

Research Article

Effects of Seeding and NPS Fertilizer Rates on Grain Yield, Yield Traits, and Quality of Durum Wheat Varieties in Bale Highlands, Southeastern Oromia

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Abstract

Despite its numerous benefits and yield potential, the current productivity of durum wheat in the highlands areas of Bale Zones, Southern Eastern Oromia is inhibited by soil fertility depletion and inappropriate plant densities per unit area and other interrelated factors. In this view, a field experiment was conducted in the 2023 and 2024 main cropping seasons at Sinana, Agarfa, and Gololcha districts to determine the optimum seeding and NPS application rates. The treatments used consisted of four seeding (125, 150, 175, 200 kg ha⁻¹) of durum wheat and three NPS rates (100, 150, 200 kg ha⁻¹), which constituted a total of 12 treatments per replication. The experiment was laid out in a Split-plot Design with a factorial arrangement in three replications. The results of the combined analysis revealed that the use of different levels of seeding and NPS rates significant affected grain yield and yield related-traits of durum wheat. At Sinana, 150 kg NPS ha⁻¹ that planted at 175 seeding rates of 175 kg ha⁻¹ produced the highest net benefit of ETB 206,433 ETB ha⁻¹ and 200096 with marginal rate of return 884.9 and 538.3%. At Gololcha, the same combination gave net benefits of ETB 210,048 and 212,472 ETB ha⁻¹ with an acceptable marginal rate of return 1011.9% and 123.8%. Whereas, at Agarfa, the higher grain yield (4,612 kg ha⁻¹) and a net benefit of ETB 253330 ha⁻¹ with an acceptable marginal rate of return 1708.2% attained when 150 kg NPS ha⁻¹ that planted by 175 seeding rates was used. Therefore, it can be concluded, that the above-mentioned combination of NPS and Seed rates per respective locations are agronomically and economically viable, and recommended for durum wheat production in the study areas.

Keywords

Durum Wheat, Grain Yield, Nps, Seeding Rate, Varieties, Economic Analysis

1. Introduction

Durum wheat (*Triticum turgidum* L. var. *durum*) is a staple crop of significant economic and cultural importance in the Ethiopian highlands. As an indigenous tetrapod species, it is uniquely adapted to the country's high-altitude environments [11]. Ethiopia is the largest producer of durum

wheat in sub-Saharan Africa, with the crop covering approximately 420,000 hectares of the 1.4 million hectares under total wheat production [31]. The Arsi and Bale highlands, where this study was conducted, are recognized as premier wheat-producing regions, contributing an estimated 30.5% of national wheat output [7]. With elevations

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ranging from 1900 to 2700 meters above sea level (m.a.s.l.) and favorable environmental conditions, these areas hold immense potential for durum wheat production.

Despite this potential, its productivity remains below genetic ceilings of durum wheat due to interrelated agronomic and soil fertility constraints. Sub-optimal planting density and imbalanced plant nutrient managements are the two critical yet poorly understood factors limiting yield and grain quality of this crop. Planting density governs resource capture by mediating intra-plant competition for light, water, and nutrients [11]; inappropriate seeding rates are common among farmers, leading to either excessive competition or inefficient land use [28]. Concurrently, soil fertility depletion is pervasive across the Ethiopian highlands. Decades of continuous cropping, complete removal of crop residues, limited organic amendments, and blanket application of di-ammonium phosphate (DAP) and urea have induced widespread deficiencies in secondary and micronutrients [29, 30]. This has prompted a national shift toward blended fertilizers such as NPS (Nitrogen, Phosphorus, Sulfur), designed to address multiple nutrient limitations simultaneously.

Although the individual effects of seeding density and nitrogen-phosphorus fertilizers on wheat are well documented globally, critical knowledge gaps exist for durum wheat production in the Bale highlands [10]. Specifically, there is no location-specific information on the interaction between seeding density and newly introduced blended NPS fertilizer rates. Optimal plant population may vary with soil fertility, as nutrient availability influences tillering capacity and plant architecture [24]. Moreover, no prior study has systematically evaluated this interaction across the distinct agro-ecological zones represented by Sinana, Agarfa, and Gololcha districts. These districts form a production gradient: Sinana (2400–4100 m.a.s.l.) represents a high-potential, intensive cereal zone; Agarfa (2500–3500 m.a.s.l.) typifies mid-altitude mixed crop-livestock systems; and Gololcha (1200–1500 m.a.s.l.) is a lowland, moisture-stressed area where wheat production is more challenging and poorly characterized. Agronomic packages developed for high-potential zones are often extrapolated to these contrasting environments, resulting in suboptimal outcomes.

Understanding how durum wheat responds to the interaction of planting density and balanced fertilization across diverse environments is essential for developing sustainable intensification strategies that enhance productivity, safeguard grain quality for the pasta industry, and improve the livelihoods of smallholder farmers in these varied landscapes. Hence, it is important to bridge the identified gap by generating location-specific agronomic recommendations. Therefore, the study was conducted to determine the effect of seeding and NPS fertilizer rates on the grain yield, yield-related traits and quality of durum wheat varieties.

2. Materials and Methods

2.1. Description of the Study Areas

The field experiment was conducted during the main cropping seasons of 2023 and 2024 at Sinana, Agarfa, and Gololcha agricultural research fields of Bale Zone, Oromia, Ethiopia. Sinana (7°00'–7°15' N, 40°00'–40°15' E; 2,400–4,100 m) is a highland area with a subtropical highland climate, dominated by barley and wheat cultivation. While Agarfa (6°45'–7°05' N, 39°45'–40°10' E; 2,500–3,500 m) features undulating plains and valleys, supporting mixed cereals and livestock. Whereas, Gololcha (6°15'–6°30' N, 40°30'–40°50' E; 1,200–1,500 m) comprises lowland plains with flat to gently rolling terrain.

2.1.1. Treatments and Experimental Design

The treatments used consisted of four seeding rates (125, 150, 175 and 200 kg ha⁻¹) and three NPS fertilizer rates (100, 150, and 200 kg ha⁻¹) using two durum wheat varieties (Begna and Bulala), resulting in 24 treatment combinations (2 × 4 × 3 = 24). The experiment was laid out in a Split-plot Design with a factorial arrangement in three replications. The size of each plot was 1.6 m × 2.5 m (4 m²), with a distance of 0.5 m between plots and 1.5 m between blocks. As inorganic fertilizer, N in the form of urea at a rate of 200 kg ha⁻¹ was applied to all plots uniformly. But NPS was applied at different rates as constituted in the treatments. Field activities, including land preparation, weed control and other agronomic management practices were carried out uniformly as per the recommendation for the varieties to all experimental plots.

2.1.2. Data Collected and Measurement

Plant height was measured from the ground level to the tip of the spike (excluding awns) at physiological maturity, using five randomly selected plants per plot. While Spike length was measured from the base of the rachis to the tip of the terminal spikelet (excluding awns) on the same five plants. The number of seeds per spike was determined from the five randomly sampled spikes taken from the net plot area. Also, grain yield was obtained by harvesting and threshing the net plot area, then converted to kg ha⁻¹. On the other hand, Total biomass weight was determined by harvesting whole plant parts (leaves, stems, and seeds) from the entire plot and expressed in kg ha⁻¹. Thousand kernel weights was measured by counting 1000 kernels from the grain yield of each net plot using an electronic seed counter and weighing them with an electronic sensitive balance. Hectoliter weight was also recorded as the weight of one hectoliter of grain per experimental plot, expressed in kg hL⁻¹.

2.2. Soil Sampling and Analysis

A representative composite soil sample was collected using an auger from the surface layer (0–20 cm) of the experimental field prior to planting. The collected soil sample was air-dried under shade, gently ground, and passed through a 2 mm mesh sieve to obtain a homogenous sample for analysis. Soil pH was measured potentiometrically in a 1:2.5 (soil: water) suspension using a digital pH meter calibrated with standard buffer solutions [36]. While organic carbon (OC) was determined using the Walkley-Black wet oxidation method, in which organic matter was oxidized with potassium dichromate in the presence of concentrated sulfuric acid, followed by titration with ferrous ammonium sulfate [37]. The total nitrogen (N) was analyzed by the Kjeldahl method, involving digestion with concentrated sulfuric acid and a catalyst mixture, distillation, and titration to quantify the ammonium content [6]. Available phosphorus (P) was extracted using the Olsen method (sodium bicarbonate, pH 8.5), and the phosphorus concentration in the extract was determined by a spectrophotometer using the ammonium molybdate blue color method [26]. Cation exchange capacity (CEC) was determined using the ammonium acetate method at pH 7.0, where the soil was leached with ammonium acetate to saturate the exchange sites with ammonium, followed by displacement with sodium chloride and quantification of the displaced ammonium. [8] Soil texture was determined using the Bouyoucos hydrometer method, dispersing the soil with sodium hexametaphosphate and measuring the proportions of sand, silt, and clay based on sedimentation rates according to Stokes' law [5]. All analyses were conducted at the Sinana and Kulumsa Agricultural Research Center Soil Laboratory section.

2.3. Data Analysis

All collected parameters were subjected to analysis of variance using of R.4.1 Software Version editions. The treatments means were compared using Least Significance Difference (LSD) test at 5% level of significance.

2.4. Partial Budget Analysis

To compare the economic feasibility of the treatments used, the economic analysis was carried out using the procedures described by [9] Economic evaluations of the effect of NPS and seeding rates were performed on the seed yield. Partial

budget was estimated for average yield of the different treatment combinations. Current costs of seeding and NPS rates were used for analysis. The potential response of crop towards the added fertilizer and price of fertilizers during planting ultimately determine the economic feasibility of fertilizer application [9]. To estimate economic parameters, grain yield was valued at an average open market price of 51 Ethiopian Birr (ETB) kg⁻¹. To estimate the total costs, mean current costs of NPS (40 ETB kg⁻¹) were collected at the time of planting. The mean current cost of seed was 65 ETB kg⁻¹. Cost of land preparation, field management, protection, storage, planting material, post-harvest, and others were not included in calculation as these are not variable costs. The dominance analysis procedure as described in [9] was used to select potentially profitable treatments from the range that were tested using the equation: $MRR = (\text{Change NI} / \text{change TVC}) \times 100$, Where NI = change in net income, TVC = change in total variable cost, MRR = Marginal rate of Return. Thus, MRR of 100% implies a return of one ETB on every Birr of expenditure in the given input. Finally, a treatment having marginal rate of return (MRR) between 50-100% was considered to be economically the best rates.

3. Results

3.1. Soil Physico-chemical Properties of the Experimental Sites Before Planting

The results of the selected physico-chemical properties of the soil before planting from the three locations (Sinana, Agarfa, and Gololcha) are presented in Table 1. The analytical results indicated that the soil textural class for the Sinana and Agarfa experimental sites was clay. While at Gololcha site the textural class was characterized by sandy clay loam class, with particle size distributions ranging from 40-65% clay, 15-50% sand, and 10-25% silt. On the other hand, the soil pH (H₂O) across the locations ranged from 5.8 to 6.5 (Table 1). The organic carbon (OC) content of the soils was 2.1%, 1.8% and 1.2% at Sinana, Agarfa and Gololcha, respectively. On the other hand, the total N content of the testing sites was 0.15% at Sinana, 0.18 at Agarfa and 0.09 at Gololcha. Cation exchange capacity (CEC) was 32.5 cmol (+) kg⁻¹ soil at Sinana, 22.1 cmol (+) kg⁻¹ at Agarfa, and 12.5 cmol (+) kg⁻¹ at Gololcha (Table 1).

Table 1. Soil physico-chemical property before planting.

No.	Soil characters	Values of soil samples			References
		Sinana	Agarfa	Gololcha	
1	Soil texture				

No.	Soil characters	Values of soil samples			References
		Sinana	Agarfa	Gololcha	
	Sand (%)	15	20	50	
	Clay (%)	65	60	40	
	Silt (%)	20	20	10	
	Texture Class	Clay	Clay	Sandy Clay Loam	
2	pH-H ₂ O (1:2.5)	6.5	6.2	5.8	
3	Organic Carbon (OC) (%)	2.1	1.8	1.2	[34]
4	CEC [cmol (+) kg ⁻¹]	32.5	22.1	12.5	[22]
5	P-Values	8–12 ppm	6–10 ppm	3–6 ppm	
6	Total Nitrogen (%)	0.15	0.18	0.09	[34]

3.2. ANOVA for Grain Yield and Yield-related Traits of Durum Wheat

As shown in Table 2, the results of the overall combined analysis of variance indicated that the application of NPS and seeding rates significantly affected grain yield and all other yield-related parameters of durum wheat varieties over locations. Also, the main effects of NPS, seeding rates and varieties were significantly affected all the tested parameters of the durum wheat varieties. On the contrary, the interaction of the NPS and seeding rates did not show significant variations between the treatments used on grain yield and yield related parameters of durum wheat varieties. On the other hand, seasons and locations had highly significant ($p < 0.001$) effects on all traits (PH, SL, SS, BM, GY, TKW, HLW), with location showing generally larger mean squares than seasons. Their significant interaction ($Y \times L$) for every trait ($p < 0.05$ to $p < 0.01$) means that year effects were not consistent across locations. For instance, a location might perform well in one year but poorly in another. So, main effects alone are misleading. As indicated in Tables 3-7, the response of grain yield and other parameters of durum wheat varieties were also varied among the tested locations to the applied treatments. Thus, a separate analysis and result discussions for each district was done as the variability in districts in their soil nutrient contents significantly affected the response of the treatments used (Table 1). Therefore, management and breeding strategies could

also account for site specific conditions. To this, at Sinana, the effects of NPS and Seeding rates, and the interaction of varieties and various levels of NPS fertilizer rates significantly affected the grain yield of durum wheat across the testing seasons. Likewise, the effects of NPS and seeding rates significantly affected the above dry-biomass. Whereas, the interaction of varieties, seeding rates and NPS rates did not show a significant effects on the all the tested parameters of durum wheat. Similarly, the main effects of Varieties, NPS and seeding rates did not show significant effects on plant height, spike length, number of grains per spike.

Similarly, at Golocha, the main effects of NPS fertilizer and seeding rates significantly influenced grain yield (Table 3). Also, the main effects of NPS and seeding rates significantly affected the above dry-biomass. Whereas, the interaction of varieties, seeding rates and NPS rates did not show a significant effects on the all the tested parameters of durum wheat over the tested seasons. Correspondingly, the main effects of varieties did not show significant effects to all the tested parameters.

On the other hand, at Agarfa, the results of the analysis of variance indicated that the interaction of various levels of seeding and applied NPS rates significantly ($P < 0.05$) grain yield of durum wheat (Table 4). The main effects of NPS and seeding rates also showed significant variations between the applied treatments on grain yield and above dry-biomass. But the interaction of the three factors and the main effects of varieties did not show a significant variation between the used treatments on the collected parameters.

Table 2. Mean squares from analysis of variance for agronomic traits of Durum wheat as affected by seed rate and NPS rate (pooled in 2023 and 2024).

Source of variation	Means square							
	DF	PH	SL	SS	BM ($\times 10^6$)	GY ($\times 10^6$)	TKW	HLW
Year (Y)	1	128.5***	15.2***	32.7***	9.84***	8.12***	22.4***	5.67***
LOC (L)	2	152.8***	12.5***	85.4***	22.9***	18.5***	37.6***	11.3***
Y $\times$ L	2	18.7**	1.23*	5.6**	1.78**	1.92**	4.1*	1.14*
Variety (V)	2	67.3***	2.45***	23.1***	6.78**	5.34**	15.2***	4.23***
Y $\times$ V	2	5.6 ^{NS}	0.32 ^{NS}	2.1 ^{NS}	0.57 ^{NS}	0.68 ^{NS}	1.8 ^{NS}	0.45 ^{NS}
L $\times$ V	4	9.8*	0.41*	4.3*	1.02 ^{NS}	1.21 ^{NS}	2.9 ^{NS}	0.82 ^{NS}
Y $\times$ L $\times$ V	4	4.2 ^{NS}	0.18 ^{NS}	1.9 ^{NS}	0.48 ^{NS}	0.55 ^{NS}	1.4 ^{NS}	0.36 ^{NS}
NPS (N)	2	40.2***	0.71***	14.8**	4.21**	4.03**	9.5**	2.82**
SR (S)	3	51.3***	0.89***	17.6***	4.98***	4.73***	11.9***	3.34***
N $\times$ S	6	12.1*	0.2 ^{NS}	5.7*	1.21 ^{NS}	1.53*	3.3*	0.99 ^{NS}
Y $\times$ N	2	7.6 ^{NS}	0.14 ^{NS}	3.1*	0.92*	1.03*	2.3 ^{NS}	0.72 ^{NS}
Y $\times$ S	3	8.3*	0.12 ^{NS}	2.9 ^{NS}	0.87 ^{NS}	0.95*	2.1 ^{NS}	0.68 ^{NS}
Y $\times$ N $\times$ S	6	5.2 ^{NS}	0.09 ^{NS}	2.1 ^{NS}	0.54 ^{NS}	0.62 ^{NS}	1.4 ^{NS}	0.43 ^{NS}
L $\times$ N	4	21.8**	0.28 ^{NS}	6.9*	1.79*	2.05**	4.2 ^{NS}	1.30 ^{NS}
L $\times$ S	6	27.5***	0.32*	9.1**	2.03**	2.38**	5.4**	1.62*
L $\times$ N $\times$ S	12	6.5 ^{NS}	0.11 ^{NS}	2.8 ^{NS}	0.76 ^{NS}	0.84 ^{NS}	1.9 ^{NS}	0.56 ^{NS}
V $\times$ N	4	15.7*	0.34*	4.9*	1.45*	1.68**	3.8 ^{NS}	1.12 ^{NS}
V $\times$ S	6	18.9**	0.41**	6.2*	1.87**	2.14**	4.7*	1.45*
V $\times$ N $\times$ S	12	8.3 ^{NS}	0.15 ^{NS}	3.4 ^{NS}	0.89 ^{NS}	0.97 ^{NS}	2.2 ^{NS}	0.67 ^{NS}
(Y $\times$ L $\times$ V $\times$ N)	*	*	*	*	*	*	*	*
Whole-plot error	46	9.2	0.21	4.1	1.12	1.23	2.5	0.79
Sub-plot error	168	6.8	0.14	2.9	0.82	0.91	1.7	0.58

DF=degree of freedom; PH=Plant height; SL=Spike length; SP= number of grains per spike, BM=Dry Biomass yield; GY=Grain yield; TKW=Thousand kernel weight, HLW=Hectoliter weight; * = Significant at P=0.05; ** = Significant at P=0.01; *** = Significant at P=0.001; NS = Non-significant. Y=Year, L=Location, SR=Seed rates, PS=N and Variety=V.

3.2.1. Mean Grain Yield of Durum Wheat Variety

NPS fertilizer rates and seed rates have significant main effects on grain yield at all the tested locations. At Sinana, the highest grain yield and above ground dry-biomass (3679.7 kg ha⁻¹ and 16769.5 kg ha⁻¹) was recorded at 200 kg NPS ha⁻¹ rates, which was statistically similar to 150 kg NPS ha⁻¹ rates (Table 3). While the lowest yield and dry bio-mass (3435.6 kg ha⁻¹ and 15648.7 kg ha⁻¹) was observed at 100 kg NPS ha⁻¹. Regarding Seed rates, the table shows a progressive increase in grain yield and above ground dry-biomass from 125 kg seeding ha⁻¹ to a maximum seeding rates of 200 kg ha⁻¹, after which yield plateaued at 200 kg seed ha⁻¹ (3675.1 kg ha⁻¹) with

no statistical improvement for grain yield. This pattern indicates that 175 kg seed ha⁻¹ is the optimal seed rate for maximizing yield at Sinana.

On the other hand, at Gololcha, mid altitude area, the main effects of NPS fertilizer and seeding rates significantly influenced grain yield of durum wheat (Table 4). Increasing the NPS rate from 100 to 200 kg ha⁻¹ raised grain yield from 3443.8 to 3849.6 kg ha⁻¹, which was not significantly different from the yield at 150 kg ha⁻¹. Regarding seeding rates, the Table 4, demonstrates a progressive increase in grain yield from 125 kg seed ha⁻¹ (3562.3 kg ha⁻¹) to 150 kg seed ha⁻¹ (3735.8 kg ha⁻¹) and further to 175 kg seed ha⁻¹ (3784.6 kg ha⁻¹), with the yield at 200 kg seed ha⁻¹ (3799.2 kg ha⁻¹) being statistically

similar to both 175 and 150 kg ha⁻¹. This indicates that the optimal seeding rate for Gololcha is 175 kg ha⁻¹, as increasing from 125 to 175 kg ha⁻¹ gave a gain of 222.3 kg ha⁻¹, while the additional increase to 200 kg ha⁻¹ added only 14.6 kg ha⁻¹a negligible and statistically insignificant difference.

At Agarfa, the interaction between various rates of NPS fertilizer rates and seeding rates significantly influenced grain yield (Table 5). The grain yields ranged from 3325.7 kg ha⁻¹ (at 125 kg seeding) to 3911 kg ha⁻¹ (at 175 kg seed), but all yields at this NPS level were statistically lower and did not differ significantly among seeding rates. Conversely, at the

medium NPS rate (150 kg ha⁻¹), raising the seed rate from 125 to 150–200 kg ha⁻¹ produced substantial yield gains. The combination of 150 kg NPS + 175 kg seed yielded 4586 kg ha⁻¹, and 150 kg NPS + 200 kg seed yielded 4612 kg ha⁻¹ both in the highest yielding category and significantly outperforming the 150 kg NPS + 125 kg seed treatment (3986.7 kg ha⁻¹). At the highest NPS rate (200 kg ha⁻¹), even the lowest seed rate (125 kg ha⁻¹) yielded 4416 kg ha⁻¹, which was statistically similar to all other seed rate combinations at this NPS level. No further yield benefit was gained by increasing seed rate beyond 125 kg ha⁻¹ under high NPS.

Table 3. The overall mean effects of seeding and NPS rates on Grain yield and dry-biomass of durum wheat varieties in 2023 and 2024 at Sinana.

NPS rates (Kg ha ⁻¹)	Grain Yield (kg ha ⁻¹)	Biomass (kg ha ⁻¹)
100	3435.6 ^b	15648.7 ^b
150	3653.8 ^a	16385.6 ^a
200	3679.7 ^a	16769.5 ^a
LSD (5%)	223.6	1224.3
Seed rates (kg ha ⁻¹)		
125	3402.5 ^b	14907.4 ^b
150	3617.2 ^{ab}	16435.2 ^a
175	3681.3 ^a	16620.4 ^a
200	3675.1 ^a	16921.3 ^a
LSD (5%)	258.3	1412.5
CV (%)	9.8	11.2

Table 4. The overall mean effects of seeding and NPS rates on Grain yield and other yield-related traits of durum wheat in 2023 and 2024 at Gololcha.

NPS rate (kg ha ⁻¹)	GY (kg ha ⁻¹)	BM (kg ha ⁻¹)	TKW (g)
100	3443.8 ^b	113,281 ^b	42.9 ^b
150	3823.9 ^a	130,52 ^a	44.7 ^a
200	3849.6 ^a	131,979 ^a	44.3 ^a
LSD (5%)	287.4	11,245	1.6
CV (%)	10.2	12.5	5.8
Seed rates			
125	3562.3 ^b	-	-
150	3735.8 ^a	-	-
175	3784.6 ^a	-	-
200	3799.2 ^a	-	-
	LSD (5%)= 189.6		

NPS rate (kg ha ⁻¹)	GY (kg ha ⁻¹)	BM (kg ha ⁻¹)	TKW (g)
CV (%)=10.2			

Table 5. Interaction effects of NPS and seeding rates on grain yield at Agarfa.

Treatment	Seed rates (kg ha ⁻¹)			
NPS Rate (Kg ha ⁻¹)	125	150	175	200
100	3325.7 ^c	3834 ^b	3911 ^b	3766 ^b
150	3986.7 ^b	4215.3 ^a	4586 ^a	4612 ^a
200	4416 ^a	4287.3 ^a	4616 ^a	4518 ^a
LSD (5%)	387.6			
CV (%)	11.4			

3.2.2. Biomass Yield (kg ha⁻¹)

At Sinana the highest Biomass yield (19352 and 18241 kg ha⁻¹) was obtained from Bulala and Begna respectively. While the lowest Biomass yields (9444.2 and 9629.56 kg ha⁻¹) was obtained from Begna and Bulala varieties with seeding rate of 125 and 125 kg ha⁻¹ at Sinana in 2023 (Table 7).

Table 6. The overall mean effects of seeding and NPS rates on Biomass yield of durum wheat in 2023 and 2024 at Agarfa.

Treatment	Level	Mean Biomass (kg ha ⁻¹)
NPS (kg/ha)	100	11,750 ^b
	150	13,903 ^a
	200	14,319 ^a
	LSD _{0.05} (NPS)	1,480
	125	11,130 ^c
Seed rate (kg/ha)	150	13,361 ^b
	175	14,204 ^a
	200	14,611 ^a
	LSD _{0.05} (SR)	1,290
	CV (%)	11.7

At Gololcha, NPS fertilizer rates had a significant mean effect on biomass yield (Table 4). Increasing the NPS rate from 100 kg ha⁻¹ (113,281 kg ha⁻¹) to 150 kg ha⁻¹ (130,520 kg ha⁻¹) resulted in a substantial biomass gain of 17,239 kg ha⁻¹. However, further increasing the NPS rate to 200 kg ha⁻¹ produced a biomass yield of 131,979 kg ha⁻¹, which was not significantly different from the 150 kg ha⁻¹ treatment [17].

At Agarfa, the overall mean effects of seeding and NPS rates on Biomass yield of durum wheat in 2023 and 2024 was significant (Table 6). Biomass yield increased progressively

with higher NPS and seeding rates, showing statistically significant differences among treatments. In case of NPS the highest biomass (13,903 kg ha⁻¹) was achieved with 150 kg NPS ha⁻¹ and 14,319 kg ha⁻¹ with 200 kg seed ha⁻¹, while the lowest (11,750 kg ha⁻¹) came from 100 kg NPS ha⁻¹. In case of seed rates, the highest biomass yield 14,204 kg ha⁻¹ was recorded from 175 kg ha⁻¹ and which was statistically significant with seed rates 200 kg ha⁻¹ (14,611).

3.2.3. Thousand Kernel Weight

At Gololcha, NPS blended fertilizer significantly influenced thousand kernel weight (Table 4). The lowest NPS rate (100 kg

ha⁻¹) produced the smallest TKW (42.9 g). The optimal rate was 150 kg NPS ha⁻¹, giving the highest TKW (44.7 g), a significant increase of 1.8 g over 100 kg ha⁻¹. Increasing NPS to 200 kg ha⁻¹ resulted in a slight, non-significant decline (44.3 g).

Table 7. Interaction effects of Varieties and Seeding rates on Biomass yield at Sinana.

Varieties	Seed rate			
	125	150	175	200
Begna	14444 ^d	17315 ^{abc}	18241 ^{ab}	17222 ^{abc}
Bulala	14444 ^{cd}	16296 ^{bcd}	16389 ^{bcd}	19352 ^a
CV (%)	4.5			
LSD (0.05)	1729.9			

3.2.4. Economic Viability of Durum Wheat Under Seeding and NPS Rates in Bale Zone

As it indicated in Table 10, the economic analysis at Sinana shown that the seeding rates at 175 kg ha⁻¹ gave the highest net benefit of ETB 206,433 ha⁻¹ was obtained from the use of 175 kg ha⁻¹ seeding rates, with an acceptable marginal rate of return (MRR) of 194.12%. Increasing seeding rate to 200 kg ha⁻¹ reduced net benefit to 204,794 ETB ha⁻¹ with a negative MRR, making it a dominated treatment. This indicates that the additional 25 kg of seed (costing 1,275 ETB) from 175 kg ha⁻¹ to 200 kg ha⁻¹ did not generate proportional yield increase. For NPS rates, the highest net benefit (200,096 ETB ha⁻¹) was achieved at 150 kg NPS ha⁻¹, with an accepting MRR of 538.3%. Increasing NPS to 200 kg ha⁻¹ reduced net benefit to 199,611 ETB ha⁻¹ with negative returns, making it dominated and uneconomical. Thus, the application of 150 kg NPS ha⁻¹ that planted in 175 kg ha⁻¹ seeding rate improved grain yield and the optimum rates for durum wheat production at Sinana.

On the other hand, the economic analysis at Gololcha revealed that the highest net benefit of 210,048 ETB ha⁻¹ and 212,472 ETB ha⁻¹ with an acceptable MRR (1011.9% and 123.8%) was obtained from the use of 150 kg NPS ha⁻¹ and 175 kg ha⁻¹ seeding rates, respectively. Increasing NPS to 200 kg ha⁻¹ reduced net benefit to 209,549 ETB ha⁻¹ with a negative MRR of -24.9%, indicating that the additional 50 kg of NPS (costing 2,000 ETB) did not generate sufficient yield increase to be economical. Also, increasing seeding rate to 200 kg ha⁻¹ reduced net benefit to 212,055 ETB ha⁻¹ with a negative MRR of -32.7%, demonstrating that excessive seed rates

are uneconomical. Hence, NPS rates at 150 kg ha⁻¹ and Seed rates at 175 kg ha⁻¹ are the optimal for durum wheat production at Gololcha, while higher rates of both inputs should be avoided due to negative marginal returns.

At Agarfa, however, the highest net benefit (253,615 ETB ha⁻¹) was obtained from the combined use of 150 kg NPS ha⁻¹ and 200 kg ha⁻¹ seeding rates, followed closely by (150 + 175 kg ha⁻¹) with 253,330 ETB ha⁻¹ and (200 + 175 kg ha⁻¹) with 253,085 ETB ha⁻¹. However, the marginal rate of return (MRR) for the 150 kg NPS and 200 kg ha⁻¹ seeding rates was only 22.35%, which is below the CIMMYT recommended threshold of 50–100%. However, the highest net benefit (253330 ETB ha⁻¹) with an acceptable MRR 1708.18% was attained from the combined use of 150 kg NPS ha⁻¹ and 175 kg ha⁻¹ seeding rates. The analysis revealed diminishing returns when increasing seeding rates beyond 175 kg ha⁻¹, as the additional 25 kg of seed (costing 1,275 ETB) generated only 285 ETB in additional net benefit. Within each NPS level, NPS (150 kg ha⁻¹) consistently outperformed NPS (200 kg ha⁻¹), confirming that excessive fertilizer application is uneconomical. For resource-limited farmers, (100 NPS ha⁻¹ + Seed rates 150 kg ha⁻¹) offers an excellent MRR of 2,235% with a respectable net benefit of 212,665 ETB ha⁻¹. So in general, the combination of NPS (150 kg ha⁻¹) and seed rates (175 kg ha⁻¹) is the most economically efficient recommendation for Agarfa, providing high net benefit with exceptional return on investment, while higher NPS rates (200 kg ha⁻¹) should be avoided due to negative marginal returns. Hence, it is advisable to use 150 kg NPS ha⁻¹ fertilizer that sown at a 175 kg ha⁻¹ seeding rates at Agarfa.

Table 8. Economic analysis of seeding and NPS fertilizer rate at Sinana.

Seed Rate (kg/ha)	GY (kg/ha)	ADGY (kg/ha)	TVC (ETB/ha)	GFB (ETB/ha)	NB (ETB/ha)	MRR (%)
125	3402.5	3062.3	6,375	199,050	192,675	-
150	3617.2	3255.5	7,650	211,608	203,958	884.9
175	3681.3	3313.2	8,925	215,358	206,433	194.12
200	3675.1	3307.6	10,200	214,994	204,794	D
NPS rates						
100	3435.6	3092	11,650	200,980	189,330	-
150	3653.8	3288.4	13,650	213,746	200,096	538.3
200	3679.7	3311.7	15,650	215,261	199,611	D

Table 9. Economic analysis of seeding and NPS fertilizer rate at Gololcha.

NPS rate (kg ha ⁻¹)	GY (kg/ha)	ADGY (kg/ha)	TVC (ETB/ha)	GFB (ETB/ha)	NB (ETB/ha)	MRR (%)
100	3443.8	3099.4	11,650	201,461	189,811	-
150	3823.9	3441.5	13,650	223,698	210,048	1,011.80
200	3849.6	3464.6	15,650	225,199	209,549	-24.9
Seed rates (kg ha ⁻¹)						
125	3562.3	3206.1	6,375	208,397	202,022	-
150	3735.8	3362.2	7,650	218,543	210,893	695.8
175	3784.6	3406.1	8,925	221,397	212,472	123.8
200	3799.2	3419.3	10,200	222,255	212,055	-32.7

Table 10. Economic analysis of seeding and NPS fertilizer rate at Agarfa.

NPS rates (Kg ha ⁻¹)	Seed rates (Kg ha ⁻¹)	GY (kg/ha)	ADGY (kg/ha)	TVC (ETB/ha)	GFB (ETB/ha)	NB (ETB/ha)	MRR (%)
100	125	3,326	2,993	10,375	194,545	184,170	-
100	150	3,834	3,451	11,650	224,315	212,665	2,235
100	175	3,911	3,520	12,925	228,800	215,875	252
100	200	3,766	3,389	14,200	220,285	206,085	-768
150	125	3,987	3,588	12,375	233,220	220,845	-
150	150	4,215	3,794	13,650	246,610	232,960	950
150	175	4,586	4,127	14,925	268,255	253,330	1,598
150	200	4,612	4,151	16,200	269,815	253,615	22
200	125	4,416	3,974	14,375	258,310	243,935	-
200	150	4,287	3,858	15,650	250,770	235,120	-691

NPS rates (Kg ha ⁻¹)	Seed rates (Kg ha ⁻¹)	GY (kg/ha)	ADGY (kg/ha)	TVC (ETB/ha)	GFB (ETB/ha)	NB (ETB/ha)	MRR (%)
200	175	4,616	4,154	16,925	270,010	253,085	1,409
200	200	4,518	4,066	18,200	264,290	246,090	-549

GY: Grain Yield; ADGY: Adjusted Grain Yield; TVC: Total Variable Cost; GFB: Gross Field Benefit; NB: Net Benefit; MRR: Marginal Rate of Return; D: Dominated treatment.

4. Discussion

4.1. Soil Physico-chemical Properties

According to [19], soil types used for cereal production vary from well-drained fertile soils to waterlogged heavy Vertisols. Thus, the soils of the highland experimental sites (Sinana and Agarfa) are suitable for the production of durum wheat, while the lowland site (Gololcha) presents a different agro-ecology. The pH values are considered moderately acidic to slightly acidic [34]. FAO (2000) reported that the preferable pH ranges for most crops and productive soils are 4.0 to 8.0. Also, [25] reported that an optimum pH range of 4.1 to 7.4 for cereal production. Thus, the pH of the experimental soils was within the suitable range for productive durum wheat growth.

4.2. Soil Chemical Properties

According to the ratings by [34] for interpreting soil test results, organic carbon values ranging between 1.5–3% fall in the medium range. Thus, the study sites ranged from low to medium in organic carbon content. This indicates a moderate to low potential of the soil to supply nitrogen to plants through mineralization. [34] has classified soil total N content between 0.12–0.25% as moderate and those values greater than 0.25% as high ranges. Cation exchange capacity (CEC) is an important parameter of soil because it gives an indication of the type of clay mineral present and its capacity to retain nutrients against leaching. According to Landon (1991), top soils having CEC greater than 40 cmol (+) kg⁻¹ are rated as very high, 25–40 cmol (+) kg⁻¹ as high, and 15–25 cmol (+) kg⁻¹ as medium. According to this classification, the soil from Sinana had a high CEC (32.5 cmol (+) kg⁻¹ soil), the soil from Agarfa had a medium CEC (22.1 cmol (+) kg⁻¹), while the soil from Gololcha (12.5 cmol (+) kg⁻¹) had a low CEC, indicating a variable capacity to retain cations across the sites.

4.3. Analysis of Variance and Treatment Effects

The significant interaction (Y × L) for every trait ($p < 0.05$ to $p < 0.01$) means that year effects were not consistent across locations. For instance, a location might perform well in one

year but poorly in another. So, main effects alone are misleading. Therefore, management and breeding strategies could also account for site specific conditions.

The finding for Sinana is consistent with [13] who reported an optimum NPS rate of 150 kg ha⁻¹ for bread wheat at Sinana due to diminishing returns and potential nutrient imbalance at higher rates. Similarly, work by the Ethiopian Institute of Agricultural Research ([12] at the Sinana Research Center (2019) confirmed that blended NPS fertilizer improves grain yield primarily through enhanced tillering and grain filling, but excess application beyond 150 kg ha⁻¹ results in lodging and reduced marginal returns, which aligns with the stagnation observed between 150 and 200 kg NPS ha⁻¹ in the present table. Regarding seed rates, [2] reported a similar optimum of 175 kg ha⁻¹ in the Sinana district, noting that lower seed rates (e.g., 125 kg ha⁻¹) result in inadequate plant population, poor canopy closure, and increased weed competition, while higher rates (200 kg ha⁻¹) cause excessive inter-plant competition.

At Gololcha, the effect likely arises because the blended NPS fertilizer (supplying nitrogen, phosphorus, and sulfur) meets crop nutrient requirements at 150 kg ha⁻¹, whereas excessive application may cause nutrient imbalances or increase lodging risk [4, 17]. The lower yield at 125 kg seed ha⁻¹ is likely due to inadequate plant population, poor canopy closure, and increased weed competition, whereas very high seeding rates (200 kg ha⁻¹) cause excessive inter-plant competition for light, moisture, and nutrients, often leading to lodging and increased disease pressure, particularly under Gololcha's relatively warmer conditions [20, 23, 27]. also noted similar patterns.

At Agarfa, the interaction is synergistic at medium NPS but becomes crossover-like (non-responsive) at high NPS. [1] indicated that under low NPS supply, increasing seed rate alone cannot compensate for nutrient limitation and yields remain poor regardless of plant density [32]. The synergistic interaction at medium NPS shows that adequate NPS supply enables crops to respond positively to higher seeding rates, likely through improved tillering and resource use efficiency [18]. The plateau at high NPS may result from excessive vegetative growth and increased lodging risk when both high NPS and high seed density are combined, particularly under Agarfa's high rainfall conditions [3]. Practically, for Agarfa, the best combinations are either 150 kg NPS ha⁻¹ with 175 or 200 kg seed ha⁻¹, or alternatively 200 kg NPS ha⁻¹ with only 125 kg seed ha⁻¹, depending on seed costs and lodging risk [16].

For Begna, near maximum yield is already achieved at 150–175 kg ha⁻¹ seeds per unit, and further increasing the rate to 200 provides no benefit in fact, a slight numerical drop occurs. In contrast, Bulala requires the highest seeding rate of 200 kg ha⁻¹ to reach its maximum yield, as lower rates (even 175 kg ha⁻¹) produce significantly less biomass. This pattern represents a crossover interaction, meaning the optimal seeding rate differs by variety.

At Gololcha, the effect on biomass is commonly attributed to the fact that blended NPS fertilizer meets crop biomass production requirements at 150 kg ha⁻¹ [17, 24], while excess application may lead to nutrient imbalances, reduced root efficiency, or increased vegetative lodging without further biomass accumulation. [14, 21]. At Agarfa, the biomass response was also significant [15].

Regarding thousand kernel weight at Gololcha, the plateau arises from two thresholds: nutrient saturation, where genetic potential for kernel weight is reached at 150 kg NPS and source-sink limitations, where excessive biomass (131,979 kg ha⁻¹) under 200 kg NPS restricts grain filling [35]. Therefore, the recommended NPS rate for Gololcha is 150 kg ha⁻¹ to maximize TKW, while seed rates (around 175 kg ha⁻¹) should support plant stand without directly affecting kernel weight [33] noted poor grain filling at low NPS, while [15] reported that adequate N, P, and S enhanced grain plumpness.

4.4. Economic Implications

The economic results confirm that both seed and NPS rates show diminishing returns beyond certain thresholds [27]. At Sinana, the MRR for increasing seeding from 150 to 175 kg ha⁻¹ was 194.12%, but further increase to 200 kg ha⁻¹ gave negative returns, indicating that the additional seed cost was not justified. Similarly, NPS at 200 kg ha⁻¹ was dominated. At Gololcha, negative MRRs for both inputs at the highest levels confirm that higher rates are uneconomical. At Agarfa, although the highest net benefit was obtained with 150 kg NPS + 200 kg seed, the MRR was only 22.35% (below the CIMMYT threshold of 50–100%), while the combination of 150 kg NPS + 175 kg seed gave a much higher MRR (1,708%) and almost the same net benefit. This makes the latter the most economically efficient recommendation for Agarfa. For resource-limited farmers, the 100 kg NPS + 150 kg seed rate also offers an excellent MRR (2,235%) with a respectable net benefit. Overall, the economic analysis strongly supports the use of 150 kg NPS ha⁻¹ and 175 kg seed ha⁻¹ as the optimal and most profitable rates across all locations, with higher rates (200 kg NPS or 200 kg seed) being consistently dominated or yielding negative marginal returns.

5. Conclusion

The appropriate use of plant density and balanced NPS fertilization is essential for enhancing sustainable durum wheat

productivity and supporting Ethiopia's food security and industrial demands. Based on two-year field trials across Sinana, Agarfa, and Gololcha in the Bale Zone, the NPS rate of 150 kg ha⁻¹ consistently produced grain and biomass yields statistically comparable to or higher than 200 kg ha⁻¹, while the seeding rate of 175 kg ha⁻¹ maximized yields at Sinana and Gololcha and delivered the best synergistic interaction (up to 4,586 kg ha⁻¹) at Agarfa when combined with 150 kg NPS. Economic analysis confirmed that this combination generated the highest net benefits (200,096–253,330 ETB ha⁻¹) with excellent marginal rates of return (194–1,598%). In contrast, increasing either input to 200 kg ha⁻¹ consistently yielded negative marginal returns, rendering such rates uneconomical. Therefore, for durum wheat varieties (Begna and Bulala) in the Bale highlands, the application of NPS at 150 kg ha⁻¹ with a seeding rate of 175 kg ha⁻¹ is agronomically optimal and economically efficient. Farmers are strongly advised to avoid higher rates of either input to ensure sustained productivity and profitability across seasons.

Abbreviation

NPS	Nitrogen, Phosphorus, Sulfur
DAP	Di-ammonium Phosphate
OC	Organic Carbon
CEC	Cation Exchange Capacity
N	Nitrogen
P	Phosphorus
S	Sulfur
PH	Plant Height
SL	Spike Length
SP	Number of Seeds per Spike
BM	Dry Biomass Yield
GY	Grain Yield
TKW	Thousand Kernel Weight
HLW	Hectoliter Weight
ANOVA	Analysis of Variance
LSD	Least Significance Difference
CV	Coefficient of Variation
DF	Degree of Freedom
Y	Year
L	Location
V	Variety
SR	Seeding/Seed Rate
MRR	Marginal Rate of Return
ETB	Ethiopian Birr (currency)
TVC	Total Variable Cost
GFB	Gross Field Benefit
NB	Net Benefit
ADGY	Adjusted Grain Yield
CIMMYT	International Maize and Wheat Improvement Center
CSA	Central Statistical Agency (Ethiopia)
EIAR	Ethiopian Institute of Agricultural Research
OARI	Oromia Agricultural Research Institute

SARC	Sinana Agricultural Research Centre
m.a.s.l.	Meters Above Sea Level
BSc	Bachelor of Science
MSc	Master of Science
E.C.	Ethiopian Calendar (used in the author's biography)

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Author Contributions

Jitu Alemi Tesega: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Data Availability Statement

All raw data collected during the 2023 and 2024 field experiments at Sinana, Agarfa, and Gololcha are stored at the Sinana Agricultural Research Centre (SARC) and Oromia Agricultural Research Institute (OARI). The summarized experimental data supporting the findings of this study are presented in the tables within the article. The full datasets are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



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Research Field

Jitu Alemi Tesega: Durum wheat agronomic optimization, Soil fertility and nutrient management, Blended fertilizer application effects, Seeding rate optimization for cereals, Grain yield and quality analysis, Economic analysis of crop production, Crop response to plant density, Sustainable wheat production systems, Yield trait evaluation in cereals, Location-specific agronomic recommendations.