

EFFECT OF DIFFERENT NPK FERTILIZER RATES ON GROWTH, FLOWERING, FRUIT CHARACTERISTICS AND YIELD OF BELL PEPPER (*CAPSICUM ANNUUM* L.) UNDER THE AGRO-CLIMATIC CONDITIONS OF UTHAL, BALOCHISTAN, PAKISTAN

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Abstract

Bell pepper (*Capsicum annuum* L.) productivity is strongly influenced by the availability and balance of essential nutrients. A field experiment was conducted during 2023–2024 at the agricultural research site of Lasbela University of Agriculture, Water and Marine Sciences (LUAWMS), Uthal, Balochistan, Pakistan, to evaluate the effects of N, P, and K fertilizer rates on growth, flowering, fruit characteristics, and yield of bell pepper cultivar 'Winer'. The experiment was arranged in a Randomized Complete Block Design with three replications and four treatments: T1, untreated control; T2, 90-60-30; T3, 120-90-60; and T4, 150-120-90 kg N-P-K ha⁻¹. Increasing NPK rates significantly affected growth, reproductive, fruit, and yield attributes ($p \leq 0.05$). T4 produced the highest number of leaves (147.73 plant⁻¹), plant height (67.20 cm), and stem diameter (11.03 mm), while T3 produced the greatest number of branches (27.13 plant⁻¹). T3 also resulted in the earliest flowering (40.00 days) and fruit set (59.67 days), and the highest numbers of flowers (26.52 plant⁻¹) and fruits (23.63 plant⁻¹), fruit length (72.71 mm), fruit width (70.27 mm), fruit weight (129.20 g), seeds fruit⁻¹ (168.83), and yield plant⁻¹ (2163 g). Although T4 enhanced vegetative growth, T3 achieved superior reproductive performance and yield. Thus, 120-90-60 kg N-P-K ha⁻¹ was the most productive treatment under the study conditions. Multi-season and multi-location studies are recommended to validate this recommendation and assess nutrient-use efficiency and economic returns.

Introduction

Bell pepper (*Capsicum annuum* L.) is an important vegetable crop and is grown worldwide in the tropics, sub-tropics, and temperate regions. The fruits are used not only for culinary purposes but also for their nutritional attributes, such as Vitamin C, carotenoids, phenolics, mineral and other phytochemicals with health promoting value. Bell pepper thus plays a significant role in multiple vegetable production, nutrition of the family and farm income. But, genotype, environmental factors, water availability, soil fertility, and nutrient management greatly affect productivity, and quality of fruits. In addition, recent global data suggest that pepper mineral nutritional quality changes significantly across the various climatic conditions, soil properties and production environments (Zhou et al., 2024), supporting the need of site-specific pepper crop and nutrient management.

Mineral nutrition is one of the agronomic factors that influence productivity of peppers since the availability of the nutrients directly controls vegetative growth, reproductive growth, fruit formation and yield. The main macronutrients for relatively high requirements by pepper are nitrogen (N), phosphorus (P), and potassium (K). Both have physiological roles but are closely related in their effects on crop performance. Nitrogen is a key element in leaf growth, enzyme function, photosynthetic activity, and biomass production and is found in all forms of chlorophyll, amino acids, proteins, and many enzymes. Phosphorus is involved in energy transfer, nucleic acid metabolism, root growth, membrane formation, flowering, and reproductive development of plants; while potassium is involved in enzyme activation, stomatal function, osmotic adjustment, water relations, transport of photosynthates, and tolerance to stress. The physiological functions, which are the end product of these nutrients, are crucial for the growth and productivity of peppers and a balanced supply of these nutrients is therefore essential.

Nitrogen availability is of special concern in pepper during the vegetative growth stage because of the potential to limit leaf area, growth habit,

chlorophyll synthesis, and plant dry matter production at this stage. However, increasing N application beyond crop requirements does not necessarily result in proportional increases in yield. In Pakistan, under the semi-arid environment, Saqib et al. (2023) showed that an increase in the rate of N application resulted in an increase in plant height, stem diameter, biomass and yield related attributes of the cultivars, and the change was cultivar dependent. For several traits, responses were similar between 125 and 150 kg N ha⁻¹, thus emphasizing the need for an N management specific to each cultivar to maximize productivity and reduce the need for fertilizer inputs.

Recent research has therefore focused on optimizing nutrient supply in response to crop demand and nutrient-use efficiency rather than on increasing the inputs of nutrients. Ma et al. (2022) found that optimized N management was able to cut N fertilizer application significantly without affecting yield in an open field pepper experiment in southwest China, and the application of enhanced-efficiency fertilizers was also found to have a positive effect on N uptake by the crop and N recovery. Such results show that there is a possibility of achieving both productivity and efficient use of fertilizers by appropriate management of N. Likewise, Wang et al. (2022) showed that under water-limited conditions, the effect of irrigation and N supply on sweet pepper yield, quality, water-use efficiency and N-use efficiency was significant. Their results highlight the lack of independence of the fertilizer response from water availability, especially in the dry and semi-arid production systems.

P is also important as it aids root establishment, energy metabolism, flowering and reproductive development. Proper P availability allows ATP dependent metabolic pathways to proceed and assures assimilate transfer into developing reproductive organs. Low soil P availability is also reported as one of the major constraints on bell pepper production in Pakistan and it is reported that the application of PSB along with organic amendments leads to higher plant growth and yield (Anwar and Quddus, 2024). But over-

fertilizing with P will decrease P-use efficiency and increase the potential for nutrient build-up and environmental losses. The two-year pepper cultivation experiment by Cui et al. (2023) showed that it was crucial to optimize, rather than maximize, P application for pepper yield, P uptake, and P-use efficiency and that both application rate and method influenced the outcomes.

Potassium is also essential for pepper productivity, playing important roles in water balance, stomatal closure, activation of enzymes, translocation of carbohydrates and partitioning of assimilates. These functions are especially significant in the flowering and fruit development stages and under environmental stress. Recent research has shown that nutrient management can have an impact on plant growth, yield and fruit quality in pepper, and increasing the concentration of K in fertigation solutions can enhance crop performance, provided that the fertilizer level is properly adjusted to the crop demand (Wickham & Davis, 2024; Navale et al., 2025). As with N and P, therefore, the productivity response to K is not likely to be linear over all fertilizer levels.

N-K interactions are also crucial because availability of N, P, and K synergize to determine plant growth as a whole, rather than the availability of individual nutrients. When nutrients are adequate, the leaf growth and photosynthetic potential lead to increased assimilate production for flower initiation and fruit development, while nutrient imbalance leads to limited vegetative vigor, reproductive development, and fruit production. Research comparing the effects of INM and conventional NPK management has shown that the integrated nutrient application can yield higher growth, yield, nutrient uptake, and fruit quality depending on the environmental conditions and cultivar (Kunwar et al., 2024; Tian et al., 2024; Stoleru et al., 2023).

The key point to remember is that the amount of fertilizer required is strongly influenced by the environment. Conditions of limited water supply, high evaporative demand, alkaline or nutrient deficient soil conditions, and temperature variability in semi-arid and arid conditions will

change the nutrient availability and plant nutrient uptake. Thus, recommendations for fertilizers based on humid or high input production systems might not be suitable for water-limited conditions. The relationship between water and nutrient supply is particularly important for pepper as both under- and over-supply of nutrients or water will affect resource-use efficiency and impact crop performance (Wang et al., 2022).

Nutrient management is not limited to yield, it also involves nutrient quality and nutrient value. Stoleru et al. (2023) showed that applying fertilization strategies could affect both the productivity and nutritional traits of sweet pepper. Likewise, through global meta-analysis, it was found that pepper fruit mineral composition was affected by yield, soil organic matter, soil pH, temperature, and precipitation, which may imply the importance of both production and nutritional quality when assessing nutrient-management strategies for pepper crops (Zhou et al., 2024). Therefore, various growth, reproductive, yield, and quality attributes must be considered rather than yield in developing an effective fertilizer strategy. This is especially important for Pakistan because bell pepper cultivation is mainly concentrated in a few agricultural regions where the productivity is restricted due to poor soil fertility management, poor fertilizer management, limited water availability, and environmental stresses. Recent studies in Pakistan have shown positive results for pepper in relation to N management under semi-arid conditions (Saqib et al., 2023) and integrated phosphorus-solubilizing bacteria and organic amendments have enhanced growth and yield of bell pepper (Anwar & Quddus, 2024). However, the best combination of NPK fertilizer doses for bell pepper cultivation in the agro-climatic condition of Uthal, Balochistan is still limited. This is a significant knowledge gap as fertilizer recommendations from other regions may not be able to fully address local soil conditions, climatic limitations, cultivar differences, and water availability.

In Uthal, a representative semi-arid environment of the Lasbela District of Balochistan, soil fertility

and climate were found to play significant role on the performance of vegetables. Therefore, field experiments are needed locally to determine the levels of nutrients required for maximum crop production without over-fertilisation. This information is especially important for designing nutrient-management plans for high-value crops, such as bell peppers, in water-limited environments.

For this purpose, the present study was conducted to assess the reaction of bell pepper cultivar 'Winer' to four levels of nutritional regime (NPK) under agro-climatic condition of Uthal, Balochistan. The experiment was conducted to compare an untreated control with three increasing rates of NPK (90-60-30, 120-90-60 and 150-120-90 kg N-P-K ha⁻¹) for vegetative growth, reproductive development, fruit characteristics and yield. Specific objective was to find the best combination of vegetative growth, reproductive performance, fruit characteristics and yield with the NPK rate. We suspected that higher amounts of NPK would lead to a greater increase in crop growth and productivity, but that the maximum fertilizer rate would not necessarily yield the greatest response because the large supply of nutrients may have resulted in greater vegetative growth than reproductive development and yield.

Materials and Methods

Experimental site and experimental design

To estimate the response of bell pepper (*Capsicum annuum* L.) to various levels of nitrogen (N), phosphorus (P), and potassium (K) under field condition, the agricultural research site of Lasbela University of Agriculture, Water and Marine Sciences (LUAWMS), Uthal, Balochistan, Pakistan was utilized for the field experiment in 2023-2024. The experiment was carried out under agro climatic condition of Uthal with bell pepper cultivar 'Winer'. Seedlings were first grown in the LUAWMS shade house and were potted out into the field when they had reached about 6" tall. The experiment was laid out in Randomized Complete Block Design (RCBD) replicated three times. Both replications were 13.8 x 18 ft, and a reported area of 745.2 ft². A spacing of 4×4 rows with 60×60 cm

spacing were used and each replication contained four rows. Field variability was minimized by randomizing the experimental treatments in each replication.

Four NPK fertilizer treatments were tested. The untreated control (T1) was not fertilized with any of the nutrients (N, P, K). Treatment T2 received 90-60-30 kg N-P-K ha⁻¹, T3 received 120-90-60 kg N-P-K ha⁻¹, and T4 received 150-120-90 kg N-P-K ha⁻¹. The corresponding fertilizer quantities recorded for the experimental plots were 0.62-0.42-0.21 kg for T2, 0.83-0.62-0.42 kg for T3, and 1.04-0.83-0.62 kg for T4, respectively.

Crop management and data collection

All crop management practices were done in the same way throughout the experiment. Each replication was supplied with irrigation water from a main side channel, which was linked to sub-channels. Weeds were manually suppressed and pest and disease control was through regular sprays to ensure plant health and reduce biotic stress. All the management practices were kept the same among the treatments and differences observed were mainly due to the applied NPK treatments. A full spectrum of vegetative, reproductive, fruit and yield related attributes was sampled. Vegetative growth was evaluated by number of leaves per plant, plant height, number of branches (plant) and stem diameter. Five plants from each treatment were randomly selected and the number of leaves was visually counted and the mean calculated. Plant height was determined at maturity based on the distance from the base of the plant to its tip, on five plants randomly selected, in centimetres. Likewise, the number of branches were counted manually in five randomly selected plants from each plot and expressed as average branches plant⁻¹. The diameter of stems was determined on 5 randomly selected plants with a Vernier caliper and reported in millimeters. Reproductive development was assessed by measuring days to first flowering, number of flowers plant⁻¹ and days to fruit set. The days to first flowering were estimated as the number of days after transplanting until the first flower was seen. The number of flowers were counted from

five random plants per plot and reported as mean flowers plant⁻¹. Time from flowering to fruit set was determined by the period from days after flowering to initiation of fruit development. The number of fruits plant⁻¹, fruit length, fruit width, fruit weight, number of seeds fruit⁻¹ and yield plant⁻¹ were recorded to determine fruit production and physical characteristics. Fruit production was measured during the entire harvest period (1st harvest to last harvest) and then averaged per treatment. A Vernier caliper was used to measure the length and width of each fruit in five fruits per treatment and reported in mm. The fruits were weighed with a digital weighing machine and the weight of each fruit was recorded in grams. Seed numbers were counted from mature, healthy fruits and the mean number of seeds fruit⁻¹ was calculated. Yield plant⁻¹ was calculated from the fruit production from first harvest to last harvest. While; the yield values were obtained following experiment procedure for determining yield and expressed in g/plant.

Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) using Statistix 8.1 statistical software. The RCBD was evaluated to assess the treatment effects on these growth, reproductive, fruit and yield parameters. The least significant difference (LSD) test with 5% probability level was used to compare the means of treatments. A p value of ≤ 0.05 was deemed to be significant. Results are presented as the means of each treatment with the standard error of the means and different lower case/upper case letters mean the treatment means are significantly different

based on the mean separation test.

Results

Effect of NPK rates on vegetative growth

All the vegetative growth parameters of bell pepper were influenced significantly by the application of the different rates of NPK. The number of leaves per plant increased in an increasing order as the rates of NPK increased. The control (T1) produced the lowest number of leaves (100.00), whereas T2, T3, and T4 produced 115.67, 131.23, and 147.73 leaves plant⁻¹, respectively. The ANOVA showed that the treatment effect was highly significant ($p < 0.0001$, $F = 335.28$). The effect of the NPK application was also significant on plant height ($F = 21.82$, $p = 0.0013$). The plant height was increased to 67.20cm in T4, 59.34cm in T3 and 53.02cm in T2, whereas it was 41.31cm in the untreated control. Therefore, T4 treatment resulted in the tallest vegetative plant.

NPK application significantly affected the number of branches plant⁻¹ ($F = 17.91$, $p = 0.0021$). The control had the least number of branches (14.60 plant⁻¹), while T3 had the highest number of branches (27.13 plant⁻¹). 23.43 branches plant⁻¹ were produced by T4. Fertilizer treatment had significant effects on stem diameter ($F = 52.02$, $p = 0.0001$). The smallest stem diameter was obtained with the control (6.46 mm); T2, T3 and T4 gave 8.19, 9.30 and 11.03 mm respectively. Thus, the greatest stem diameter was produced by T4.

In general, the highest NPK rate resulted in the maximum vegetative growth especially in leaf production, plant height and stem thickening.

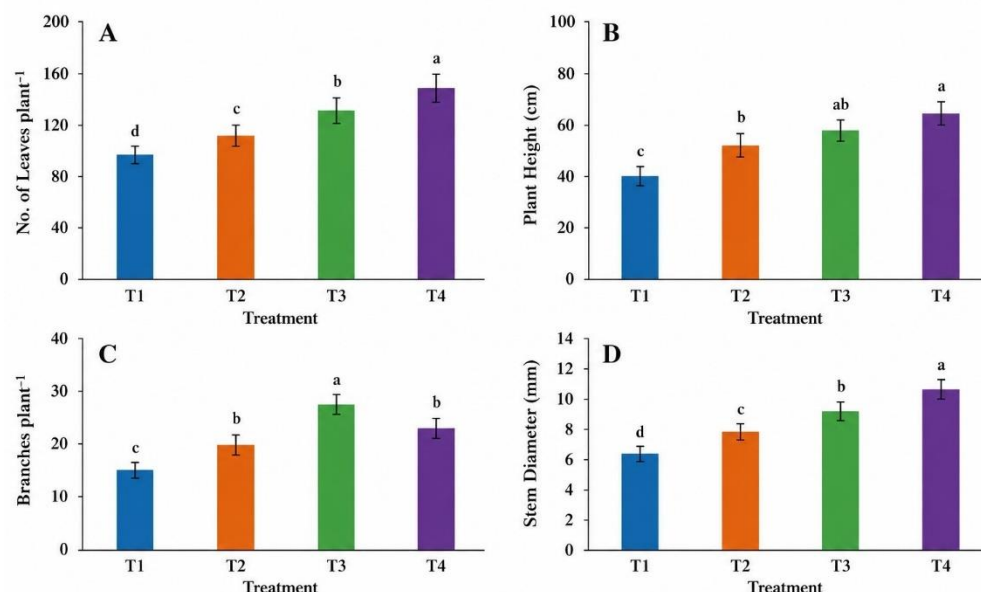


Figure 1. Effect of different NPK fertilizer treatments on vegetative growth attributes of bell pepper (*Capsicum annuum* L.): (A) number of leaves plant⁻¹, (B) plant height (cm), (C) number of branches plant⁻¹, and (D) stem diameter (mm). Values represent means $\pm$ SE (n = 3). Different lowercase letters above the bars indicate significant differences among treatments at $P \leq 0.05$.

Effect of NPK rates on flowering and fruit set

Flowering time, number of flowers and fruit setting time were greatly influenced by the application of NPK. Treatment significantly affected number of days to first flowering ($F = 38.14$, $p = 0.0003$). Control took the longest time to flower first (53.00 days) followed by T2 (50.33 days). T3 flowered earliest at 40.00 days whereas T4 flowered at about 43.33 days.

The rate of NPK application ($F = 43.58$, $p = 0.0005$) was also found to be significantly affecting the number of flowers plant⁻¹. Fewest flowers (13.50 plant⁻¹) were produced in the untreated

control while T2 produced 18.24 flowers per plant. T3 (26.52 plant⁻¹) had the highest number of flowers followed by T4 (22.33 plant⁻¹).

The days to fruit set also were significantly affected by NPK treatment ($F = 16.19$, $p = 0.0028$). Fruit set was latest in the control (72.67 days), and T2 and T4 had 67.00 and 65.33 days, respectively. Fruit set was earliest with T3 at 59.67 days. These findings suggest that an intermediate rate of NPK (120-90-60 kg ha⁻¹) caused premature reproductive development when compared to the control and higher rate of fertilizer application.

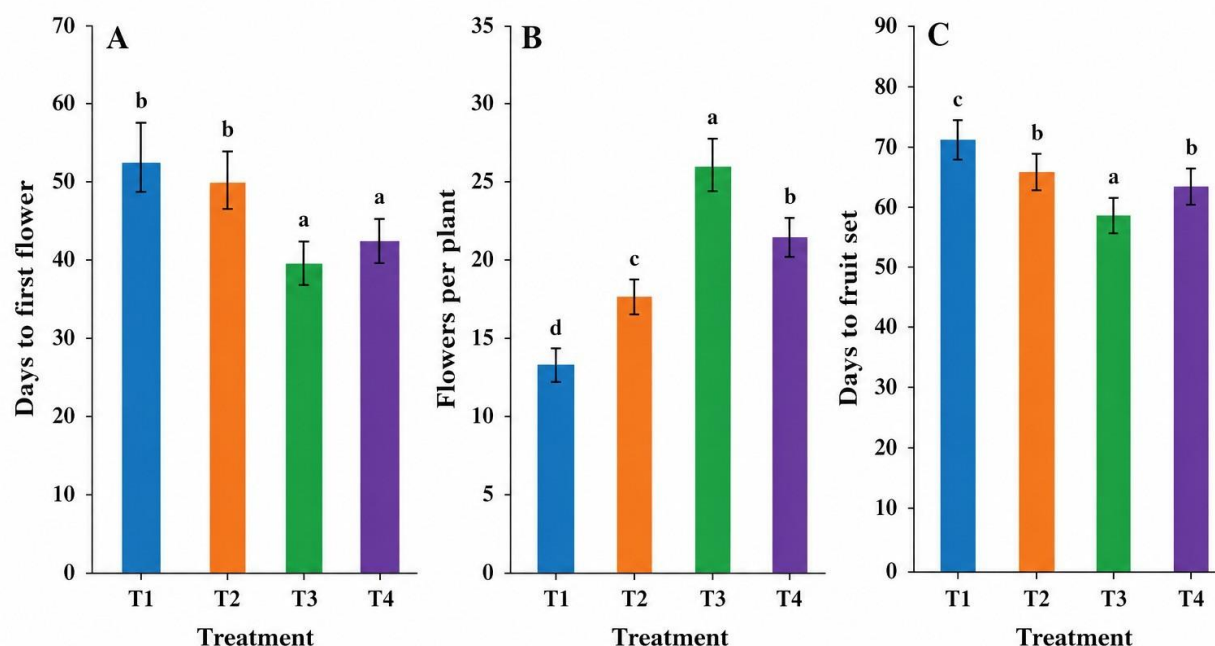


Figure 2. Effect of different NPK fertilizer treatments on flowering and fruit-setting characteristics of bell pepper (*Capsicum annuum* L.): (A) days to first flowering, (B) number of flowers plant⁻¹, and (C) days to fruit set. Values represent means $\pm$ SE (n = 3). Different lowercase letters above the bars indicate significant differences among treatments at $P \leq 0.05$.

Effect of NPK rates on fruit characteristics

The number of fruits and physical traits of fruits were significantly influenced by the different rates of NPK. A significant difference ($p = 0.0001$) was observed between the different treatments with respect to the number of fruits per plant. T3 produced the maximum number of fruits (23.63 plant⁻¹), followed by T4 (20.42), T2 (17.03), and the control (11.28).

Fertilizer treatment ($F = 38.41$, $p = 0.0003$) significantly affected fruit length. Control (57.13 mm) had the shortest length of fruit, while the fruit length in T2 and T3 increased to 63.45 mm and 72.71 mm respectively. T4 had a fruit length of 69.39 mm.

The width of fruits was also significantly affected by NPK application ($F = 27.31$, $p = 0.0007$). The width of the fruits produced by T2, T3 and T4

were 61.04, 70.27 and 64.86 mm respectively while the narrowest fruits produced by the control was 49.81 mm. In T3, the maximum fruit width was therefore measured.

The weight of fruits varied significantly between the different fertiliser treatments ($F = 447.46$, $p = 0.0004$). The fruit weight in the control (84.51 g) was lower than the rest of the treatments, while T2 was 98.83 g and T4 was 120.24 g. The highest fruit weight was obtained in T3 (129.20 g).

The effect of NPK application also was significant on the number of seeds fruit⁻¹ ($F = 94.59$, $p < 0.0001$). The maximum number of seeds (168.83 fruit⁻¹) was recorded by T3 followed by T4 (149.43) and T2 (136.80); while the lowest number of seeds (119.17 seed fruit⁻¹) was recorded by the control.

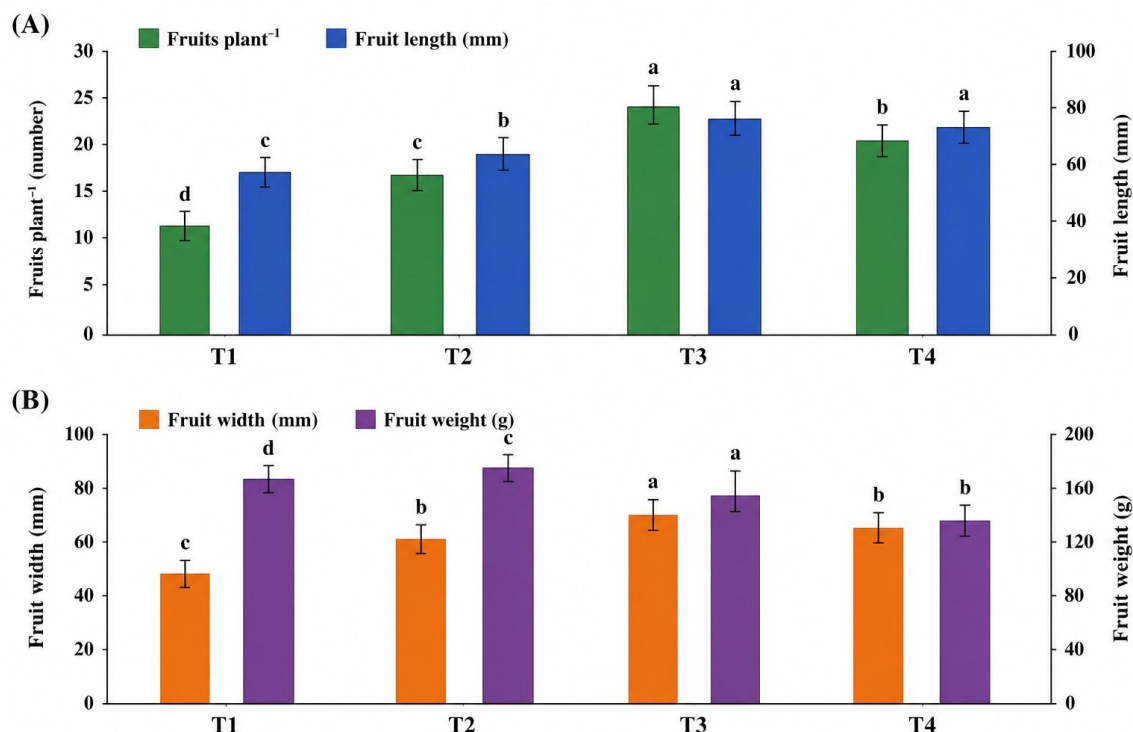


Figure 3. Effect of different NPK fertilizer treatments on fruit production and physical characteristics of bell pepper (*Capsicum annuum* L.): (A) number of fruits plant⁻¹, (B) fruit length (mm), (C) fruit width (mm), and (D) fruit weight (g). Values represent means $\pm$ SE ($n = 3$). Different lowercase letters above the bars indicate significant differences among treatments at $P \leq 0.05$.

Effect of NPK rates on yield

The application of NPK greatly influenced yield plant⁻¹ and significantly affected yields in all cases. According to the ANOVA, there was a highly significant treatment effect ($F = 194.35$, $p < 0.0001$). The untreated control had the lowest yield (919.2 g plant⁻¹). The yield got improved at T2 (1463.0 g plant⁻¹) and T4 (1844.5 g plant⁻¹) with highest yield recorded under T3 (2163 g plant⁻¹).

The yield plant⁻¹ of T3 was about 135% higher than that of the untreated while the yield of T4

was about 101% higher than the untreated. In spite of the highest vegetative development, the highest yield was not produced by T4. The intermediate fertilizer level (120-90-60 kg N-P-K ha⁻¹) however, gave the maximum yield. This overall response thus suggested that there was a non-linear relationship between fertilizer rate and productivity, with the intermediate NPK rate giving the best combination of reproductive development, fruit production, fruit size and yield.

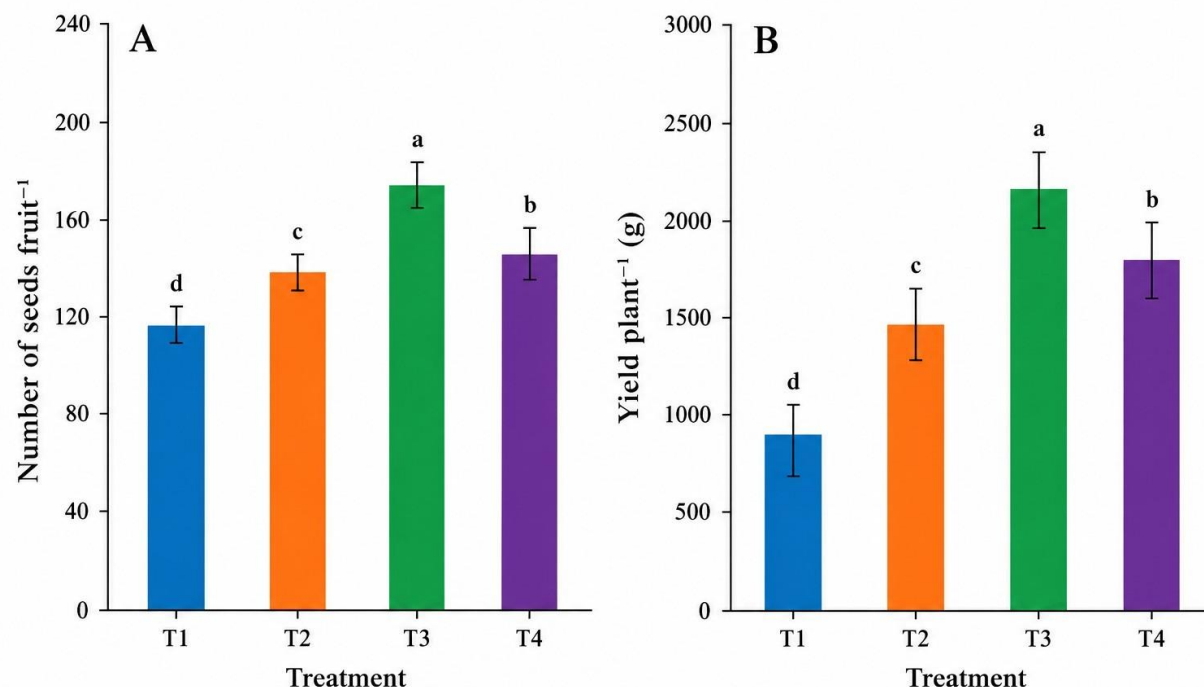


Figure 4. Effect of different NPK fertilizer treatments on (A) number of seeds fruit⁻¹ and (B) fruit yield plant⁻¹ (g) of bell pepper (*Capsicum annuum* L.). Values represent means $\pm$ SE (n = 3). Different lowercase letters above the bars indicate significant differences among treatments at $P \leq 0.05$.

Correlation heat-map of Bell Pepper to NPK treatments

The heat-map revealed distinct treatment-dependent patterns across vegetative, reproductive, fruit, and yield-related attributes of bell pepper. Overall, T1 exhibited predominantly negative standardized responses, particularly for fruit production and yield-related traits, indicating poor performance under the unfertilized control. T2 resulted in moderate improvements, with most parameters remaining close to or slightly below the overall treatment mean. In contrast, T3 exhibited the strongest positive response across most reproductive, fruit, and yield attributes, including flowers plant⁻¹, fruits plant⁻¹, fruit length, fruit

width, fruit weight, seeds fruit⁻¹, and yield plant⁻¹. The highest standardized response for yield was recorded under T3 ($Z = 1.64$), followed by T4 ($Z = 0.23$), whereas T1 showed the lowest response ($Z = -1.50$). T4 produced particularly strong responses for vegetative attributes, including plant height and stem diameter, but these improvements were not accompanied by a greater yield than T3. Collectively, the heatmap demonstrates that T3 provided the most balanced and favorable response across reproductive, fruit-quality, and yield characteristics, whereas the higher fertilizer rate under T4 primarily enhanced vegetative growth.

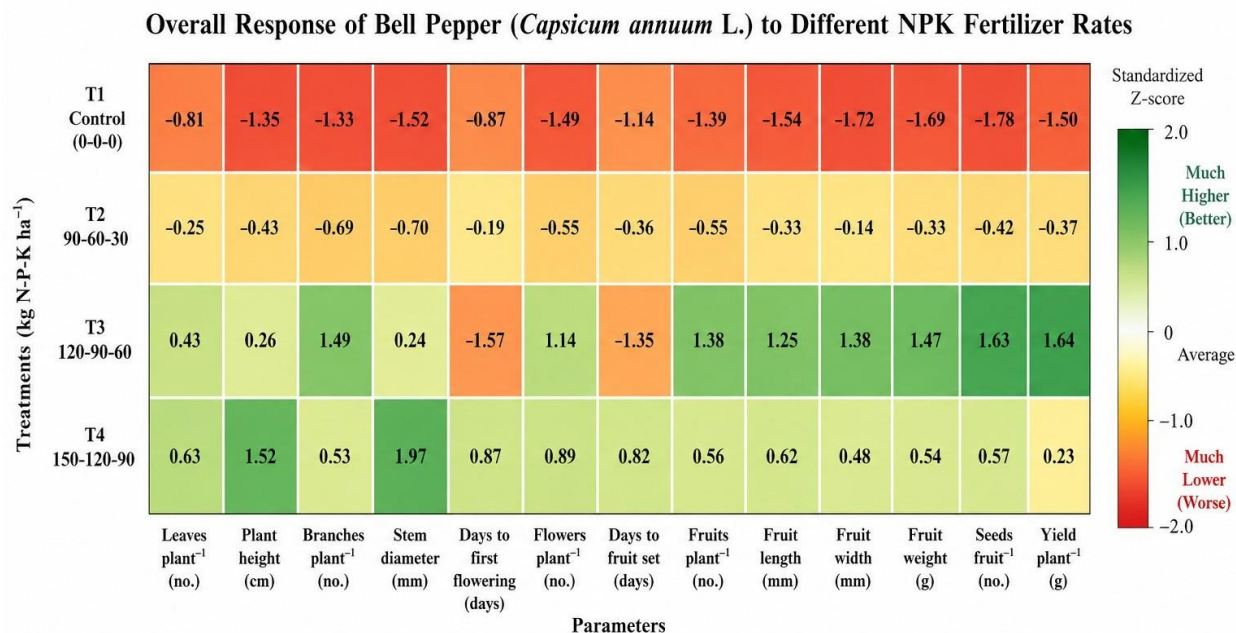


Figure 5. Heat-map illustrating the overall response of bell pepper (*Capsicum annuum* L.) to different NPK fertilizer treatments across vegetative, reproductive, fruit, seed, and yield-related attributes. Cell colors represent standardized Z-scores calculated independently for each parameter across treatments, with positive values indicating responses above the parameter mean and negative values indicating responses below the parameter mean. Green and red shades represent relatively higher and lower standardized responses, respectively. Values represent treatment means (n = 3).

Discussion

NPK regulation of vegetative and reproductive development

The present study showed significant effect of NPK fertilization on vegetative growth of bell pepper. As NPK was increased in a progressive way, the leaf production, plant height, branching and diameter of the stems increased, with the plants in T4 group (150-120-90 kg N-P-K ha⁻¹) generally showing the maximum vegetative growth. Leaves plant⁻¹ also increased from 100.00 in the unfertilized control to 147.73 in T4. The height of the plant was increased from 41.31 cm in the unfertilized control to 67.20 cm in T4 and stem diameter was increased from 6.46 mm to 11.03 mm in T4. These responses suggest that there was more nutrient availability which led to canopy development and structural growth. N is closely related to chlorophyll formation, proteins synthesis, photosynthetic capacity and biomass accumulation, while P is involved in energy

metabolism and root growth; and K in enzyme activation, osmotic relations, water relations and assimilate transport.

The vegetative response of the present experiment was strong, in accordance with previous experiments conducted on peppers. Aminifard and Bayat (2018) reported that the plant height, lateral stem development and leaf characteristics were significantly influenced by N supply, while Kunwar et al. (2024) observed that plant height, stem diameter, leaf number and branching were significantly affected by levels of NPK. At semi-arid conditions in Pakistan, Saqib et al. (2023) identified that the higher the N level (from 75 to 125 kg ha⁻¹), the more favourable the results for plant height, stem diameter, canopy development and biomass, but the effects were cultivar dependent. They found that the cultivar 'Winner' reacted differently than other cultivars, which is significant for the present study as the cultivar 'Winner' was also used in the current study.

The findings under semi-arid condition are also in agreement with that of Hemida et al. (2022) who observed that integrated soil and foliar NPK application significantly enhanced the leaf area, shoot biomass, fruit number, fruit weight and yield of *Capsicum annuum* in sandy soil condition under semi-arid condition. Their findings suggest that soil fertility and moisture availability are factors that limit nutrient uptake, and that nutrient availability may be particularly important. In the same way, Mishra et al. (2021) found that the plants in the integrated nutrient management system exhibited better growth and yield parameters than the unfertilized ones.

One of the key aspects of the present study was that the responses of vegetative growth were not the same as those of reproductive growth. Although T4 had the highest plant height, the greatest number of leaves and stem diameter, T3 had the earliest flowering and fruit set. The time to first flowering at 40.00 days was significantly earlier than the control (53.00 days), and the time to fruit set at 59.67 days was also significantly earlier than the control (72.67 days). This difference indicates that the intermediate NPK application rate favoured between vegetative growth and reproductive transition a more favourable balance than the other treatments, which were nutrient deficient or the highest rate of fertilizer.

The improvement in reproductive development under T3 could be due to availability of better nutrients at the transition of vegetative to reproductive development. N is important for photosynthesis and production of assimilates, P for energy metabolism and reproductive processes, and K for assimilate transport and physiological regulation. But too much N availability will promote high vegetative growth and slow or delay reproductive allocation. This interpretation is corroborated by Rodriguez et al. (2020), who showed that as the total available N was increased in sweet pepper, N-uptake and biomass production also increased, but the efficiency of N-uptake decreased as the N increased. Maximum production was found at an intermediate N

nutritional status, rather than at the highest N available.

Under other production conditions, similar evidence has been reported. Optimizing N supply led to an increase in pepper yield and quality, demonstrating that feeding too much N or improperly balanced N does not necessarily result in better crop performance (Han et al., 2021). Similarly, Saqib et al. (2023) showed that nutrient responses were cultivar-specific in the Pakistani context, emphasizing the need for cultivar-specific optimum nutrient response.

Fruit development, yield response, and optimum NPK rate

In the present experiment, the most favorable agronomic response was those related to fruit development and yield. The fruits plant⁻¹, fruit length, fruit width and mean fruit weight produced by T3 were 23.63, 72.71 mm, 70.27 mm and 129.20 g respectively, greater than the other treatments and the control which produced 11.28, 57.13 mm, 49.81 mm and 84.51 g respectively. Thus, the best yield (2163 g plant⁻¹) was obtained with T3, which is about 135% higher than the unfertilized control.

The advantage in fruit growth with sufficient NPK fertilization is due to higher photosynthetic rates, increased assimilate production and improved nutrient partitioning to fruit. K is especially vital in the fruit development stage due to its role in the regulation of osmotic balance, enzyme activity, carbohydrate transport and partitioning of assimilates. Botella et al. (2017) showed that the concentration of K affected the yield of pepper fruits, fruit firmness, soluble solids, soluble sugars and ascorbic acid. They conclude that sufficient K availability throughout fruit development is important, and not to be underestimated as part of vegetative nutrition.

Availability of phosphorus may also have contributed to the better reproductive performance under T3. Cui et al. (2023) found that yield, P uptake and P-use efficiency of pepper plant varied significantly with the application rate and method of P, showing that P application does not directly correlate with the yield of the crop, but

is dependent on how much P the crop needs. The current yield response also agrees with the findings of fertigation experiments which indicate the need for optimal rather than maximal nutrient supply. Oliveira et al. (2017) found that sweet pepper vegetative growth and yield and the nitrogen and potassium use efficiency were the parameters that were improved in the fertigation management by monitoring soil-solution condition. Recently, Wang et al. (2022) demonstrated that watermelon yield, dry matter production, harvest index and water- and N-use efficiency increased with water and N supply up to an optimum level, but decreased above it. Their optimized treatment fitted an intermediate rate of N as compared to the top rate which helped to validate the response pattern they noticed in the present study. The most significant result of the present experiment was, then, the non-linear relationship between the level of the fertilizer input and the agronomic output. The vegetative growth of T4 was greatest but fruit production was not. Instead, T3 (120–90–60 kg N–P–K ha⁻¹) produced the maximum yield. This means that these extra nutrients under T4 led to an excess production of vegetative biomass without producing a corresponding excess of reproductive productivity. This reaction is of agronomic significance because fertilizer recommendations should seek to maximize the harvestable yield and nutrient-use efficiency, not just plant size. This interpretation is confirmed by the findings of Rodríguez et al. (2020) who found that as total N supply increased, so did the N-uptake efficiency decrease and potential N loss increase in sweet pepper. Likewise, Wang et al. (2022) reported a decline in partial factor productivity for nitrogen with its application rate, highlighting the potential for inefficiencies in nutrient use when crop growth is high.

This principle is also observed in more recent investigations of fertigation. Ningoji et al. (2024) revealed, through optimization of the irrigation system using sensors, that the use of fertigation led to an improvement in the growth, yield, and resource-use efficiency of pepper plants and that the correlation analysis between the different variables produced significant results in the case of

fruit weight with yield, fruit number with yield, dry matter accumulation, and fruit volume with yield. Therefore, the present findings indicate that the higher efficiency of T3 was not only because of maximum vegetative biomass, but due to more beneficial utilization of vegetative resources into reproductive output.

Trait relationships and implications for nutrient management

The correlation heatmap was an extra confirmation of the interrelationships between vegetative, reproductive, fruit and yield parameters. As a whole, it was suggested that plant attributes related to fruit development and reproductive output were more closely related to final yield than vegetative plant attributes alone. The positive correlations between fruit number, fruit size/weight and yield indicate that the higher reproductive sink strength and fruit development were key factors in the higher yield experienced in T3. This is in line with the findings of Ningoji et al. (2024) that pepper yield has significant positive correlation with fruit weight, fruit number, dry matter accumulation and fruit volume.

The heat-map also sheds light on why T4, even with the highest number of leaves, a tall plant and stem diameter, did not yield the highest. Vegetative traits are the crop's ability to intercept light and to generate assimilates, whereas final yield will depend on the efficiency of assimilate allocation to reproductive sinks. For this reason a treatment can yield a bigger canopy without necessarily giving the highest yield of fruit. The correlation structure of the present study supports this distinction, and the correlations among vegetative growth, reproductive development, fruit formation and yield suggest that optimization of fertilizers should take into account the interaction among these growth parameters instead of basing it on the vegetative plant growth parameter.

In terms of nutrient management, it was found that the nutrient rate of 120–90–60 kg N–P–K ha⁻¹ (T3) gave the best nutrient balance for crop growth and reproductive productivity in the present experiment. The same study by Hemida et al. (2022) showed that an intermediate application

strategy for integrated fertilization could lead to better growth and yield, with lower risks of nutrient losses, than less efficiently managed applications, under semi-arid conditions.

The results are of special significance for the cultivation of bell pepper in Uthal and similar semi-arid conditions. The control (no fertilization) had smaller vegetative growth, fruit set, fruit number and fruit size, and yielded significantly lower due to insufficient nutrient supply. The superior yield for T3 compared to T4, however, shows that there is no guarantee that an increase in fertilizer rates beyond optimal will increase productivity. However, too much nutrient application can result in higher production costs and lower nutrient-use efficiency, as well as risk nutrient losses. This is particularly relevant in intensive vegetable systems, where nutrient supply is likely to be significantly higher than crop demand.

However, this recommendation should be taken in the context of the experiment. Only one cultivar, location and growing period were evaluated. Thus, the recommended application rate of 120-90-60 kg N-P-K ha⁻¹ should be viewed at first as an optimum for a specific site and cultivar, and not as a general guideline. This recommendation needs to be expanded further in Balochistan until multi-season trials of various cultivars, contrasting initial soil fertility ratings, irrigation practices and economic evaluations are completed. Despite this, the present study offers valuable field data that confirm that moderate levels of NPK fertilization can result in a more favorable vegetative versus reproductive development and yield balance compared to fertilizer omission and nutrient over-application.

Conclusion

The present study revealed that NPK fertilization significantly affected vegetative growth, flowering, fruit setting, fruit characteristics and yield of bell pepper (*Capsicum annuum* L.) cultivar 'Winer' in the agro-climatic conditions of Uthal (Balochistan province), Pakistan. The rate of 150-120-90 kg N-P-K ha⁻¹ resulted in the highest vegetative growth such as number of leaves, plant height, and stem

diameter. The intermediate (120-90-60 kg N-P-K ha⁻¹) rate had the best reproductive response, earlier flowering and fruit set, more flowers and fruit, larger fruit sizes, heavier fruit weight and highest yield (2163 g plant⁻¹).

The results show that for getting maximum yield, maximum fertilizer dose is not necessary. Rather, there should be a proper ratio between N, P and K for optimal reproductive productivity. At the experimental conditions, 120-90-60 kg N-P-K ha⁻¹ was the optimum dose for the production of maximum number of bell peppers and can be used as a recommended fertilizer rate for 'Winer' cultivar under similar growing environments in Uthal. This is to be confirmed by multiyear and multi-location testing and economic and nutrient-use-efficiency analysis before spreading from the pilot sites.

Author Contributions: Muhammad Ikram contributed to the study design, literature review, data collection, and manuscript preparation; Aadil Hameed contributed to study conceptualization, research supervision, methodological guidance, and critical revision of the manuscript; Muhammad Abuzar Jaffar provided overall scientific supervision, guided the experimental work, and critically reviewed the manuscript; Shahmir Ali Kalhoro contributed to statistical analysis, data interpretation, figure preparation, and critical revision of the manuscript; Muhammad Ilyas conducted field sampling, data collection, and laboratory analyses; Muhammad Yousaf assisted with field sampling, laboratory analyses, and data organization; Mushtaq Shah contributed to data interpretation, literature review, and manuscript revision; and Nimra assisted with data collection, literature review, and manuscript preparation. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Data and material availability

This article contains all the soil and plant analysis data generated during the course of this research study. The analysis and the resulting data

presented herein may be obtained at the reasonable request of the corresponding author.

Conflicts of interest

Authors declare no potential conflicts of interests

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