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Effect of Different Levels of Urea on Growth, Yield, and Yield Attributes of Mustard under Kabul Agro-Climatic Conditions

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ABSTRACT: Nitrogen is a key macronutrient that plays an essential role in plant growth, development, and yield formation in oilseed crops such as mustard (Brassica juncea L.). Proper nitrogen management is important for improving productivity while ensuring economic efficiency and environmental sustainability, particularly in low-input farming systems like those in Afghanistan. This study was conducted to assess the effect of different urea (nitrogen) levels on the growth, yield attributes, phenology, and grain yield of mustard under Kabul agro-climatic conditions. A field experiment was arranged with four treatments: T_1 (0 kg urea ha^{-1}), T_2 (60 kg urea ha^{-1}), T_3 (80 kg urea ha^{-1}), and T_4 (100 kg urea ha^{-1}) using a randomized design. Data were collected on plant height, number of branches per plant, number of pods per plant, phenological traits (flowering and maturity), and grain yield. The results showed that nitrogen application significantly improved vegetative growth and yield components of mustard. Increasing nitrogen levels enhanced plant height, number of branches, and pods per plant. Grain yield responded positively to nitrogen application, with the highest yield consistently obtained at 80 kg urea ha^{-1}. However, further increase in nitrogen above this level did not result in proportional yield improvement, indicating diminishing returns. Phenological traits such as days to flowering and maturity were not significantly affected by nitrogen levels. Overall, the study concludes that moderate nitrogen application optimizes growth and yield of mustard without affecting its growth duration. The application of 80 kg urea ha^{-1} is recommended as the optimal rate for mustard production under Kabul conditions, as it improves productivity, enhances nitrogen use efficiency, reduces production costs, and supports sustainable agriculture.

KEYWORDS: Mustard, Brassica juncea, nitrogen management, urea, grain yield, oilseed crops.

INTRODUCTION

Mustard (Brassica juncea L.) is one of the most important oilseed crops cultivated globally, particularly in South Asia, East Asia, Africa, and parts of Europe. It is widely recognized for its high oil content (35–45%), adaptability to diverse environmental conditions, and multiple economic uses. Mustard oil is extensively consumed for cooking, traditional medicine, and industrial applications, while its by-products, especially the oilcake, serve as a protein-rich animal feed and an effective organic manure that contributes to soil fertility improvement[1,2]. Because of these attributes, mustard plays a significant role in improving food security, enhancing nutritional intake, generating rural income, and supporting employment in agricultural value chains in developing economies.

From an agronomic and ecological standpoint, mustard is considered a beneficial crop in sustainable farming systems. Its deep taproot system allows it to penetrate deeper soil layers, improving soil structure through enhanced porosity, aeration, and water infiltration. These improvements facilitate better root growth for subsequent crops in rotation systems. Furthermore, mustard residues contribute organic matter to the soil, which enhances microbial activity and promotes efficient nutrient cycling processes. Its inclusion in crop rotation systems is also important for breaking pest and disease cycles, thereby improving long-term soil health and crop productivity[3,1]. Due to these characteristics, mustard is increasingly recognized as a key component of sustainable and resource-efficient agricultural systems.

Mustard is particularly well adapted to marginal and low-input environments. Its relatively short growth duration, moderate water requirement, and ability to perform under rainfed and semi-arid conditions make it suitable for regions with limited agricultural resources. These characteristics are especially important for countries like Afghanistan, where agriculture is challenged by water scarcity, soil fertility decline, irregular rainfall, and limited access to agricultural inputs. Under such conditions, mustard provides an opportunity to improve cropping intensity, land-use efficiency, and farmer income during the rabi season.

In Afghanistan, domestic edible oil production is insufficient to meet national demand, resulting in a heavy reliance on imports. This situation places a financial burden on the national economy and highlights the need to increase local oilseed production. Mustard has strong potential to contribute to this goal due to its adaptability and economic value. However, actual productivity remains low compared to its genetic potential. Among several limiting factors, inefficient nutrient management—particularly nitrogen (N) fertilization—remains one of the most critical constraints affecting yield performance.

Nitrogen is a primary macronutrient essential for plant growth, development, and productivity. It is a key structural component of chlorophyll, amino acids, proteins, nucleic acids, and enzymes, all of which are fundamental to plant metabolism and physiological functioning. Nitrogen plays a central role in regulating photosynthesis, vegetative growth, and biomass accumulation. In mustard, adequate nitrogen supply promotes vigorous plant growth, increases leaf area development, enhances chlorophyll concentration, and improves overall photosynthetic efficiency, which collectively support higher yield formation.

The influence of nitrogen on mustard is particularly evident in vegetative and reproductive development. Adequate nitrogen enhances plant height, branching, leaf production, and dry matter accumulation, which serve as the foundation for reproductive success. It also improves siliquae formation, seed setting, and seed filling by increasing assimilate availability and translocation. In contrast, nitrogen deficiency leads to reduced chlorophyll content, poor vegetative growth, early leaf senescence, fewer branches, reduced siliquae formation, smaller seeds, and ultimately low yield[4,5].

However, nitrogen response is highly dependent on its rate, timing, and environmental conditions. While optimal nitrogen application improves both growth and yield, excessive nitrogen can lead to undesirable effects such as excessive vegetative growth, delayed flowering, increased susceptibility to lodging, and poor partitioning of assimilates toward reproductive organs. Additionally, over-application reduces nitrogen use efficiency and increases nitrogen losses through leaching, volatilization, and denitrification, which not only increases production costs but also contributes to environmental pollution and greenhouse gas emissions[6].

Urea is the most widely used nitrogen fertilizer in global agriculture due to its high nitrogen content (46%), low cost, and easy availability. In mustard cultivation, urea serves as the primary nitrogen source and is commonly applied either as a basal dose or in split applications. Split application is particularly effective in improving nitrogen uptake efficiency and reducing nutrient losses. However, the efficiency of urea depends on several factors, including soil type, temperature, moisture availability, and application method. Improper management often leads to low nitrogen use efficiency and suboptimal crop performance, despite adequate fertilizer input[4,7].

Recent studies have also highlighted that nitrogen not only affects yield quantity but also influences yield quality. In mustard, nitrogen affects oil content, protein synthesis, and seed composition. While moderate nitrogen levels generally enhance yield, excessive application may reduce oil percentage due to increased allocation of assimilates toward protein formation. This dual effect emphasizes the need for precise nitrogen management to balance both yield and quality parameters.

Integrated nutrient management strategies combining organic and inorganic fertilizers have been shown to improve soil fertility, enhance nutrient availability, and increase crop productivity. Organic amendments improve soil physical conditions, water-holding capacity, and microbial activity, while inorganic fertilizers provide immediately available nutrients required for rapid plant growth. The combined use of both sources has been reported to improve nutrient use efficiency and sustain productivity over time[8,7].

Despite extensive global research on nitrogen management in mustard, there remains a significant gap in region-specific information for Afghanistan, particularly under the agro-climatic conditions of Kabul. Soil fertility status, temperature fluctuations, rainfall distribution, and elevation strongly influence nutrient behavior and crop response. Therefore, findings from other regions cannot be directly applied without local validation.

In Afghanistan, farmers generally depend on traditional knowledge or generalized fertilizer recommendations, which often leads to either under-fertilization or over-fertilization. Both situations negatively affect crop growth, reduce yield potential, increase production costs, and decrease nitrogen use efficiency. This highlights the urgent need for systematic research to determine the optimum nitrogen level under local conditions.

Therefore, the present study was conducted to evaluate the effect of different urea levels on the growth, yield, and yield components of mustard (Brassica juncea L.) under the agro-climatic conditions of Kabul. The specific objective was to identify the most appropriate nitrogen rate that maximizes crop productivity, improves nitrogen use efficiency, and ensures environmentally sustainable mustard production. The findings of this study are expected to provide practical recommendations for farmers and contribute to improving oilseed production systems in Afghanistan.

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MATERIALS AND METHODS

The present study entitled "Effect of Different Levels of Urea on Growth, Yield, and Yield Attributes of Mustard (Brassica juncea L.) Under Kabul Agro-Climatic Conditions" was conducted at the Research Farm of the Agriculture Faculty, Kabul University during the 2025 growing season. The study aimed to evaluate the response of mustard to different nitrogen levels under field conditions representative of Kabul's semi-arid environment.

The experimental site is located at 34.3104°N latitude and 69.0823°E longitude at an elevation of about 1809 m above sea level. The field was uniform in fertility and topography, with irrigation supplied through a canal-connected tube well system, ensuring regular and controlled water availability throughout the experiment.

Kabul has a cold semi-arid climate characterized by hot summers, cold winters, and low annual rainfall. Seasonal variations in temperature, rainfall, and humidity strongly influence crop growth and nutrient dynamics. These conditions provided a suitable environment to evaluate nitrogen response under water-limited and variable climatic conditions.

Soil samples collected from 0–30 cm depth were analysed prior to the experiment. The soil was silty clay in texture with moderate fertility status and slightly alkaline pH. It contained adequate organic matter, phosphorus, and potassium, but required nitrogen supplementation for optimal crop performance.

The mustard variety Mustard 106, commonly cultivated and locally available, was used as planting material. This variety was selected due to its adaptability to local agro-climatic conditions.

Four nitrogen treatments were tested using urea as the nitrogen source: control (0 kg urea ha^{-1}), 60 kg urea ha^{-1}, 80 kg urea ha^{-1}, and 100 kg urea ha^{-1}. These levels were selected to represent a gradient of nitrogen supply for identifying the optimum dose for mustard production. Phosphorus was applied uniformly to all plots using DAP, while nitrogen was applied in split doses to improve efficiency and reduce losses.

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Each plot measured 2 m × 2 m, and rows were spaced 30 cm apart. Treatments were randomly assigned within each block to reduce experimental error.

Land preparation involved ploughing, harrowing, and levelling to obtain a fine seedbed. Sowing was carried out manually on 5 March 2025 at a depth of approximately 3 cm using a seed rate of 6 kg ha^{-1}. Germination started within five days, and more than 80% emergence was recorded by the sixth day.

Standard agronomic practices were followed throughout the growing season. Weeds were controlled manually through repeated hoeing. Irrigation was applied ten times based on crop requirement to avoid water stress. Nitrogen was applied in two splits: half at sowing and half at 25 days after sowing.

Harvesting was done on 14 July 2025 at physiological maturity. Plants were harvested manually, and post-harvest operations including drying, threshing, cleaning, and weighing were carried out carefully for yield determination.

Data were collected from ten randomly selected plants per plot, excluding border rows. Observations included plant height, number of branches per plant, number of pods per plant, pod length, number of seeds per pod, and grain yield. Phenological traits such as days to flowering and maturity were also recorded.

Statistical analysis was performed using STAR software. Data were analysed using ANOVA appropriate for RCBD, and treatment means were compared using LSD at 5% probability level ($P \leq 0.05$). Coefficient of variation (CV%) and correlation analysis were also used to assess variability and relationships among measured traits.

RESULTS

Field 1: The number of branches per plant was highly significantly influenced by urea levels. The control treatment (T_1) recorded the minimum number of branches (4.20), indicating limited vegetative branching under zero nitrogen. T_2 (60 kg urea ha^{-1}) produced a marginally higher number of branches (4.20) but was not significantly different from the control. T_3 (80 kg urea ha^{-1}) resulted in a substantial increase in branches (5.20), and T_4 (100 kg urea ha^{-1}) produced the highest number of branches per plant (5.50), which was statistically at par with T_3. The low coefficient of variation (2.84%) and a highly significant F-value (49.73**) indicate reliable and precise measurements, confirming a strong positive response to increased urea application.

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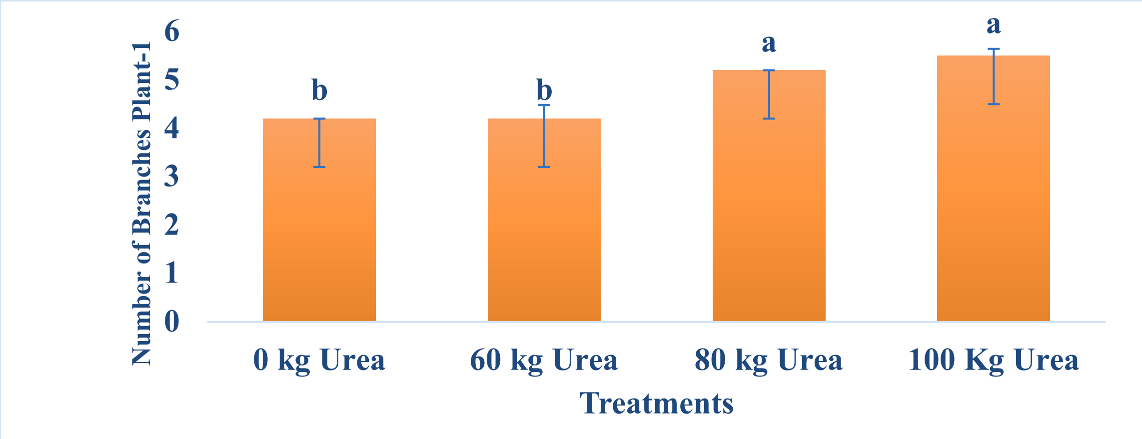

Figure 1: Number of Branches per plant F1

Field 2: Similarly, in Field 2, urea application significantly influenced branching. The control produced the lowest number of branches (3.50), followed by T_2 (3.70), which were statistically similar. T_3 produced the highest branching (5.60), with T_4 slightly lower (5.40), yet both were statistically superior to the lower urea treatments. The higher CV (9.66%) reflects slightly more field variability, but the F-value (12.59*) confirms statistical significance. These results suggest that increased nitrogen availability directly promotes lateral shoot development.

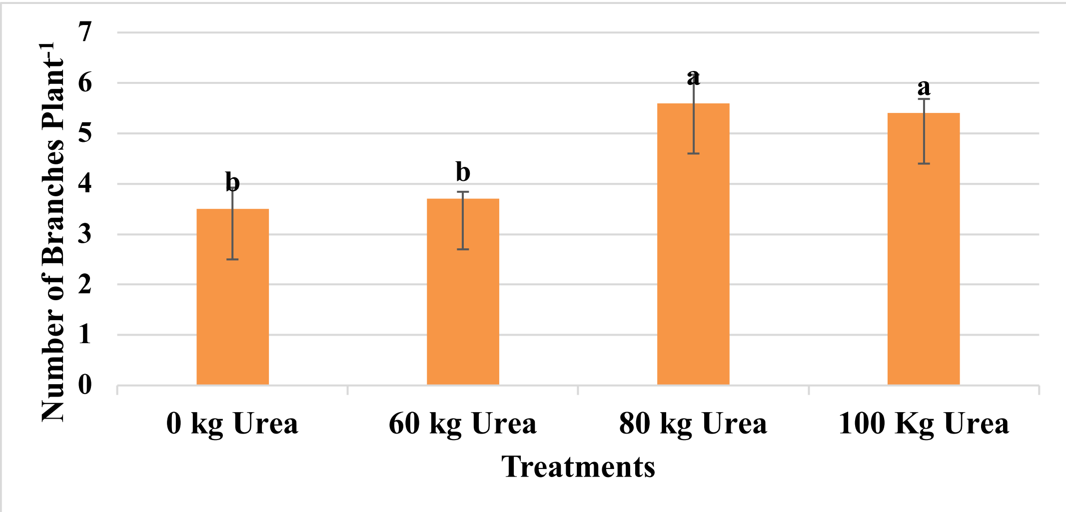

Figure 2: Number of Branches per plant F2

Combined interpretation: When considering both fields together, it is evident that higher urea levels (80–100 kg ha^{-1}) consistently enhance branching. This indicates that mustard plants respond positively to nitrogen in terms of vegetative proliferation, which is an essential trait for improved canopy development and potential yield formation. Across both fields, treatments T_3 and T_4 consistently produced the highest number of branches, establishing them as the most effective for vegetative growth under the studied conditions.

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Plant Height (cm)

Field 1: Differences in plant height were observed but not statistically significant. T_1 recorded the shortest plants (59.70 cm), while T_3 had the tallest (93.90 cm). T_2 and T_4 produced intermediate heights (76.60 and 91.30 cm, respectively). Although numerical trends suggest increased height with nitrogen, the F-value (5.79 ns) and moderate CV (11.52%) indicate that environmental or experimental variability may have masked statistical significance.

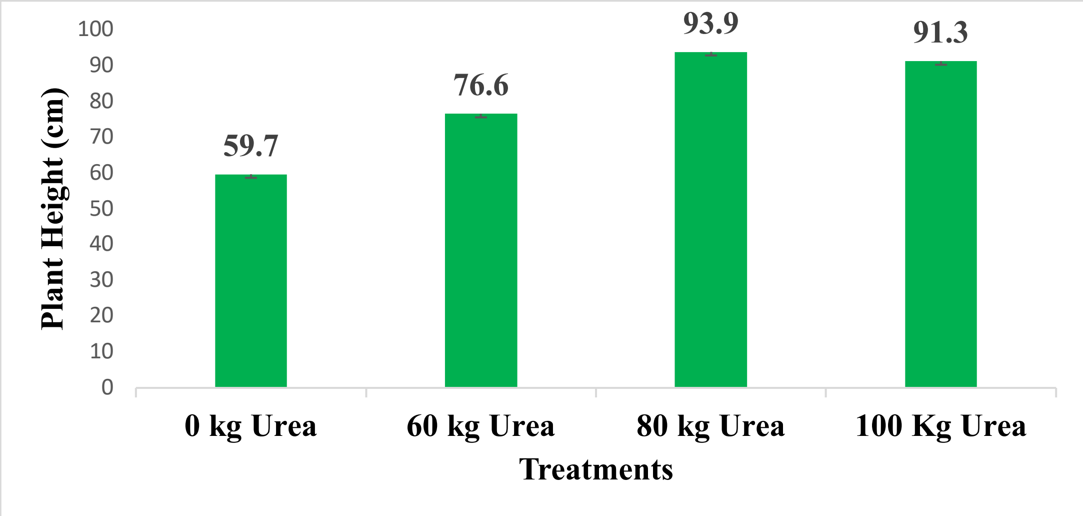

Figure 3. Plant height (cm) F1

Field 2: In contrast, Field 2 showed significant variation in plant height due to urea application. The tallest plants were observed under T_3 (93.40 cm), significantly exceeding the control (67.40 cm) and T_2 (73.20 cm). T_4 produced intermediate height (80.50 cm) and was statistically at par with T_2. The F-value (9.98*) and CV (6.38%) suggest a clear positive response of plant height to nitrogen, reflecting improved cell elongation and vegetative vigor.

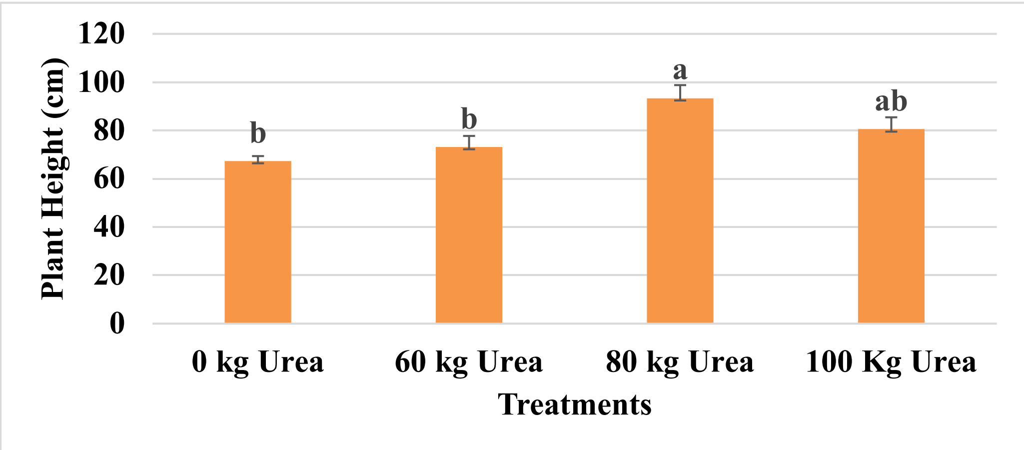

Figure 4. Plant height (cm) F2

Combined interpretation: Across both fields, plant height exhibited variable responses. While Field 1 did not show a significant trend, Field 2 confirmed that moderate to high urea application enhances plant height. Overall, T_3 consistently produced taller plants and can be considered the optimal urea level for maximum vegetative growth.

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Effect of Different Levels of Urea on Yield Attributes

Number of Pods per Plant

Field 1: Pod number increased significantly with urea application. The control produced only 44.70 pods per plant, while T_2 yielded 69.50 pods, T_3 147.80 pods, and T_4 222.90 pods per plant. The extremely high F-value (417.68**) and low CV (4.61%) indicate robust statistical significance and consistency across replications.

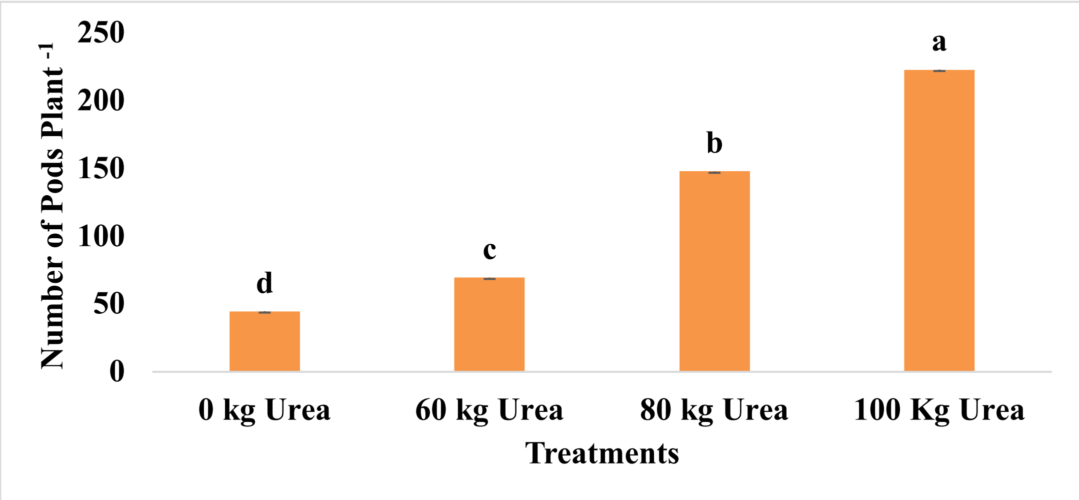

Figure 5: Number of pods per plant F1

Field 2: Similar trends were recorded, with control plants producing 68.40 pods per plant, T_2 84.30, T_3 105.90, and T_4 194.70. F-value (302.52**) and CV (4.05%) indicate that pod formation is highly responsive to nitrogen levels.

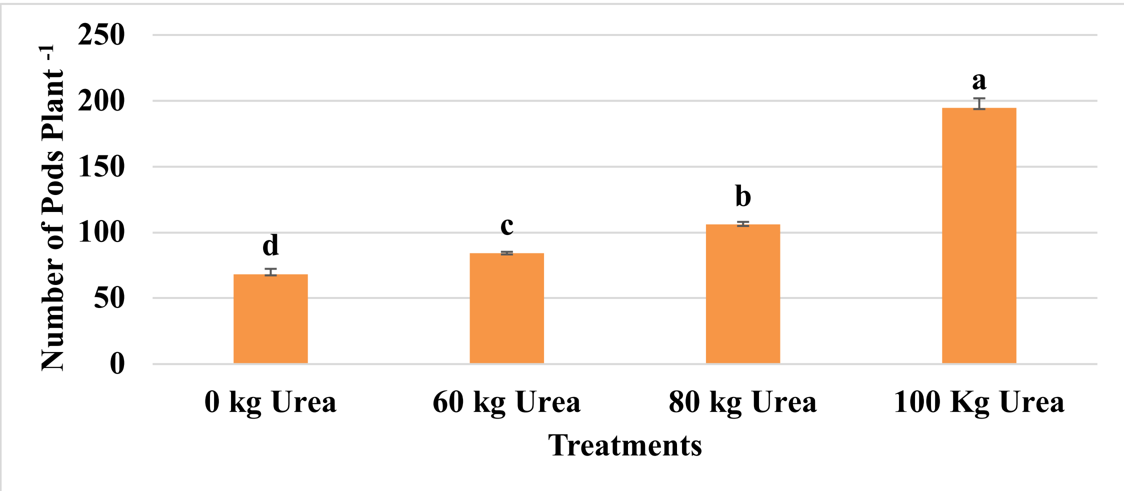

Figure 6: Number of pods per plant F2

Combined interpretation: Across both fields, pod number increased progressively with urea levels. T_3 and T_4 consistently produced the highest pod numbers, indicating that moderate to high nitrogen levels are critical for enhancing reproductive output in mustard.

Number of Grains per Pod

Field 1: Significant differences were observed among treatments for the number of grains per pod. Treatments 3 and 4 produced the highest number of grains per pod and were statistically similar to each other. Treatments 1 and 2 recorded lower values

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and were also statistically similar. This indicates that nitrogen application significantly increased the number of grains per pod under Field 1 conditions.

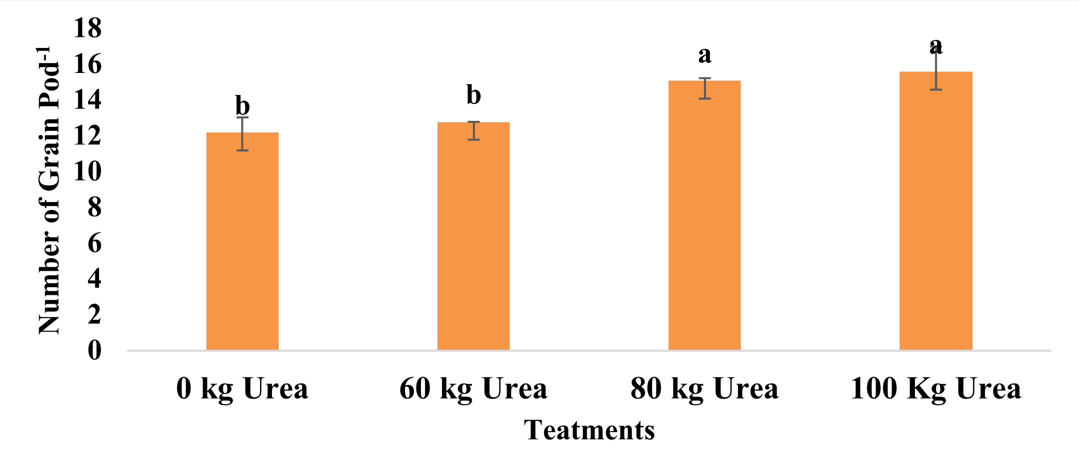

Figure 7. Number of grains per pod F1

Field 2: No significant differences were observed among treatments. Although Treatment 3 recorded the highest numerical value, the differences were not statistically significant. This suggests that nitrogen application had no effect on grains per pod in Field 2.

Combined interpretation: The response of grains per pod varied between fields. A significant effect of nitrogen was observed in Field 1, while no effect was detected in Field 2. This indicates that the influence of nitrogen on grain formation per pod may depend on field conditions.

100-Seed Weight

Field 1: The 100-seed weight did not differ significantly among treatments. Although Treatment 3 recorded the highest numerical value, the differences were not statistically significant. This indicates that nitrogen application had no significant effect on seed weight under Field 1 conditions.

Field 2: Significant differences were observed among treatments. Treatment 2 produced the highest 100-seed weight, followed by Treatments 3 and 4, while Treatment 1 recorded the lowest value. This shows that nitrogen application significantly influenced seed weight in Field 2.

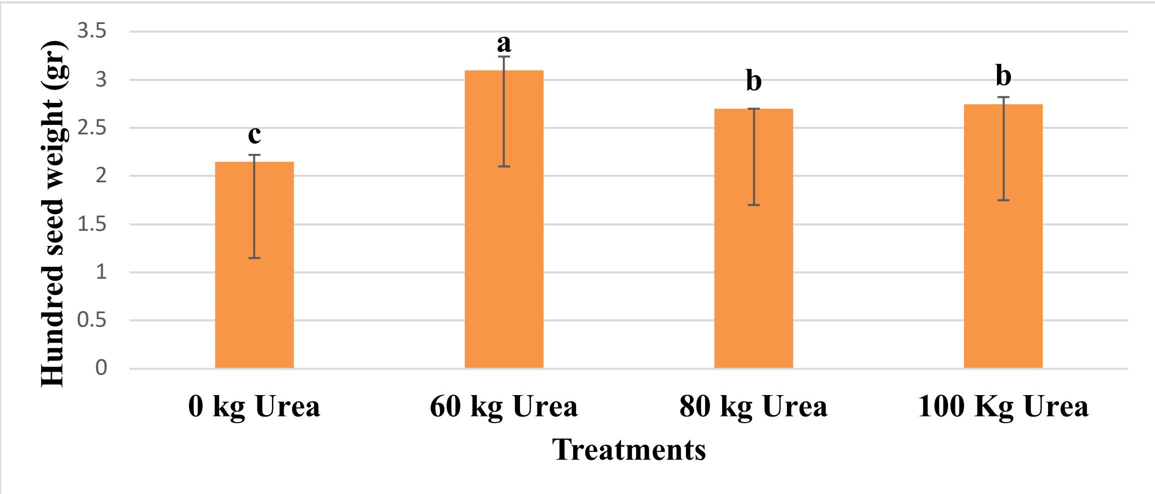

Figure 8. Hundred seed weight (gr) F2

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Combined interpretation: Unlike phenological traits, 100-seed weight responded differently across fields. No effect was observed in Field 1, whereas significant improvement was recorded in Field 2, particularly under Treatment 2. This suggests that the influence of nitrogen on seed weight may depend on field conditions.

Grain Yield (kg ha⁻¹)

Field 1: Grain yield followed a strong response to urea application. The lowest yield was recorded in the control (696.25 kg ha^{-1}). T_2 increased yield to 1112.50 kg ha^{-1}, T_3 achieved the highest yield (1990.00 kg ha^{-1}), and T_4 produced 981.25 kg ha^{-1}. The high F-value (63.29**) and CV (8.30%) confirm the statistical significance of the treatments.

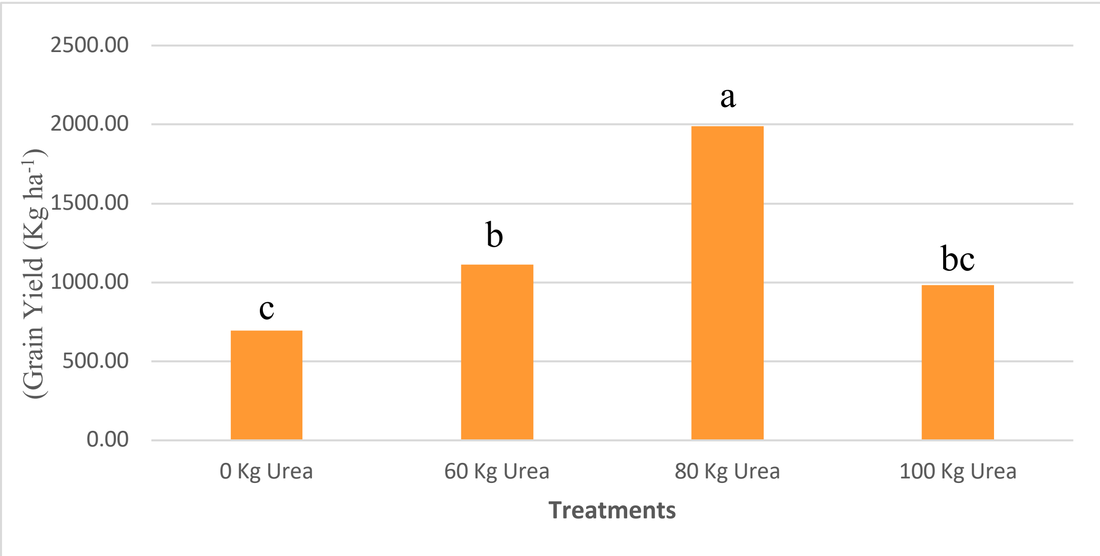

Figure 9. Grain yield (kg per ha) F1

Field 2: Grain yield in Field 2 showed a similar pattern. Control plants produced 888.90 kg ha^{-1}, T_2 1142.50 kg ha^{-1}, T_3 the maximum yield (2241.25 kg ha^{-1}), and T_4 1610.00 kg ha^{-1}. F-value (30.79**) and CV (10.30%) again support strong treatment effects.

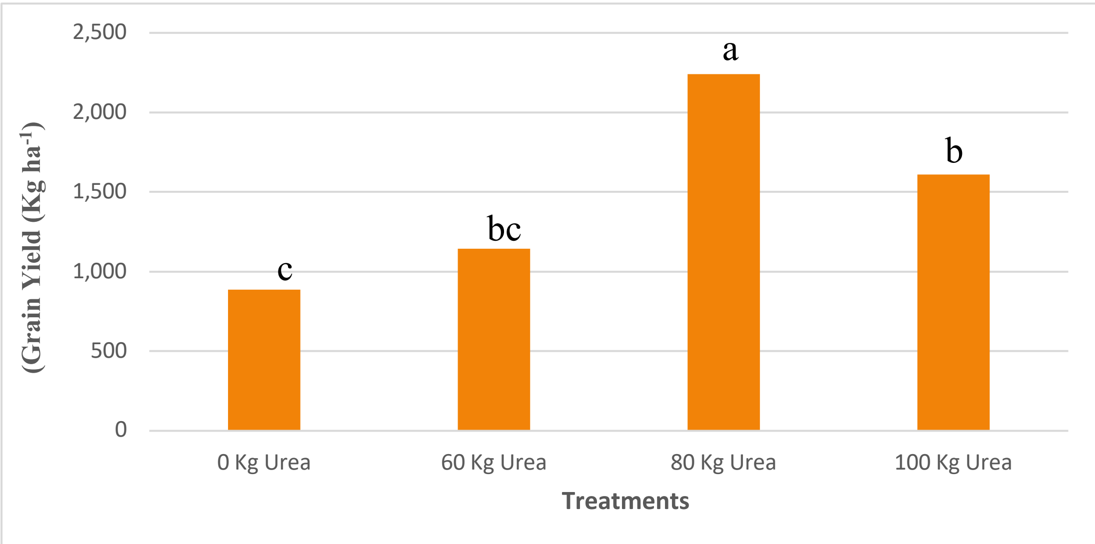

Figure 10. Grain yield (kg per ha) F2

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Combined interpretation: Across both fields, T_3 (80 kg urea ha^{-1}) consistently produced the highest grain yield, confirming its optimality. Although T_4 received the highest nitrogen dose, the yield did not exceed T_3, suggesting that 100 kg ha^{-1} may not provide additional benefit and may lead to diminishing returns. This reinforces T_3 as the most agronomically efficient treatment for maximizing yield under Kabul agro-climatic conditions.

Phenology (Days to Flowering & Maturity)

Field 1: Days to flowering and maturity remained constant across all treatments. Control and urea-applied plots showed identical durations, indicating no effect of nitrogen on phenology.

Field 2: Similarly, no differences in flowering or maturity were observed among treatments.

Combined interpretation: Since phenological data were identical in both fields, they were combined. This demonstrates that urea application does not alter the crop cycle of mustard, and all treatments reached flowering and maturity at the same time.

Overall Combined Observations

When considering both fields collectively, the data indicate that urea application significantly enhances vegetative and reproductive growth parameters, including branching, plant height, pod number, and grain yield, with T_3 consistently producing superior results. Parameters that were non-responsive to urea, such as pod length and phenology, were presented in combined form. The comprehensive data illustrate that moderate urea application (80 kg ha^{-1}) is optimal for maximizing mustard performance under the studied agro-climatic conditions.

DISCUSSION

Nitrogen (N) is one of the most critical macronutrients regulating plant growth and productivity due to its central role in the synthesis of amino acids, proteins, nucleic acids, chlorophyll, hormones, and key enzymes (Leghari et al., 2016; Wang et al., 2024). Nitrogen availability influences both vegetative and reproductive phases in mustard (Brassica juncea L.) by modulating cell division, elongation, leaf area expansion, and assimilate partitioning (Rajput et al., 2018; Fathi, 2022). In the present study, the application of urea, a widely used and highly concentrated nitrogen source, significantly influenced vegetative growth parameters, particularly the number of branches per plant and plant height, across two experimental fields under Kabul agro-climatic conditions.

The number of branches per plant is a crucial vegetative trait that determines canopy structure, photosynthetic capacity, and source-sink dynamics, which in turn influence reproductive success and yield potential. In Field 1, the control treatment (T_1) produced the lowest number of branches (4.20), reflecting limited vegetative proliferation under zero nitrogen conditions. Incremental urea application from 60 kg ha^{-1} (T_2) to 100 kg ha^{-1} (T_4) progressively increased the number of branches, with T_3 (80 kg ha^{-1}) and T_4 producing 5.20 and 5.50 branches, respectively. The low coefficient of variation (CV = 2.84%) and highly significant F-value (49.73**) indicate robust and precise measurements, highlighting a clear positive response of branching to nitrogen availability.

Similarly, in Field 2, branching showed a consistent upward trend with increased nitrogen supply. The control (3.50 branches) and T_2 (3.70 branches) were statistically similar, whereas T_3 (5.60) and T_4 (5.40) produced significantly higher branch numbers. The slightly higher CV (9.66%) in this field indicates natural field variability, possibly due to micro-environmental differences, soil heterogeneity, and irrigation patterns. The significant F-value (12.59*) confirms that nitrogen positively regulates lateral shoot initiation. These results are in agreement with findings from Rajput et al. (2018), Kumar et al. (2017), and Shorna et al. (2020), who demonstrated that nitrogen enhances cytokinin activity and promotes axillary bud activation, leading to increased branching in mustard and other oilseed crops.

Combined interpretation across both fields indicates that moderate to high urea levels (80–100 kg ha^{-1}) consistently enhance branching. Increased branching improves canopy development, light interception, and assimilate production, creating a favorable source for reproductive growth. The superior performance of T_3 (80 kg ha^{-1}) across both fields suggests this as the optimal nitrogen dose for balancing vegetative proliferation with economic and environmental efficiency.

Plant height, an indicator of vegetative vigor, was also influenced by nitrogen application, although responses varied between fields. In Field 1, T_3 produced the tallest plants (93.90 cm), with T_4 (91.30 cm) slightly shorter. Despite numerical differences, the variation was not statistically significant (F-value = 5.79 ns), likely due to environmental variability and sandy loam soil conditions limiting uniform growth responses. In contrast, Field 2 showed significant height variation (F-value = 9.98*), with T_3 plants achieving the maximum height (93.40 cm) compared to the control (67.40 cm). These observations indicate that nitrogen enhances cell division and elongation, promoting vegetative growth and canopy development, consistent with prior studies by Hashan et al. (2023) and Chaurasiya et al. (2019).

Across both fields, the T_3 treatment consistently produced taller plants, suggesting that 80 kg urea ha^{-1} is sufficient to maximize vegetative growth without incurring diminishing returns or excessive vegetative investment, which can predispose plants to lodging. These findings align with the physiological principles of nitrogen-mediated chlorophyll synthesis, photosynthetic efficiency, and hormonal regulation of stem elongation (Fathi, 2022; Singh et al., 2022).

Yield attributes, including pod number, seeds per pod, and 1000-seed weight, are directly influenced by nitrogen availability as it regulates assimilate partitioning, photosynthetic activity, and sink strength (Islam, 2021; Chaurasiya et al., 2019).

Nitrogen significantly increased the number of pods per plant across both experimental fields. In Field 1, the control produced only 44.70 pods, whereas T_3 and T_4 produced 147.80 and 222.90 pods, respectively, reflecting a three- to fivefold increase with nitrogen fertilization. Similar trends were observed in Field 2, with T_3 and T_4 achieving 105.90 and 194.70 pods per plant. High F-values (417.68** in Field 1 and 302.52** in Field 2) and low CVs (4–5%) indicate high statistical reliability and uniform response. These findings highlight nitrogen's role in reproductive development, particularly in stimulating flower differentiation, fertilization, and pod set.

The positive effect of nitrogen on pod formation is corroborated by Kumar Sharma et al. (2022), who reported enhanced pod numbers with combined nitrogen and sulfur nutrition. Nitrogen increases photosynthate production, which supports flower and pod development, while also prolonging leaf area duration, thereby improving assimilate availability during critical reproductive stages (Islam, 2021; Singh et al., 2022).

Grain yield followed a similar response pattern. Field 1 yielded 696.25 kg ha^{-1} in the control, which increased to 1990.00 kg ha^{-1} under T_3 (80 kg ha^{-1}), whereas T_4 produced slightly lower yield (981.25 kg ha^{-1}), suggesting diminishing returns at higher nitrogen levels. Field 2 demonstrated a consistent trend, with T_3 achieving the highest grain yield (2241.25 kg ha^{-1}). These results indicate that while nitrogen promotes vegetative and reproductive growth, excessive nitrogen may redirect assimilates toward vegetative biomass or increase lodging risk, reducing effective yield (Waladi et al., 2023; Jankowski et al., 2020).

The superior performance of T_3 emphasizes the importance of optimizing nitrogen doses to balance vegetative vigor with reproductive efficiency. Nitrogen management is crucial for improving nitrogen use efficiency (NUE), reducing environmental losses, and maximizing economic returns (Ola, 2024). These findings are consistent with previous studies in Poland, India, and Bangladesh (Jankowski et al., 2024; Kumar et al., 2017; Shorna et al., 2020), demonstrating that 70–90 kg N ha^{-1} is optimal for maximizing mustard yield under diverse agro-climatic conditions.

Interestingly, nitrogen application did not significantly alter days to flowering or maturity in either field. Both control and urea-treated plots reached phenological stages simultaneously, indicating that mustard's developmental timeline is relatively insensitive to nitrogen supply under the studied conditions. This stability is advantageous for crop scheduling, particularly in regions like Kabul, where climatic constraints necessitate fixed planting and harvesting windows (Chaurasiya et al., 2019; Jankowski et al., 2020).

The observed improvements in vegetative and reproductive traits under moderate nitrogen application (T_3) can be explained through physiological mechanisms. Nitrogen enhances chlorophyll content, photosynthetic rate, and assimilate transport, thereby supporting both vegetative growth and reproductive organ development (Fathi, 2022; Singh et al., 2022). Nitrogen also increases seed protein content and modifies fatty acid composition, impacting oil quality a critical parameter for mustard's nutritional and industrial value (Jankowski et al., 2024; Islam, 2021).

Interaction with other nutrients, such as sulfur and boron, further amplifies nitrogen's effect on yield. Sulfur is essential for amino acid synthesis, particularly methionine and cysteine, while boron facilitates reproductive development and pollen viability (Kumar et al., 2017; Jankowski et al., 2020). The integration of optimal nitrogen with complementary nutrients is therefore vital for maximizing both yield and quality.

Differences between Field 1 and Field 2 in plant height and branching can be attributed to micro-environmental factors, including soil texture, nutrient heterogeneity, and water availability. Field 1, with sandy loam and lower nitrogen availability, showed higher variability in plant height, whereas Field 2 exhibited more uniform growth due to slightly better soil fertility. These results highlight the need for site-specific fertilizer recommendations, particularly in regions with heterogeneous soil conditions like Kabul, Afghanistan.

From an agronomic perspective, the T_3 treatment (80 kg urea ha^{-1}) represents the optimal nitrogen rate, balancing vegetative growth, reproductive output, and grain yield. Excessive nitrogen (T_4, 100 kg ha^{-1}) did not provide additional benefits and may increase input costs and environmental risk. Economic analysis, although not detailed here, would likely favor T_3 due to reduced fertilizer input, higher NUE, and maximized returns, aligning with the findings of Kumar Sharma et al. (2022) and Waladi et al. (2023).

The findings of this study are consistent with international research. In Poland, mustard varieties responded positively to nitrogen up to 80–120 kg ha^{-1}, with excessive nitrogen reducing yield efficiency (Jankowski et al., 2020). In India, optimal nitrogen application enhanced vegetative growth, pod formation, and seed yield in both mustard and rapeseed (Kumar et al., 2017; Chaurasiya et al., 2019). In Bangladesh, nitrogen management in mustard green production improved shoot height, leaf area, and seed yield (Shorna et al., 2020). These global comparisons validate the current findings and emphasize the universal physiological role of nitrogen in mustard.

CONCLUSION

The present study showed that different levels of urea significantly influenced the growth and yield of mustard (Brassica juncea L.) under Kabul agro-climatic conditions. Nitrogen application improved plant growth, particularly plant height and number of branches, indicating better vegetative development with increased nutrient availability.

Yield components, especially the number of pods per plant and grain yield, responded more strongly to nitrogen levels. Among all treatments, 80 kg urea ha^{-1} consistently produced the best overall performance, resulting in higher yield attributes and maximum grain yield compared to other treatments.

Increasing urea beyond 80 kg ha^{-1} did not further improve yield, suggesting a decline in response efficiency at higher nitrogen levels. Phenological traits such as flowering and maturity were not significantly affected, showing that nitrogen mainly influenced growth and yield rather than crop duration.

Overall, the study identifies 80 kg urea ha^{-1} as the most suitable rate for mustard production under Kabul conditions. This level ensures better yield, improved nitrogen use efficiency, and more balanced plant growth, making it a practical recommendation for farmers in the region.

RECOMMENDATIONS

The study recommends the application of 80 kg urea ha^{-1} as the optimum nitrogen rate for mustard under Kabul agro-climatic conditions, as it consistently improved growth and grain yield.

Fertilizer guidelines should be updated using local research to ensure site-specific recommendations. Strengthening soil testing services is also essential to support accurate and efficient nitrogen use.

Farmers should be encouraged to adopt split application of urea and proper timing of fertilizer use to improve nitrogen efficiency and reduce losses.

Mustard production should be promoted within national oilseed programs with emphasis on balanced fertilization to enhance productivity and reduce edible oil imports.

Extension services should focus on training farmers in efficient nitrogen management and the economic and environmental benefits of optimal fertilizer use.

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