root development and grain formation, increased boron improves reproductive success and seed set, while sulfur enrichment contributes to protein synthesis and crop quality.

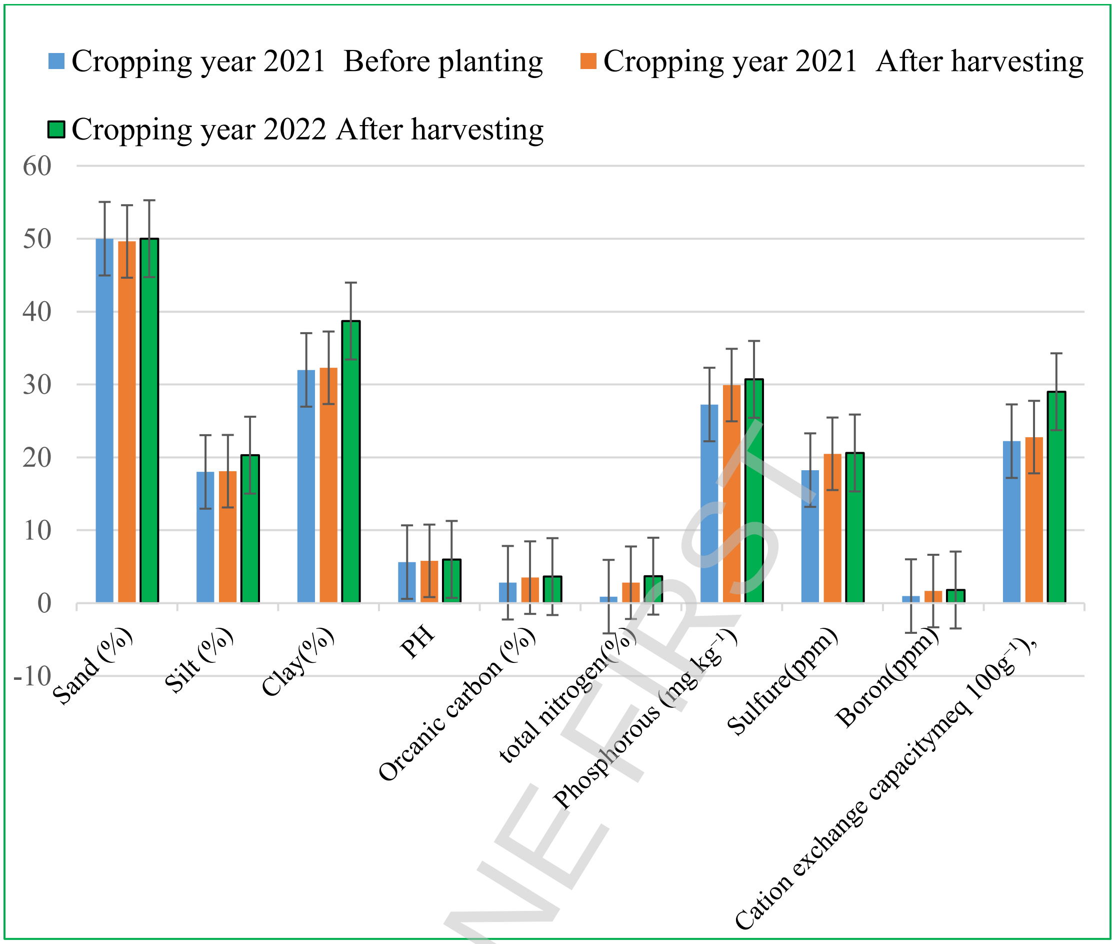

Figure 3. Soil analysis before and after crop harvest (Laboratory result, 2021 & 2022)

Crop Phenology and Growth Parameters

Effects on the Plant Height. The variety Danda (54.7 cm) was significantly taller than Wane (52.3 cm). The greatest plant height was recorded at seeding rates of 75 kg ha^{-1} (58.2 cm) and 100 kg ha^{-1} (57.5 cm), compared with 125 kg ha^{-1} (54.3 cm). Plant height also increased with higher NPSB fertilizer rates, reaching a maximum at 150 kg ha^{-1} (92.5 cm), followed by 100 kg ha^{-1} (78.8 cm), 50 kg ha^{-1} (53.5 cm), and the control (47.1 cm) (Table 1). In line with Luo et al. (2021), enhanced nutrient availability stimulates cell elongation, thereby promoting growth in nutrient-responsive varieties such as Danda, even under higher planting densities.

Effects on the Leaf Area Index. The leaf area index (LAI) showed significant variation across the two cropping years and under different NPSB application rates in both varieties (Table 1). Treatments applied during the 2022 season produced a higher LAI, with values that were statistically comparable across treatments. The Danda variety consistently exhibited superior performance, while NPSB application rates of 100 kg ha^{-1} and 150 kg ha^{-1} resulted in statistically similar LAI values, in agreement with the findings of Desta and Almayehu (2020).

Effects on the Days to 50% Heading. The Danda variety (≈58 days) required significantly more time to reach 50% heading compared with Wane (54 days). Increased seeding rates accelerated heading, with 125 kg ha^{-1} reaching 50% heading in 59 days, significantly earlier than 75 kg ha^{-1} (53 days). In contrast, NPSB application at 100 and 150 kg ha^{-1} delayed heading to 61 days, compared with 55 days under the control (0 kg ha^{-1}). The delayed heading observed in Danda may be attributed to genetic traits associated with slower development, which could enhance yield potential through improved tillering and root growth (Msundi et al., 2021).

Effects on the Spike Length and Kernels per Spike. The Wane variety produced significantly longer spikes (8.3 cm) compared with Danda (7.4 cm). Spike length increased with seeding rate, reaching a maximum at 125 kg ha^{-1} (9.1 cm), followed by 100 kg ha^{-1} (7.6 cm), and the lowest at 75 kg ha^{-1} (6.5 cm), consistent with the findings of Zardari et al. (2025). Similarly, NPSB application at 150 kg ha^{-1} resulted in the longest spikes (8.9 cm), whereas the control (0 kg ha^{-1}) produced the shortest (5.8 cm), in agreement with Abdisa et al. (2022). The number of kernels per spike was highest at seeding rates of 100–125 kg ha^{-1} (43.2–43.6) and under 150 kg ha^{-1} NPSB (55.1), compared with only 32.1 kernels at 0 kg ha^{-1}.

Effects on the Thousand Kernel Weight (TKW). The Danda variety recorded a higher thousand-kernel weight (TKW) of 38.7 g compared with Wane (34.5 g). Application of NPSB fertilizer significantly increased TKW, rising from 34.4 g under the control (0 kg ha^{-1}) to 38.8 g at 150 kg ha^{-1}, underscoring the critical role of nutrient supply in kernel filling (Muhammad Irfan et al., 2018; Pandey et al., 2020).

Effects on the Days to 90% Maturity. Days to 90% maturity were significantly affected by variety, seeding rate, and NPSB application across both years (Tables 1 & 2). The Wane variety consistently matured earlier, ranging from 106 to 126 days, whereas Danda required longer, extending from 116 to 142 days. The shortest maturity period was observed under low seeding and no fertilizer (Wane 125×0), while the longest occurred under high seeding and maximum NPSB application (Danda 125×150). Increasing seeding rates and NPSB levels delayed maturity in both varieties, with the effect more pronounced in Danda, reflecting genetic traits associated with extended vegetative growth. Seasonal variation also contributed, as values in 2022 were generally 1–2 days longer than in 2021, likely due to differences in rainfall and temperature. These results are consistent with recent studies. Biramo et al. (2023) reported that barley maturity was significantly delayed under higher NPSB application, while Yadete et al. (2024) observed that increased plant density extended maize maturity through competition for assimilates. Likewise, Wakwaya et al. (2023) confirmed that higher NPS fertilizer rates prolonged wheat maturity by enhancing vegetative growth. Collectively, these findings reinforce that genotype, plant density, and nutrient management are critical determinants of wheat phenology.

Effects on the Total and Productive Number of Tillers per m^2. The total tiller number in wheat was influenced by variety, seeding rate, and NPSB application. Wane produced 150–285 tillers per m^2, while Danda ranged from 150–287 tillers per m^2, with Danda 125×150 achieving the maximum (286.6–287 m$^{)}$ slightly exceeding Wane. At low seeding rates (75 kg ha^{-1}), tiller numbers were lowest (≈151–156 m^2), but increasing to 125 kg ha^{-1} markedly enhanced tiller production, especially with NPSB fertilizer. Without NPSB, tillers remained low (≈150–152 m^2), whereas 150 kg ha^{-1} NPSB raised values to 240–287 m^2. These results agree with Shigedib & Bitew (2023) and Yang et al. (2010), who reported that optimal seed density and nutrient supply significantly improved tillering. Slightly higher values in 2022 suggest seasonal conditions favoured tiller survival. Productive tiller number in wheat was significantly affected by variety, seeding rate, and NPSB application in both years (Tables 1 & 2). Wane produced 103–253 tillers m^2, while Danda ranged from 102–261 tillers/m^2, with the maximum under 125×150 seeding and fertilizer. At low seeding rates and without fertilizer, productive tillers were lowest (≈103–108 m^2), whereas higher seeding rates combined with 150 kg ha^{-1} NPSB markedly increased fertile tillers, exceeding 250 m^2. Danda consistently outperformed Wane under intensive inputs, reflecting stronger tillering capacity and better conversion of total tillers into spikes.

These results agree with Shigedib & Bitew (2023, who reported that optimal seed density and nutrient supply enhanced productive tillers.

Table 1. Main effects of Cropping year, Varieties, Seeding Rates, and NPSB Fertilizer Blends on Wheat Yield Components and Productivity, N=144

Treatment	Plant Height (cm)	Leaf area index (%)	Days to 50% Heading	Spike length (cm)	Kernels per spike	Thousand kernels weight (g)	90% maturity	Total tillers	Productive tiller	Biomass Yield (t ha^{-1})	Grain yield (t ha^{-1})	Harvest index (%)
Cropping year (CY)												
2021	50	45^{b}	54	8.3	44	34	119	149	139	9.2	4.7	46.7
2022	51	48^{a}	55	8.4	43	37	124	157	149	9.6	4.8	57.8
LSD (5%)	ns	2.5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Varieties (V)												
Wane	52.3^{b}	44^{b}	54^{b}	8.3^{a}	43	34.5^{b}	118	151	133^{b}	9.83	4.32^{b}	46.5^{b}
Danda	54.7^{a}	53^{a}	57^{a}	7.4^{b}	42.6	38.7^{a}	120	163	147^{a}	9.32	5.36^{a}	57.8^{a}
LSD	1.9	13	1.5	0.64	ns	0.5	ns	ns	15	ns	0.97	ns
Seed Rate (SR) (kg ha^{-1})												
75	58.2^{a}	48	53^{b}	6.5^{c}	41.6^{b}	36.68	118^{a}	155	136.6	5.6^{c}	3.7^{c}	32^{c}
100	57.5^{a}	49	55^{ab}	7.6^{ab}	43.2^{a}	36.63	122^{a}	152	129	6.2^{b}	3.9^{b}	33^{b}
125	54.3^{b}	49	59^{a}	9.1^{a}	43.6^{a}	36.52	119^{b}	157	139	7.08^{a}	4.3^{a}	42^{a}
LSD	8.5	ns	1.57	1.3	1.03	ns	0.6	ns	ns	0.07	0.06	0.5
NPSB rate (kg ha^{-1})												
0	47.1^{d}	39^{c}	55^{b}	5.8^{c}	32.1^{d}	34.4^{d}	116^{c}	187^{ab}	105^{d}	5.6^{c}	3.5^{d}	32^{c}
50	53.5^{c}	42^{b}	57^{b}	6.3^{c}	36.2^{c}	35.5^{c}	120^{b}	188^{ab}	134^{c}	6.2^{b}	4.1^{c}	33^{b}
100	78.8^{b}	48^{a}	61^{a}	7.7^{b}	$47.\ 7^{b}$	37.5^{b}	136^{b}	178^{b}	152.3^{b}	7.1^{a}	4.9^{b}	40^{a}
150	92.5^{a}	49^{a}	61^{a}	8.9^{a}	55.1^{a}	38.8^{a}	139^{a}	190^{a}	195.6^{ca}	7.0^{a}	4.9^{a}	44^{a}
LSD (5%)	12	1.8	0.87	1.02	1.18	0.30	2.5	1.2	19.3	0.10	1.1	0.81
P values												
CY	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V	*	*	*	*	ns	*	ns	ns	*	ns	*	*
SR	*	ns	*	*	*	ns	*	ns	ns	*	*	*
NPSB	*	*	*	*	*	*	*	*	*	*	*	*
CY* V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY* SR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V* SR	ns	ns	ns	ns	ns	ns	ns	*	*	ns	ns	ns
V* NPSB	ns	ns	ns	ns	ns	ns	*	*	ns	*	*	*
CY*V* SR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY*V* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V*SR* NPSB	ns	ns	ns	ns	ns	ns	***	**	**	ns	ns	ns
CY*V*SR* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

This means sharing the same letters in a column do not significantly differ at the 5% probability level (ns = non-significant). Significance levels are denoted as *5%, **1%, and ***0.1%.

Table 2. Interaction Effects of Wheat Varieties, Seeding Rates, and NPSB Fertilizer on Maturity and Tiller Number across Two Years

Treatment combinations	Parameters					
Variety × Seed rate × NPSB (kg ha⁻¹)	90% Maturity (days)		Total tillers m^{-2}		Productive tillers m^{-2}	
	2021	2022	2021	2022	2021	2022
Wane 75×0	114^{p}	115^{o}	151.3^{k}	152^{k}	107^{g}	108^{g}
Wane 75×50	118^{m}	119^{m}	153^{j}	154^{j}	136^{ef}	137^{ef}
Wane 75×100	120^{k}	121^{k}	155.6^{h}	156^{h}	127.6^{f}	128^{f}
Wane 75×150	122^{i}	123^{i}	155^{h}	156^{h}	138^{ef}	139^{ef}
Wane 100×0	118q	119q	152^{k}	153^{k}	105^{g}	106^{g}
Wane 100×50	120^{k}	121^{k}	157^{g}	158^{g}	133.3^{ef}	134^{ef}
Wane 100×100	119^{l}	120^{l}	185.3^{e}	186^{e}	152.3^{de}	153de
Wane 100×150	124^{g}	125^{g}	240^{c}	241^{c}	228^{b}	229^{b}
Wane 125×0	106^{r}	107^{r}	150^{l}	151^{l}	103^{g}	104^{g}
Wane 125×50	118^{m}	119^{m}	161^{f}	162^{f}	131^{f}	132^{f}
Wane 125×100	120^{k}	121^{k}	194.3^{d}	195^{d}	162.3^{d}	163^{d}
Wane 125×150	125^{f}	126^{f}	285.3^{b}	286^{b}	253.3^{a}	254^{a}
Danda 75×0	118^{m}	119^{m}	151.3^{k}	152^{k}	107.6^{g}	108^{g}
Danda 75×50	122^{i}	123^{i}	153^{j}	154^{j}	136.6^{ef}	137^{ef}
Danda 75×100	122^{l}	123^{h}	154^{i}	155^{i}	129^{f}	130^{f}
Danda 75×150	130^{d}	131^{d}	155^{h}	156^{h}	139^{ef}	140^{ef}
Danda 100×0	117^{n}	118^{n}	152^{k}	153^{k}	105^{g}	106^{g}
Danda 100×50	121^{j}	122^{j}	156.6^{g}	157^{g}	134^{ef}	135^{ef}
Danda 100×100	128^{e}	129^{e}	185.6^{e}	186^{e}	152.3^{de}	153de
Danda 100×150	134^{c}	135^{b}	240.6^{c}	241^{c}	195.6^{c}	196^{c}
Danda 125×0	116^{o}	117^{o}	150^{l}	151^{l}	102.6^{g}	103^{g}
Danda 125×50	120^{k}	121^{k}	161^{f}	162^{f}	132.3^{f}	133^{f}
Danda 125×100	134^{c}	135^{c}	194.3^{d}	195^{d}	162.3^{d}	163^{d}
Danda 125×150	141^{a}	142^{a}	286.6^{a}	287^{a}	261^{a}	262^{a}
LSD (5%)	0.54	0.63	0.98	0.76	19.33	23
CV (%)	7.2	6.8	8.5	12	26	24

Whereas LSD, or Least Significant Difference, means that followed by the same letters within a column are not significantly different at a 5% probability level

Effects on the Biomass Yields. Biomass yield of wheat was significantly affected by variety and NPSB application (Table 3). Values ranged from 5.3 to 7.6 t ha⁻¹ in 2021 and 5.4–7.7 t ha⁻¹ in 2022. The lowest yield occurred under zero fertilizer (Wane *0*), while the highest was recorded at 150 kg NPSB in Danda (7.6–7.7 t ha⁻¹). Both varieties responded positively to increasing NPSB, with Danda consistently producing slightly higher biomass than Wane. Seasonal variation also contributed, as 2022 yields were marginally higher. These results agree with Panhwar et al. (2019), who reported that genotype and nutrient management strongly enhance wheat biomass production.

Effects on the Grain Yield and Harvest Index. Grain yield of wheat was significantly affected by variety and NPSB application. Yields ranged from 3.7 to 5.1 t ha⁻¹ in 2021 and 3.8–5.2 t ha⁻¹ in 2022. The lowest yield occurred under zero fertilizer (Wane 0), while the highest was recorded at 150 kg NPSB in Danda. Both varieties responded positively to increasing NPSB, with Danda consistently producing slightly higher yields than Wane. Seasonal variation contributed, as 2022 yields were marginally higher, reflecting favorable conditions. These results agree with Irfan et al. (2018) and Elsayed et al. (2025), who reported that genotype and nutrient management strongly enhance wheat grain yield. Harvest index (HI) was significantly affected by variety and NPSB application, ranging from 31–45% in 2021 and 31.5% to 45.5% in 2022. The lowest HI occurred under zero fertilizer (Wane 0), while the highest was recorded at 150 kg NPSB in Danda. Both varieties showed progressive increases with higher NPSB, with Danda consistently outperforming Wane. Slightly higher values in 2022 suggest favorable seasonal conditions. These results agree with earlier studies (Irfan et al., 2018).

Table 3. Interaction Effects of Variety and NPSB Fertilizer on Wheat Yield Metrics

	Parameters					
Variety × NPSB (kg ha^{-1})	Biomass Yield (t ha^{-1})		Grain Yield (t ha^{-1})		Harvest Index (%)	
	2021	2022	2021	2022	2021	2022
Wane 0	5.3^{c}	5.4^{c}	3.7^{c}	3.8^{c}	31^{c}	31.5^{c}
Wane 50	6.0^{b}	6.2^{b}	3.9^{b}	4.0^{b}	33^{b}	34^{b}
Wane 100	7.1^{a}	7.3^{a}	4.8^{a}	4.9^{a}	39^{a}	40^{a}
Wane 150	7.0^{a}	7.2^{a}	4.9^{a}	5.0^{a}	43^{a}	44^{a}
Danda 0	5.6^{c}	5.7^{c}	3.8^{c}	3.9^{c}	32^{c}	32.5^{c}
Danda 50	6.4^{b}	6.5^{b}	4.1^{b}	4.2^{b}	38^{b}	38.5^{b}
Danda 100	7.5^{a}	7.6^{a}	4.92^{a}	5.0^{a}	44^{a}	44.5^{a}
Danda 150	7.6^{a}	7.7^{a}	5.1^{a}	5.2^{a}	45^{a}	45.5^{a}
LSD (5%)	2	1.7	1.4	1.6	0.95	0.57
CV (%)	7.3	6.3	4.5	3.2	2.5	1.9

The least significant difference (LSD) test indicates that values followed by the same letter within a column are not significantly different at the 5% probability level.

Effects of Cropping years, Seeding and NPSB fertilization on the Resource Use Efficiency

Effects on Grain Nutrient Concentrations. Wheat varieties, seeding rates, and NPSB fertilization significantly affected grain nutrient concentrations (Table 4). Danda showed higher N (24.9 g kg-1), P (3.6 g kg-1), and K (6.2 g kg-1) than Wane (21.6, 2.2, and 5.2 g kg-1), consistent with Dobocha et al. (2019) and Abdisa et al. (2022). Increasing NPSB rates raised N, P, and K, peaking at 150 kg ha^{-1} (23.9 g kg-1 N, 3.8 g kg-1 P, 6.8 g kg-1 K), while the control recorded the lowest values. The highest seeding rate (125 kg ha^{-1}) also enhanced K (5.8 g kg^{-1}). Sulfur and boron showed minimal variation, aligning with Juhász et al. (2024).

Effects on the Nutrient Uptake and Efficiency. Nutrient uptake (kg ha^{-1}) was significantly influenced by both varieties and NPSB application rates (Table 4). The variety Danda (867.9 kg ha^{-1}) exhibited higher uptake compared to Wane (842.8 kg ha^{-1}), consistent with the findings of Wang et al. (2024). Increasing NPSB rates, particularly at 150 kg ha^{-1} (2232.9 kg ha^{-1}), markedly enhanced nutrient uptake, underscoring the importance of optimal fertilization practices (Adare et al., 2024).

Effects on the Physiological and Recovery Efficiency. The variety Danda (9.5% PE) outperformed Wane (8.2%), demonstrating superior nutrient-to-biomass conversion efficiency. Physiological efficiency (PE) increased with higher seeding rates, rising from 7.6% at 75 kg ha^{-1} to 10.6% at 125 kg ha^{-1}, indicating that denser planting enhances nutrient use efficiency. PE reached its maximum at 100 kg ha^{-1} NPSB (10.6%) but declined slightly at 150 kg ha^{-1} (9.15%), suggesting that excessive fertilization reduces efficiency (Abdeta et al., 2023). Nutrient recovery efficiency (NRE) was highest at 50 kg ha^{-1} NPSB (109.1%) and decreased progressively with increasing fertilizer rates.

Agronomic and Nutrient Use Efficiency. The Danda variety demonstrated superior agronomic efficiency (AE), recording 2.88 kg^{-1}, compared to Wane, which achieved 2.47 kg^{-1}. This difference highlights the genetic potential of Danda to utilize applied nutrients more effectively.

Table 4. Main effects of Cropping year, Varieties, Seeding Rates, and NPSB fertilization rates on wheat grain nutrient concentrations (g kg⁻¹) and nutrient use efficiency

Treatment	N (g kg⁻¹)	P (g kg⁻¹)	K (g kg⁻¹)	S (g kg⁻¹)	B (g kg⁻¹)	Nutrient uptake (kg ha⁻¹)	PE (%)	NRE (%)	AE (kg kg⁻¹)	NUE (%)
Cropping year (CY)										
2021	22	2.4	5.2	1.6	3.3	842	8.2	107	2.6	870
2022	23	2.6	5.8	1.9	3.2	857	8.5	109	2.8	875
LSD (5%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Varieties (V)										
Wane	21.6^{b}	2.2^{b}	5.2^{b}	1.7	3.1^{b}	842.8^{b}	8.2^{b}	$100.^{b}$	2.47^{b}	869.76
Danda	24.9^{a}	3.6^{a}	6.2^{a}	1.8	4.2^{a}	867.9^{a}	9.5^{a}	108.2^{a}	2.88^{a}	872.55
LSD	4.2	1.01	0.84	ns	1.37	24.2	0.9	6.5	0.36	ns
Seed Rate (SR) (kg ha⁻¹)										
75	17.8	3.3	4.7^{c}	1.28^{c}	3.6	1014.5	7.6^{c}	100.1^{c}	2.45^{b}	768.3^{C}
100	17.8	3.5	4.9^{c}	1.5^{b}	3.5	1047.8	9.07^{b}	95.1^{c}	2.5^{b}	930.42^{b}
125	18.3	3.6	5.8^{a}	1.52^{b}	3.5	1054.0	10.6^{a}	117.2^{a}	2.97^{a}	1038.22^{a}
LSD	ns	ns	0.97	0.52	ns	ns	0.76	7.5	0.32	66.12
NPSB rate (kg ha⁻¹)										
0	16.5^{c}	2.2^{d}	4.6^{c}	1.1^{d}	2.4^{c}	835.5^{c}	-	-	-	-
50	17.8^{c}	2.5^{c}	4.7^{c}	1.28^{c}	2.9c	857.8^{c}	7.99^{c}	109.1^{a}	2.01^{c}	903.5^{ba}
100	20.6^{b}	3.6^{b}	5.8^{b}	1.5^{b}	3.2^{b}	1229.6^{a}	10.6^{a}	103.8^{bc}	2.88^{b}	963.8^{a}
150	23.9^{a}	3.8^{a}	6.8^{a}	1.8^{a}	4.8^{a}	2232.9^{a}	9.15^{b}	100.4^{c}	3.07^{a}	869.74^{b}
LSD (0.05)	5.47	1.05	0.92	0.56	1.48	125	07.65	7.45	0.35	59.4
P statistics										
CY	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V	*	*	*	ns	*	*	*	*	*	ns
SR	ns	ns	*	*	ns	ns	*	*	*	*
NPSB	*	*	*	*	*	*	*	*	*	*
CY* V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY* SR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V* SR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY*V* SR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY*V* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V*SR* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CY*V*SR* NPSB	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by the same letter within a column are not significantly different at the 5% level (ns = non-significant). Significance levels: * = 5%, ** = 1%, *** = 0.1%. N, P, K, S, and B (g kg⁻¹) denote grain nitrogen, phosphorus, potassium, sulfur, and boron concentrations. PE (%) = Physiological Efficiency, NRE (%) = Nutrient Recovery Efficiency, AE (kg kg⁻¹) = Agronomic Efficiency, and NUE (%) = Nitrogen Use Efficiency.

Agronomic efficiency further improved with increasing fertilizer application, rising to 2.97 kg⁻¹ at a seed rate of 125 kg ha⁻¹ and peaking at 3.07 kg⁻¹ under 150 kg ha⁻¹ NPSB fertilization. Such results underscore the positive relationship between nutrient supply and yield performance, confirming earlier findings that higher nutrient inputs can enhance crop productivity (Abdisa et al., 2022). However, efficiency gains were not uniform across all indicators. Nutrient use efficiency (NUE) reached its maximum at a seed rate of 125 kg ha⁻¹, with a remarkable value of 138.22%, reflecting optimal synchronization between nutrient uptake and yield response. Beyond this threshold, NUE declined sharply to 869.74% at 150 kg ha⁻¹ NPSB, suggesting that excessive fertilization may surpass the crop's absorptive capacity, leading to nutrient imbalances and potential losses through leaching or volatilization.

Correlation Analyses among Growth and Yield Parameters

Grain yield (GY) in bread wheat was strongly associated with productive tillers (NPT, r = 0.88), kernel number (NK, r = 0.73**), above-ground biomass (AGBD, r = 0.93**), and thousand kernel weight (TKW, r = 0.78**). These traits represent the primary yield components, confirming that tillering capacity, kernel number, and biomass accumulation are the most critical determinants of yield. Similar findings were reported by Nasri et al. (2014) and Assefa et al. (2017), who emphasized the role of productive tillers and kernel number in yield improvement.

Phenological traits such as days to heading (DH) and days to maturity (DM) showed highly significant correlations with yield, indicating indirect influence through their effect on growth duration (Kumar et al., 2018). Plant height (PH) also correlated positively with GY (r = 0.86**), reflecting its contribution to biomass production, though excessive height may increase lodging risk (Lakew et al., 2019). Finally, harvest index (HI) was strongly linked to GY (r = 0.86**), highlighting the importance of efficient assimilate partitioning into grain. This agrees with Reynolds et al. (2017), who identified HI as a key physiological trait for yield improvement.

Table 5. Simple correlation coefficient (r) of growth and yield parameters of bread wheat varieties

	DH	DM	PH	NTT	NPT	SL	NK	TKW	AGBD	GY	HI
DH	1										
DM	0.60**	1									
PH	0.74**	0.78**	1								
NTT	0.76**	0.81**	0.83**	1							
NPT	0.90**	0.63**	0.75**	0.64**	1						
SL	0.67**	0.76**	0.71**	0.60**	0.5**	1					
NK	0.76**	0.79**	0.84**	0.91**	0.90**	0.82**	1				
TKW	0.77**	0.9**	0.6**	0.55*	0.71*	0.61**	0.56**	1			
AGBD	0.78**	0.80**	0.89**	0.93**	0.92**	0.69**	0.60**	0.06	1		
GY	0.73**	0.78**	0.86***	0.94**	0.88**	0.77**	0.73**	0.78**	0.93**	1	
HI	0.44	0.41	0.67**	0.61*	0.77**	0.54	0.58	0.38	0.34	0.86**	1

DH (Days to heading), DM (Days to maturity), PH (Plant height), NTT (Number of total tillers), NPT (Number of productive tillers), SL (Spike length), NK (Number of kernels), TKW (Thousand kernel weight), AGDB (Above ground dry biomass), GY (Grain yield), and HI (Harvest index)

Conclusions

This study concludes that synchronizing seed rate with balanced fertilization is essential for optimizing bread wheat production in Central Ethiopia. The superior-performing variety, Danda, combined with a seed rate of 125 kg ha⁻¹ and 150 kg ha⁻¹ of blended NPSB fertilizer, formed the optimal strategy. This package maximized grain yield (5.2 t ha⁻¹) and nutrient use efficiency by enhancing productive tillers, thousand-kernel weight, and harvest index. Adopting this integrated approach is recommended to close the yield gap, improve input efficacy, and increase farmer profitability in the Kambeta Zone and similar agro-ecologies.

Author contributions: D.M.: Conceptualization, Methodology, Data Curation, Analysis; H.K.: Supervision, Validation, Writing - review & editing; M.M.: Investigation, Resources, Data Collection; B.M.: Analysis, Visualization, Literature Review, Writing – review & editing.

Acknowledgements: We thank Wachemo University for research facilities and the Hossana Agricultural Research Center staff for technical assistance. Permissions have been obtained to acknowledge them.

Funding statement: There are no funding institutions for this study.

Data availability: Data are available from the corresponding author upon reasonable request.

Competing interests` statement: No competing interests were disclosed.

Ethical Statement: Microsoft M365 Copilot was used only for language editing and formatting; no AI tools were used for data analysis or research activities.

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Optimizacija setvene norme i NPSB đubriva za povećanje prinosa i efikasnosti korišćenja hranljivih materija hlebne pšenice (*Triticum aestivum* L.) u zoni Kambeta, centralna Etiopija

Daniel Manore · Hiwot Kellbo · Melkamu Mathewos · Birhanu Mecha

Sažetak: Hlebna pšenica je vitalna osnovna kultura u Etiopiji, ali prinosi ostaju kritično niski zbog neoptimalnih agronomskih praksi. Značajan problem i dalje postoji u zoni Kambeta, gde niska plodnost zemljišta, prekomerne stope setve i preporuke za opšte đubrenje dovode do lošeg staništa za useve i ozbiljnog nedostatka hranljivih materija (N, P, S, B), što rezultira neprihvatljivo niskom efikasnošću korišćenja hranljivih materija (NUE <40%). Iako mešano NPSB đubrivo nudi potencijalno rešenje, precizna interakcija između normi setve, nivoa NPSB i modernih sorti pšenice ostaje nekvantificirana, što ometa razvoj lokalizovanih, efikasnih strategija upravljanja. Ovo istraživanje je dakle istražilo ovakve interakcije na sortama Wane i Danda. Faktorijalni eksperiment je testirao tri norme setve (75, 100, 125 kg ha^{-1}) i četiri nivoa NPSB (0, 50, 100, 150 kg ha^{-1}). Rezultati su pokazali da je sorta Danda konstantno nadmašila Wane u prinosu zrna i komponentama prinosa. Optimalna kombinacija bila je setvena norma od 125 kg ha^{-1} sa 150 kg ha^{-1} NPSB, koja je postigla najveći prinos zrna (5,2 t ha^{-1}) i superiornu produktivnost bočnih izdanaka značajnim poboljšanjem produktivnih bočnih izdanaka, masu hiljadu zrna i žetvenog indeksa. Ovo istraživanje pruža definitivnu strategiju za smanjenje jaza u prinosima sinhronizacijom gustine setve sa adekvatnim đubrenjem NPSB-om, nudeći poljoprivrednicima precizan recept za povećanje produktivnosti i efikasnosti hranljivih materija u uzgoju pšenice.

Ključne reči: agrotehnologija, efikasnost korišćenja hranljivih materija, Etiopija, hlebna pšenica, NPSB đubriva, NUE, setvena norma