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Effect of NPK fertilization and seed rate on barley (*Hordeum vulgare*) yield, yield component and nitrogen dynamics in semi-arid conditions

NPK gübreleme ve tohum oranının, yarı- kurak koşullarda arpa (*Hoordeum vulgare*) verimi, verim bileşenleri ve azot dinamikleri üzerindeki etkisi

Rahila ISLAMZADE [1*]

Tariverdi ISLAMZADE [1]

Gatiba HASANOVA [2]

Sultan HUSEYNOVA [1]

Tunzala BABAYEVA [1]

[1] Institute of Soil Science & Agrochemistry, 1073, Baku, Azerbaijan

[2] Research Institute Crop Husbandry, 1098, Baku, Azerbaijan

***** Corresponding author (Sorumlu yazar):

rehile.islamzade@gmail.com

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ABSTRACT

Objective: This study aimed to investigate the impact of varying of NPK fertilization doses and seed rates on barley (*Hordeum vulgare)* yield, yield components, and inorganic nitrogen (NH_4-N and NO_3-N) dynamics in semi-arid conditions without artificial irrigation.

Material and Methods: The field experiment was conducted at the Gobustan Experimental Station from October 2018 to June 2019, utilizing the "Celilabad-19" barley variety. A randomized complete block design with four replications was employed, incorporating various seed rates and NPK fertilizer treatments. Plant and soil samples were collected at different phenological stages, and analyses included grain and straw yield, yield parameters, total N content of plant, and soil NH_4-N and NO_3-N levels.

Results and Discussion: The results the treatment with a seed rate of 140 kg/ha and $N_{60}P_{45}K_{45}$ fertilizer application consistently demonstrated the highest aboveground biomass, grain, and straw yields. This treatment exhibited optimal N content during the Full Maturity stage of plant.

Conclusion: In conclusion, this study has provided insights into optimizing barley cultivation practices in semi-arid climates, such as seed rate and NPK fertilizer dose. With a seed rate of 140 kg/ha and $N_{60}P_{45}K_{45}$ fertilizer application, the highest yield and performance indicators were achieved in the “Celilabad-19” barley variety.

Keywords: Barley, fertilization, N dynamics, semi-arid climate, yield

ÖZ

Amaç: Bu çalışma, sulama yapılmayan yarı-kurak koşullarda değişen NPK gübreleme dozları ve tohum miktarlarının arpa (*Hordeum vulgare*) verimi, verim bileşenleri ve inorganik azot (NH_4-N ve NO_3-N) dinamikleri üzerindeki etkisini incelemeyi amaçlamaktadır.

Materyal ve Yöntem: Tarla denemesi, Ekim 2018-Haziran 2019 arasında Gobustan Deneme İstasyonu'nda "Celilabad-19" arpa çeşidi ile gerçekleştirilmiştir. Deneme farklı tohum miktarları ile NPK gübre uygulamalarını içermektedir. Bitkinin farklı fenolojik aşamalarda bitki ve toprak örnekleri alınmış ve bitkide tane ve sap verimi, verim parametreleri, bitkinin toplam N içeriği ile topraktaki NH_4-N ve NO_3-N seviyeleri belirlenmiştir.

Araştırma Bulguları: Sonuçlara göre, 140 kg/ha tohum miktarı ve $N_{60}P_{45}K_{45}$ gübre uygulamalarında, en yüksek toprak üstü bitki bioması, tane ve sap verimi elde edilmiş, bitkinin tam olgunluk aşamasında optimum N içeriğini sağlamıştır.

Sonuç : Bu çalışmada yarı-kurak iklimlerde tohum miktarı ve NPK gübre dozu gibi arpa yetiştirme uygulamalarını optimize etme konusunda bazı bilgiler elde edilmiştir. 140 kg/ha tohum miktarı ve $N_{60}P_{45}K_{45}$ gübre uygulamasıyla, Celilabad-19" arpa çeşidinde, en yüksek verim ve verim unsurları elde edilmiştir.

Anahtar sözcükler: Arpa, gübreleme, N dinamikleri, yarı-kurak iklim, verim

INTRODUCTION

Nitrogen (N) is a vital mineral nutrient essential for crop growth and yield, playing a pivotal role in plant productivity through its dynamic distribution and transformation within the soil (Stevenson 1982). The majority of total N, over 90%, exists in organic forms in the surface layer of most soils, with soil organic N significantly influencing plant nutrition by affecting microbial activity and nutrient availability (Bremner 1965). Inorganic N forms, like NH_4^+-N and NO_3^--N, availability, further affect plant and microbial utilization. In conventional agricultural fields, the primary entry of N into soils, apart from organic matter addition, predominantly occurs through chemical fertilizers. The potential movement of NO_3^--N below the root zone underscores the importance of efficient fertilizer N utilization (González-Prieto et al., 1997). N management in agricultural systems involves intricate interactions with other nutrients, such as phosphorus (P) and potassium (K), and judicious fertilizer application is crucial for maintaining soil fertility and optimizing crop growth (Srivastava & Lal, 1998). In specific agroecosystems, like rice-wheat cropping sequences in Vertisols of Chattishgarh, understanding the long-term effects of nutrient management on various N fractions is essential for precise N management and sustainable agricultural practices (González-Prieto et al., 1997). As demonstrated in China, rice cultivation's pivotal role underscores the significance of proper nitrogen fertilization for yield and quality improvement (Wang et al., 2019; Dong et al., 2020). However, excessive chemical fertilizer usage raises concerns about nutrient loss and reduced efficiency, necessitating rational nitrogen fertilization to alleviate soil quality degradation, environmental pollution, and declining rice yield and quality (Zhang et al., 2009; Li et al., 2020).

Phosphorus (P) and Potassium (K) are other essential plant nutrients, influencing various physiological processes and stress tolerance, often comparable in importance to nitrogen (Amtmann et al., 2008; Römheld & Kirkby, 2010). Its deficiency can lead to reduced crop yield and quality, especially in the face of climate change-induced droughts and heat stresses (Pettigrew, 2008; Sardans & Peñuelas, 2015). The interactions between N, P, and K have significant implications for plant functions, nutrient dynamics, and fertilizer use efficiency. Considering the potential impact of nutrient management on soil and plant interactions, it becomes evident that N, P, and K are common limiting factors affecting plant primary productivity (Usherwood & Segars, 2001; Du et al., 2022). In soils, N undergoes rapid processes such as transformation, mineralization, and nitrification, resulting in high mobility in the soil. In contrast, P and K are tightly adsorbed by soil components such as clay and lime, exhibiting much slower mobility in the soil compared to nitrogen (Strawn et al., 2015; Singh et al., 2023). The intricate dynamics between nitrogen dynamics in soils and NPK fertilization necessitate a comprehensive understanding for effective fertilization strategies (Arbačauskas et al., 2023).

Plant density stands out as a pivotal agronomic factor that significantly impacts yield, influenced by various factors such as cultivars, climatic conditions, and the chosen production system (Zandi et al., 2011). The ideal density for crop plants varies depending on the specific conditions of the growing area and the fertility status of the soil. Proper plant spacing plays a critical role in enhancing overall production by ensuring that each plant has equal access to essential resources like water and nutrients. Numerous research studies have been undertaken to ascertain the optimal plant density or seeding rate, reflecting the importance of this aspect in agricultural practices (Cupina et al., 2010; Dahmardeh et al., 2010; Uzun et al., 2017). Therefore, changes in nutrient quantities in plants and the availability of nutrients in soils will undoubtedly occur depending on plant density or seeding rate.

Several environmental factors, with soil moisture content being one of the most critical, affect the effectiveness of added nutrients or fertilizers to soils. Soil moisture content is crucial for nitrogen's oxidation from NH_4 to NO_3 and significantly influences the mobility of NO_3 formed as the final product of nitrification (Trevors et al., 2007). This situation particularly results in plants in arid and semi-arid regions being unable to utilize nitrogen adequately from the soil. In arid and semi-arid regions like Azerbaijan, barley stands as a vital cereal crop, playing a pivotal role in food security. The unique interplay of factors, including soil properties, climate change, and agricultural practices, significantly influences barley cultivation (Islamzade et al., 2023, 2024).

In this study, the impact of NPK fertilization applied to soils in different doses, along with varying seed quantities, on barley (Hordeum vulgare) yield, yield components, and changes in inorganic N forms in semi-arid climate conditions without any agricultural irrigation, was investigated through field experiment.

MATERIALS and METHODS

The field experiment was conducted at the Gobustan Experimental Station in the Mereze region, which is affiliated with the Azerbaijan Research Institute of Crop Husbandry (40°31’07.6372”N, 48°53’50.8362”E), spanning from October 2018 to June 2019. This experiment was carried out under rainfed conditions in Gobustan, Azerbaijan.

The Mountainous Shirvan region, where the Gobustan district is situated, manifests distinctive long-term climate patterns. The region experiences average annual temperatures ranging from 6 to 14°C, with the coldest months recording temperatures between 2 to 4°C, while the warmest period sees temperatures ranging from 15 to 25°C. Despite these fluctuations, the temperature generally maintains a stable attern. Annual precipitation in the area varies from 360 mm to 543 mm (average, 412 mm). Remarkably, the distribution of rainfall during the crop vegetation period fluctuates annually, influencing agricultural practices and necessitating adaptive water management strategies. These climatic characteristics play a crucial role in influencing agricultural sustainability and the overall well-being of the local population. The climate (precipitation and temperature) data for the experimental area over the long years and throughout the trial period are presented in Figure 1.

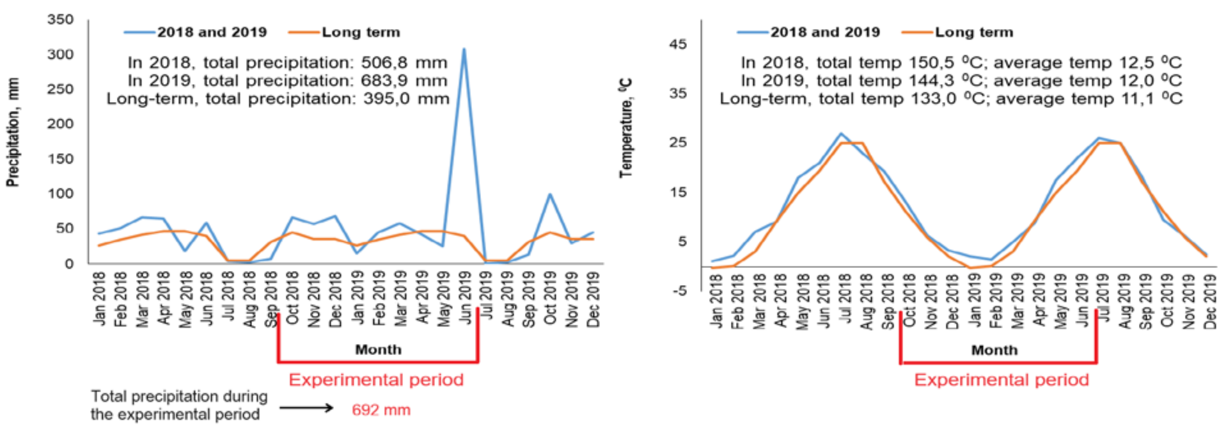


Figure 1. The climatic (precipitation and temperature) data of the experimental area.

***Şekil 1.** Deneme alanına ait iklim (yağış ve sıcaklık) verileri.*

At the commencement of the experiment, a soil sample from the experimental field was gathered, specifically a chestnut soil type. Various chemical properties of the soil were analyzed using methodologies delineated in Rowell (1996) and Jones (2001).

Experimental Design

The experimental framework incorporated the "Celillabad-19" barley (*Hordeum vulgare)* variety, renowned for its resistance to drought and rust diseases, and widely cultivated in the area. Executed between October 2018 and June 2019, the field trial adopted a randomized complete block design with 4 replications, yielding a total of 48 plots. Each plot, spanning 50 m² (25 m × 2 m), featured a 0.30 m gap between adjacent plots. Agricultural mechanization tools were employed to sow barley seeds 5 cm below the soil surface during the second week of October, aligning with the climatic conditions in Gobustan, Azerbaijan. Harvesting took place in June.

The experimental factors included diverse seed rates and NPK fertilizer doses. Seed rates in the experiment comprised 120 kg/ha, 140 kg/ha, and 160 kg/ha. Table 1 outlines the distinct NPK fertilizer treatments, encompassing application doses of 30, 45, and 60 kg/ha. The N fertilizer employed was NH_4NO_3 (33% N), P fertilizer was single superphosphate (Ca $(H_2PO_4)_2.H_2O$, 20.5% P_2O_5), and K fertilizer was Potassium sulphate (K_2SO_4, 46% K_2O). At seeding, the entire dose of P and K fertilizers, along with 30% of the N fertilizer, was applied. Subsequently, during the tillering stage in March, the remaining 70% of the N fertilizer was administered to the barley.

Table 1. Experimental design

Çizelge 1. *Deneme deseni*

Treatments	Seed Rate (kg/ha)	Nitrogen fertilizer rate (kg/ha)	Phosphorus fertilizer rate (kg/ha)	Potassium fertilizer rate (kg/ha)
120-$N_0P_0K_0$	120	0	0	0
120-$N_{30}P_{30}K_{30}$	120	30	30	30
120-$N_{45}P_{45}K_{45}$	120	45	45	45
120-$N_{60}P_{45}K_{45}$	120	60	45	45
140-$N_0P_0K_0$	140	0	0	0
140-$N_{30}P_{30}K_{30}$	140	30	30	30
140-$N_{45}P_{45}K_{45}$	140	45	45	45
140-$N_{60}P_{45}K_{45}$	140	60	45	45
160-$N_0P_0K_0$	160	0	0	0
160-$N_{30}P_{30}K_{30}$	160	30	30	30
160-$N_{45}P_{45}K_{45}$	160	45	45	45
160-$N_{60}P_{45}K_{45}$	160	60	45	45

Throughout the experimental duration, no artificial irrigation was implemented, and the utilization of pesticides was omitted. The trial was meticulously structured to explore the impacts of varying rates of seed and doses of NPK fertilizer on the growth, development, and yield of the barley, considering the inherent soil and climatic conditions. By concentrating on these specific elements, the experiment aspires to furnish valuable insights into sustainable barley cultivation practices tailored to the distinctive environmental characteristics in Gobustan, Azerbaijan.

Plant and Soil Sampling and Analyses

Prior to harvest, the plant height and spike height of plants in all plots were determined, and subsequently, plants in all plots were harvested. Following harvest, grain and straw yields, as well as yield parameters (spike weight, number of grains per spike, weight of grain per spike, and 1000 kernel weight), were determined for all plots. After harvest, grain and straw samples were dried at 65°C until reaching constant weight, ground (<0.5mm), and analyzed by the Kjeldahl method as described by Jones (2001). Additionally, plant samples taken at different phenological stages of the barley plant (tillering, stem extension, heading, and full maturity) were analyzed for total biomass and total N content of the aboveground parts of the plants using the Kjeldahl method (Jones, 2001).

Furthermore, soil samples were gathered at a depth of 25 cm across various phenological stages (tillering, heading, and full maturity) of the barley plant. The NH_4+-N and NO_3--N contents of these soil samples from all plots were determined by the Kjeldahl method in a 1 N KCl extraction. Available P_2O_5 was determined by spectrophotometry in a 0.5M $NaHCO_3$ extraction, and exchangeable K_2O was determined by flame photometry in a 1 N NH_4OAc extraction (Rowell, 1996).

Statistical Analysis

The data obtained from the research findings underwent statistical analysis through the utilization of the SPSS ver.26 software (Pallant, 2020).

RESULTS AND DISCUSSION

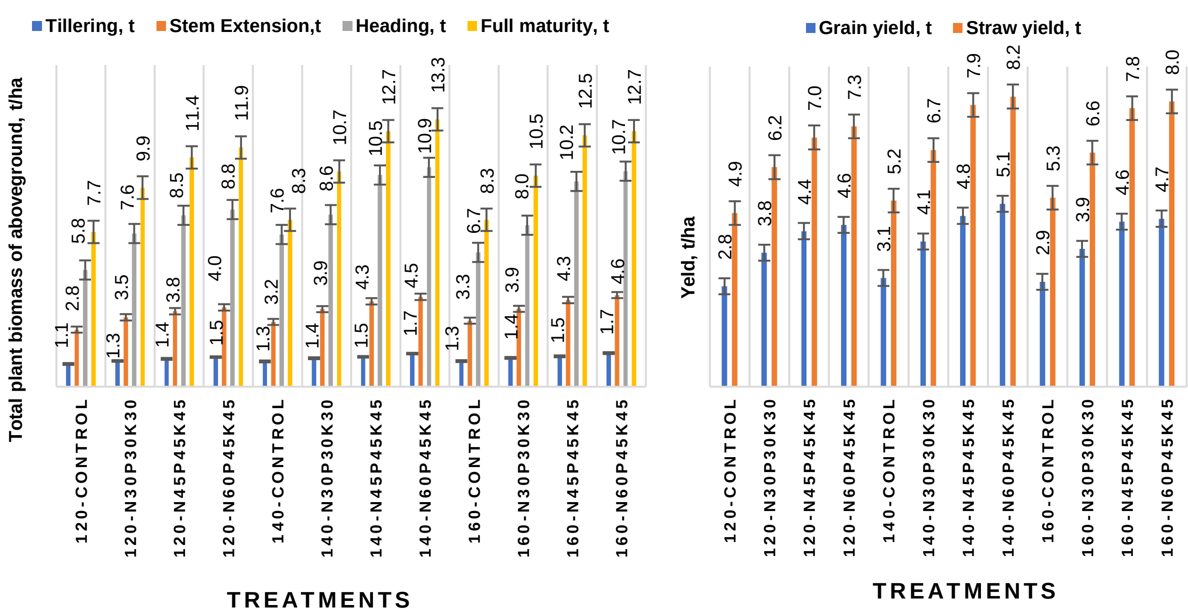
The outcomes derived from the analysis of soil samples gathered at depths of 0-25 cm, 25-50 cm, and 50-70 cm, aimed at investigating the soil properties of the experimental site characterized by Chestnut soil type, are outlined in Table 2. According to the findings, there is an evident increase in the content of calcium carbonate ($CaCO_3$) and a subsequent rise in soil pH as the subsoil depth increases. Conversely, in the uppermost 0-20 cm soil layer, higher concentrations of soil organic matter, total N, available N forms (NH_4 and NO_3), available P_2O_5, and exchangeable K_2O were observed. However, with increasing subsoil depth, a notable decrease in these nutrients was identified.

Table 2. Characteristics of Kastanozems soil type in the experimental area

Çizelge 2. *Deneme alanındaki Kastanozem toprak tipinin özellikleri*

Soil Dept (cm)	pH	$CaCO_3$ (%)	Organic Matter (%)	Total N (%)	NH_4-N (mg/kg)	NO_3-N (mg/kg)	Available P_2O_5 (mg/kg)	Exchangeable K_2O (mg/kg)
0-25	8.25	4.34	2.23	0.165	18.2	14.0	30.45	292
25-50	8.45	5.90	1.37	0.099	12.8	8.5	12.60	167
50-70	8.60	7.70	0.73	0.056	8.2	5.2	5.75	112

Figure 2 illustrates the effects of various fertilizer doses and seed rates on the aboveground total plant biomass of barley and yield at different phenological stages, including tillering, stem extension, heading, and full maturity. The analysis reveals that the maximum aboveground plant biomass was consistently achieved during the full maturity phenological stage across all NPK fertilizer applications (Figure 2a).



(a) (b)

	F value		F value	F value
Seed rate	1476754670.999***	Seed rate	21.500***	5.658***
Fertilizer dose	1966235571.665***	Fertilizer dose	141.044***	31.650***
Plant phenology	38970482942.307***			

Figure 2. Changes in total plant biomass of aboveground (a) and yield of grain and straw (b) across treatments.

Şekil 2. *Deneme süresince toprak üstü toplam bitki biyokütlesi (a) ile tahıl ve saman veriminin (b) uygulamalara göre değişimi.*

Additionally, a noteworthy trend indicates that as the nitrogen (N) application doses to the soil increased, there was a corresponding increase in aboveground plant biomass. The highest aboveground biomass was recorded with a seed application dose of 140 kg/ha and an $N_{60}P_{45}K_{45}$ fertilizer application dose. The analysis of grain yield and straw yield indicates notable trends (Figure 2b). The highest grain yield was consistently recorded in treatments with increased nitrogen (N) application doses and optimal seed rates. Similarly, the straw yield exhibited a positive correlation with the NPK fertilizer applications, with the maximum values observed in treatments involving higher nitrogen doses, specifically in the 140-$N_{60}P_{45}K_{45}$ application. These findings underscore the significance of balanced fertilizer doses and seed rates in enhancing both grain and straw yields in the specific semi-arid conditions of the study area.

Similarly, prior studies have corroborated that augmenting fertilizer application doses contributes to the improvement of plant biomass and crop yields (Shah et al., 2009; Nogalska et al., 2011; Wilczewski et al., 2013; Agegnehu et al., 2016). Papastylianou (1995) conducted a study investigating the effects of varying seed rates (60-150 kg/ha) and nitrogen (N) fertilizer applications (0-150 kg N/ha) on the productivity and yield components of barley over six growing seasons (1987-93) under rainfed conditions in Cyprus. Across all years and nitrogen levels, the highest seed rate elevated barley grain yield by 6 percent, while nitrogen fertilizer application increased yield by up to 25 percent. Under these rainfed conditions, maximum grain yield could be achieved at a low seed rate with the addition of N fertilizer. At low N levels, an increase in the seed rate did not significantly improve grain yield. Elevated seed rates and N fertilization levels suppressed yield, primarily due to their negative impact on the number of seeds per spike and the weight of individual grains. In seasons with assured early rain establishment, a low seed rate (140 kernels/m^2) is recommended, whereas in years with potential establishment challenges, an intermediate seed rate (240 kernels/m^2) is advisable. These recommended seed rates should be coupled with the optimum N fertilization for the specific site.

The consistent trend of achieving the maximum aboveground total plant biomass during the full maturity stage is grounded in the natural growth cycle of barley. This stage marks the culmination of the plant's reproductive phase, where it allocates energy towards maximizing biomass. The positive correlation between nitrogen (N) application doses and biomass can be attributed to the critical role of nitrogen in chlorophyll synthesis, photosynthesis, and overall plant growth. As nitrogen availability increases, the plant's metabolic processes are enhanced, leading to greater biomass accumulation. The noteworthy peak in aboveground biomass observed with a seed application dose of 140 kg/ha and an $N_{60}P_{45}K_{45}$ fertilizer application dose suggests a synergistic effect between optimal seed rates and a well-balanced NPK fertilizer composition, amplifying the growth-promoting impact of nitrogen.

The observed trends in grain and straw yields are intricately linked to the dynamics of nitrogen availability and its influence on barley's reproductive and vegetative phases. The positive correlation between N application doses and yield of grain underscores the pivotal role of nitrogen in supporting the development of grains. Nitrogen is a key component of proteins, enzymes, and chlorophyll, essential for photosynthesis, grain filling, and overall yield. Optimal seed rates complement nitrogen's effects by ensuring an adequate number of plants per unit area, maximizing the utilization of available nutrients. The peak in grain yield, consistently found in treatments with increased nitrogen doses and optimal seed rates, reflects the synergistic impact of these factors on barley productivity. Similarly, the positive relationship between straw yield and nitrogen doses, specifically in the 140-$N_{60}P_{45}K_{45}$ treatment, suggests that higher nitrogen availability contributes not only to grain development but also to increased vegetative biomass.

In essence, the observed patterns underscore the nuanced interplay between nitrogen availability, seed rates, and the distinct phenological stages in determining barley growth and yield. The treatment yielding the highest values in both biomass and yield metrics (140-$N_{60}P_{45}K_{45}$) showcases the intricate balance required for optimal results. This balanced approach ensures that the crop receives sufficient nitrogen for growth, complemented by an appropriate seed rate to maximize the utilization of available resources. The findings provide practical insights for optimizing agricultural practices in semi-arid climates, aligning with the principles of precision agriculture and sustainable crop management.

Table 3 encapsulates the variations in plant height, spike length, spike weight, number of grains per spike, weight of grain per spike, and 1000-kernel weight in response to different fertilizer doses and seed rates, providing insights into diverse yield parameters. The analysis of plant height reveals distinctive patterns influenced by varying fertilizer doses and seed rates. The treatment with the most substantial impact on plant height is observed in the 120-$N_{60}P_{45}K_{45}$ application, recording a notable increase. This suggests that the synergistic effect of well-balanced NPK fertilizer doses and seed rates, especially in the 120-$N_{60}P_{45}K_{45}$ treatment, contributes to enhanced plant height. Spike length exhibits variations across treatments, with the 120-$N_{60}P_{45}K_{45}$ treatment again standing out with an increased spike length. The positive correlation between nitrogen application doses and spike length aligns with the understanding that nitrogen is a key driver of plant growth and development. Spike weight demonstrates variations influenced by different fertilizer doses and seed rates.

Table 3. The effect of seed rates and NPK fertilizer treatments on barley crop yield components

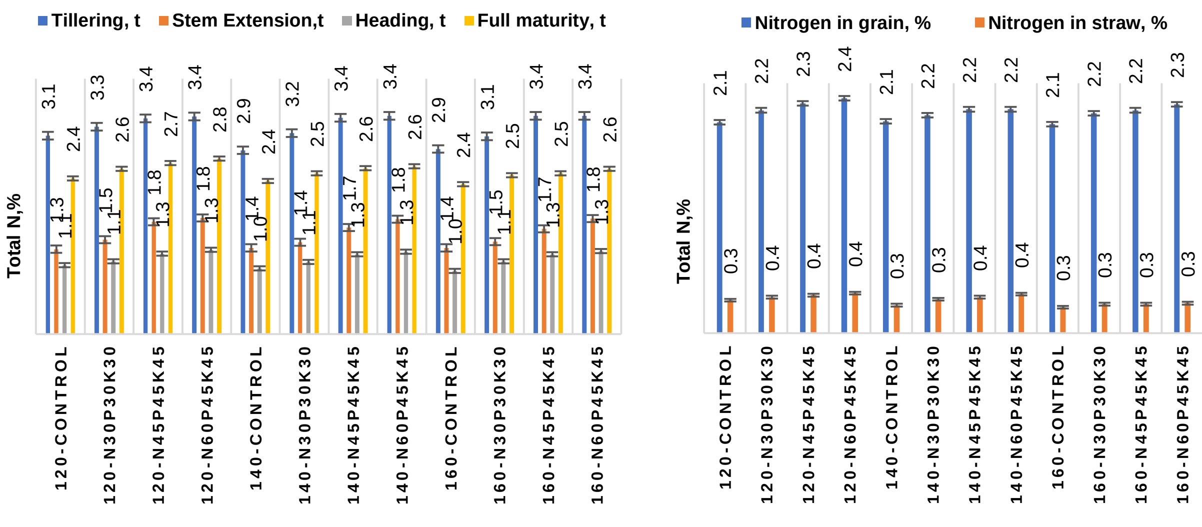
Çizelge 3. *Tohum miktarı ve NPK gübre uygulamalarının arpa verimi ve verim bileşenleri üzerine etkisi*

Treatments	Plant height (cm)	Spike length (cm)	Spike weight (g)	Number of grains per spike	Weight of grain per spike (g)	1000 kernel weight (g)
120-$N_0P_0K_0$	112.80 ± 1.55	13.20 ± 0.18	1.80 ± 0.04	27.70 ± 0.38	1.20 ± 0.02	45.60 ± 0.63
120-$N_{30}P_{30}K_{30}$	110.70 ± 1.51	15.40 ± 0.22	2.07 ± 0.09	28.25 ± 0.39	1.23 ± 0.02	46.00 ± 0.63
120-$N_{45}P_{45}K_{45}$	111.50 ± 1.53	15.00 ± 0.20	1.94 ± 0.03	29.70 ± 0.40	1.32 ± 0.031	46.20 ± 0.63
120-$N_{60}P_{45}K_{45}$	130.20 ± 2.35	15.70 ± 0.24	1.86 ± 0.04	28.60 ± 0.39	1.47 ± 0.03	47.60 ± 0.66
140-$N_0P_0K_0$	100.00 ± 1.37	16.80 ± 0.35	1.80 ± 0.04	27.50 ± 0.38	1.44 ± 0.03	46.90 ± 0.65
140-$N_{30}P_{30}K_{30}$	107.50 ± 1.46	17.60 ± 0.43	1.56 ± 0.02	23.70 ± 0.31	1.48 ± 0.031	49.20 ± 0.68
140-$N_{45}P_{45}K_{45}$	107.60 ± 1.46	17.70 ± 0.44	1.83 ±0.04	28.90 ± 0.39	1.57 ± 0.045	49.70 ± 0.68
140-$N_{60}P_{45}K_{45}$	100.50 ± 1.37	17.20 ± 0.41	1.90 ± 0.03	26.00 ± 0.37	1.69 ± 0.47	51.00 ± 0.70
160-$N_0P_0K_0$	112.00 ± 1.54	17.30 ± 0.41	1.73 ± 0.09	26.60 ± 0.37	1.38 ± 0.03	46.00 ± 0.62
160-$N_{30}P_{30}K_{30}$	100.90 ± 1.40	17.00 ± 0.40	1.54 ± 0.02	24.12 ± 0.32	1.45 ± 0.032	48.20 ± 0.66
160-$N_{45}P_{45}K_{45}$	105.60 ± 1.42	17.80 ± 0.45	1.85 ± 0.04	26.11 ± 0.37	1.54 ± 0.042	48.60 ± 0.67
160-$N_{60}P_{45}K_{45}$	111.20 ± 1.52	17.80 ± 0.45	1.65 ± 0.02	26.60 ± 0.37	1.62 ± 0.05	48.20 ± 0.66
	F value	F value	F value	F value	F value	F value
Seed rate	9.091***	25.467***	203.394***	126.292***	194.181***	6.703***
Fertilizer norm	4.012***	1.210***	9.952***	19.945***	214.206***	3.771***

The treatment with the most substantial impact on spike weight is observed in the 140-$N_{60}P_{45}K_{45}$ application. This emphasizes the importance of balanced nutrient availability, particularly nitrogen, in supporting the development of spikes. The number of grains per spike reveals an interesting trend, with the 120-$N_{45}P_{45}K_{45}$ treatment exhibiting the highest count. This suggests that the specific combination of seed rates and NPK fertilizer doses in this treatment optimally supports grain formation within the spikes. The weight of grain per spike exhibits variations, with the 140-$N_{60}P_{45}K_{45}$ treatment showing the highest value. This underscores the significance of nitrogen supplementation, particularly in treatments with well-balanced NPK fertilizer doses and seed rates, in promoting grain development within individual spikes. The analysis of 1000-kernel weight showcases variations influenced by different fertilizer doses and seed rates. The treatment with the most substantial impact is observed in the 140-$N_{60}P_{45}K_{45}$ application, emphasizing the role of balanced nutrient availability in supporting kernel development.

The results from Table 3 highlight the multifaceted impact of varying fertilizer doses and seed rates on diverse barley yield parameters. The treatments exhibiting the most substantial impacts underscore the importance of a well-balanced approach to nutrient management for optimizing plant growth, spike development, and grain yield. These insights provide practical implications for tailored fertilizer management strategies, contributing to enhanced barley yield and overall crop performance in semi-arid climates.

Figure 3 illustrates the variations in the total nitrogen (N) content of barley aboveground parts (tillering, stem extension, heading, and full maturity) in response to different fertilizer doses and seed rates. The examination of total nitrogen content in barley aboveground parts reveals notable dynamics across different phenological stages. The highest total nitrogen content consistently occurred during the Full Maturity stage for all treatments. Additionally, an upward trend in total nitrogen content was observed with increasing N application doses, suggesting a positive correlation between nitrogen supplementation and the nitrogen content in the aboveground parts of barley. The treatment with the most substantial impact was recorded in the 120-$N_{60}P_{45}K_{45}$ application during the Full Maturity stage (Figure 3a). These findings highlight the influence of varying rates of seed and NPK fertilizer doses on the N dynamics in barley, emphasizing their importance in optimizing nitrogen content at different growth stages. Observing the total nitrogen content in barley grain and straw, it is evident that the highest values are consistently achieved with the 120-$N_{60}P_{45}K_{45}$ treatment. Notably, there is a general trend of increased N content in both grain and straw with higher N application doses (Figure 3b). These findings emphasize the effect of NPK fertilizer doses and rates of seed on the nitrogen dynamics within barley components, shedding light on the potential for optimizing nitrogen content in both grain and straw through strategic fertilizer management.



(a) (b)

	F value		F value	F value
Seed rate	24.732***	Seed rate	102.722***	292.455***
Fertilizer dose	122.020***	Fertilizer dose	526.519***	121.788***
Plant phenology	3882.392***			

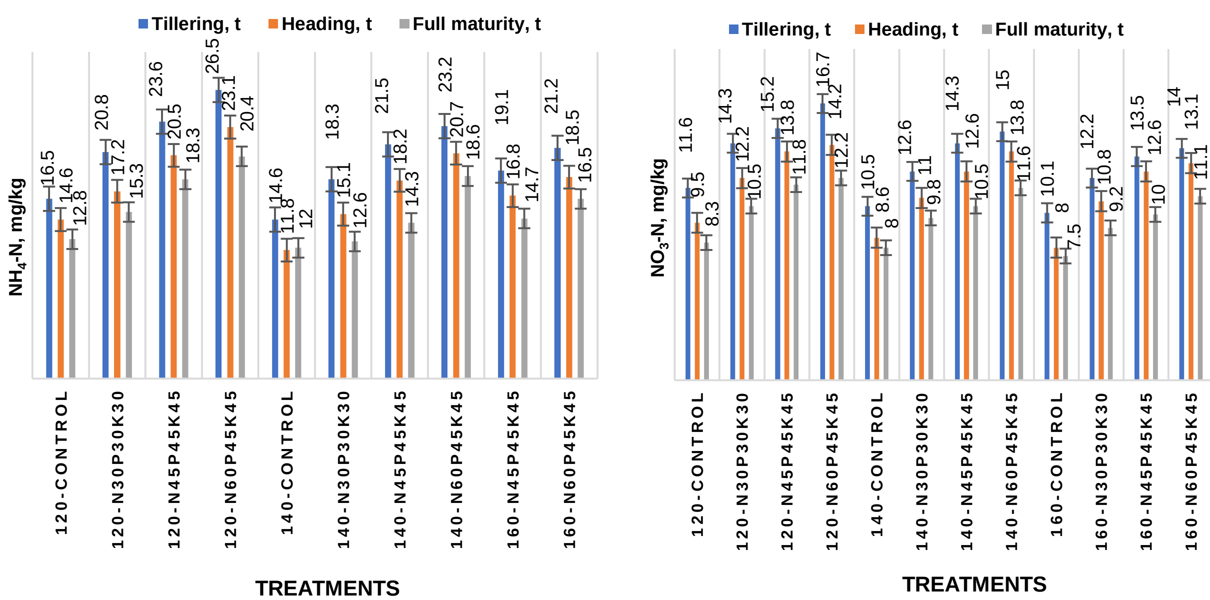
Figure 3. Changes in total N contents in total plant biomass of aboveground (a) and, grain and straw (b) across treatments.

Şekil 3. *Deneme süresince toprak üstü toplam bitki biyokütlesi (a) ile tane ve samanın (b) toplam N içeriğinin uygulamalara göre değişimi.*

The depiction of total nitrogen content in barley aboveground parts (tillering, stem extension, heading, and full maturity) reveals intriguing patterns throughout the growth cycle. The consistently higher total nitrogen content during the Full Maturity stage aligns with the plant's increased demand for nitrogen during the reproductive phase. This stage represents a critical period for grain filling, where a substantial allocation of nitrogen is directed towards protein synthesis in grains. The positive correlation between N treatment doses and total N content underscores the significance of nitrogen availability in supporting the plant's nitrogen requirements. The treatment with the most substantial impact, particularly evident in the 120-$N_{60}P_{45}K_{45}$ application during the Full Maturity stage, emphasizes the synergistic effect of well-balanced NPK fertilizer doses and seed rates in optimizing nitrogen content during the crucial reproductive phase. Similarly, studies conducted by Gülser et al. (2019), Alimkhanov et al. (2021), and Kızılkaya et al. (2022) have determined that fertilizer applications to plants not only increase the yield components and yield of the plant but also significantly enhance nutrient content in the plant. The assessment of total nitrogen content in barley grain and straw (Figure 3b) elucidates the impact of NPK fertilizer doses and rates of seed on nitrogen dynamics within these components. The consistent observation of the highest nitrogen content in both grain and straw with the 120-$N_{60}P_{45}K_{45}$ treatment aligns with the trends observed in aboveground biomass and yield components. This further underscores the interconnected influence of nitrogen, seed rates, and biomass accumulation. The general trend of increased nitrogen content in both grain and straw with higher N application doses highlights the pivotal role of nitrogen fertilization in enhancing nitrogen accumulation in barley components. The results emphasize the potential for strategic fertilizer management to optimize nitrogen content in both grain and straw, contributing to improved barley quality and overall crop performance.

The findings from Figure 3 underscore the intricate dynamics of nitrogen content in barley aboveground parts, grain, and straw. The results affirm the importance of a balanced approach to NPK fertilizer applications and seed rates in maximizing nitrogen content, particularly during critical growth stages. These insights provide valuable guidance for precision nitrogen management strategies, enhancing the sustainability and productivity of barley cultivation in semi-arid climates.

Figure 4 presents the variations in NH_4-N and NO_3-N contents in the soil at various phenological stages, influenced by different fertilizer doses and seed rates. The NH_4-N content in the soil exhibits variations across different growth stages, influenced by diverse fertilizer doses and seed rates. Generally, an increasing trend in NH_4-N content is observed with higher N application doses, emphasizing the impact of nitrogen fertilization on soil ammonium levels.



(a) (b)

	F value
Seed rate	2437.045***
Fertilizer dose	6612.035***
Plant phenology	4034.951***

	F value
Seed rate	510.795***
Fertilizer dose	2456.463***
Plant phenology	2404.830***

Figure 4. Changes in soil NH_4-N (a) and soil NO_3-N (b) contents across phenological stages of barley plant and treatments.

Şekil 4. *Arpa bitkisinin fenolojik aşamaları ve uygulamalara göre toprak NH4-N (a) ve NO3-N (b) içeriklerindeki değişiklikler.*

The highest NH_4-N content is consistently recorded in treatments with elevated nitrogen doses, particularly in the 120-$N_{60}P_{45}K_{45}$ treatment at Full Maturity (Figure 4a). Likewise, Rutkowski & Łysiak (2023) observed that incremental doses of N fertilizer application (0,60, and 120 kg N/ha) in soils dedicated to cherry cultivation led to a rise in the ammonium content within the soil. The NO_3-N content in the soil displays variations across different growth stages, responding to diverse fertilizer doses and seed rates. Generally, an increasing trend in NO_3-N content is observed with higher nitrogen (N) application doses, highlighting the influence of nitrogen fertilization on soil nitrate levels. The highest NO_3-N content is consistently recorded in treatments with elevated nitrogen doses, particularly in the 120-$N_{60}P_{45}K_{45}$ treatment at Full Maturity (Figure 4b). These findings emphasize the significance of nitrogen management in influencing NH_4-N and NO_3-N contents in the soil, providing valuable insights for optimizing soil nitrogen levels at different phenological stages.

Treatment impacts on soil NO^-_3 levels varied significantly. As the barley plant progressed from tillering to full maturity, a clear pattern in soil NO^-_3 content emerged (Alimkhanov et al., 2021). The decrease in soil nitrate content observed during the plant's growth stages is attributed to the active uptake of NO_3-N by the plant from the soil. This is in accordance with the notion that the growth of barley plants is contingent upon NO_3-N as a crucial nutrient for their development and overall growth (Tischner, 2000; Nacry et al., 2013).

The variations in NH_4-N content across different phenological stages illustrate the intricate relationship between nitrogen application doses and soil ammonium levels. The consistent upward trend in NH_4-N content with higher nitrogen doses reaffirms the direct influence of nitrogen fertilization on soil ammonium levels. This observation aligns with the fundamental role of ammonium in nitrogen cycling within the soil. The treatment with the most substantial impact, particularly evident in the 120-$N_{60}P_{45}K_{45}$ treatment at Full Maturity, highlights the importance of strategic nitrogen management. The higher NH_4-N content in this treatment underscores the synergistic effect of well-balanced NPK fertilizer doses and seed rates in optimizing ammonium availability in the soil during crucial growth stages. Similarly, the variations in NO_3-N content across phenological stages reveal the intricate dynamics influenced by nitrogen application doses and seed rates. The observed increasing trend in NO_3-N content with higher nitrogen application doses emphasizes the role of nitrogen fertilization in shaping soil nitrate levels. The highest NO_3-N content consistently recorded in treatments with elevated nitrogen doses, especially in the 120-$N_{60}P_{45}K_{45}$ treatment at Full Maturity, underscores the significance of nitrogen management in influencing soil nitrate dynamics. This finding aligns with the understanding that nitrate is a crucial form of nitrogen readily available to plants. The treatment exhibiting the highest NO_3-N content highlights the cooperative effect of well-balanced NPK fertilizer doses and seed rates in optimizing nitrate availability in the soil during critical growth stages. These observations contribute practical insights for tailored nitrogen management strategies, aiming to optimize soil nitrate levels and support the nutritional needs of the growing crops. In summary, the results from Figure 4 emphasize the nuanced influence of nitrogen application doses and seed rates on soil ammonium (NH_4-N) and nitrate (NO_3-N) dynamics. These insights contribute valuable information for optimizing soil nitrogen levels at different phenological stages, aligning with sustainable soil management practices in semi-arid climates.

CONCLUSION

The findings revealed significant trends in barley growth, yield components, and soil nutrient dynamics in response to different fertilizer applications and rates of seed. Notably, the synergistic effects of well-balanced NPK fertilizer doses and optimal seed rates, as observed in the 140-$N_{60}P_{45}K_{45}$ treatment, resulted in the highest aboveground biomass, grain yield, and straw yield during the Full Maturity stage. This underscores the importance of precision nutrient management in maximizing barley productivity under semi-arid conditions. The comprehensive analysis of plant parameters, including plant height, spike length, spike weight, number of grains per spike, weight of grain per spike, and 1000-kernel weight, highlighted the nuanced impact of fertilizer doses and seed rates on diverse yield parameters. The treatment-specific trends observed in these parameters underscore the need for tailored nutrient management strategies to optimize plant growth and yield components in semi-arid climates.

Furthermore, the investigation into the nitrogen content in barley aboveground parts, grain, and straw demonstrated consistent trends across different phenological stages. The positive correlation between N application doses and total N content, particularly during the full maturity stage, emphasizes the critical role of nitrogen in supporting barley's reproductive phase. The highest nitrogen content in both grain and straw in the 120-$N_{60}P_{45}K_{45}$ treatment underscores the potential for strategic fertilizer management to enhance nitrogen accumulation, contributing to improved barley quality and overall crop performance. Moreover, the study explored the variations in soil NH_4-N and NO_3-N contents at different phenological stages, shedding light on the influence of nitrogen fertilization on soil ammonium and nitrate dynamics. The observed trends provide practical insights for optimizing soil nitrogen levels, especially during critical growth stages, contributing to sustainable soil management practices in semi-arid climates.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: RI; sample collection: GH; analysis and interpretation of data:TI; statistical analysis: RI; visualization: SH; writing manuscript: TB.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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