

DOI: [https://doi.org/10.71317/kjard.2.9\(s\).2026.641](https://doi.org/10.71317/kjard.2.9(s).2026.641)

# Kashmir Journal of Academic Research and Development

Journal homepage: <https://rjsaonline.org/index.php/KJARD>

## Unlocking Olive Productivity in the Pothwar Plateau through Optimized Nutrient Management Strategies

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### ARTICLE INFO

#### Received:

August 07, 2026

#### Revised:

August 24, 2026

#### Accepted:

September 06, 2026

#### Available Online:

September 19, 2026

#### Keywords:

Olive, fruit yield, fruit quality, fertilizer, Pothwar

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### ABSTRACT

Olive (*Olea europaea* L.) cultivation is gaining attention and expanding rapidly in Pakistan, predominantly in the Pothwar region. Being a new intervention, optimized nutrient recommendations for olive are lacking and need appropriate nutrient recommendation for achieving high fruit yield and oil productivity. During this study different nitrogen (N) and phosphorus (P) fertilizer combinations were tested on the yield performance of olive trees (Arbequina cv.) of ten years age at Chakwal, Pakistan. Treatments consisted of three N levels (400, 500, and 600 g tree<sup>-1</sup>) and two P levels (200 and 300 g tree<sup>-1</sup>), while potassium was applied uniformly at 300 g tree<sup>-1</sup>. Two plants were selected under each treatment and laid in randomized complete block design (RBCD) arrangement. Fertilizer application was completed according to treatment plan, all phosphorus,  $\frac{1}{3}$  nitrogen and  $\frac{1}{2}$  potash was applied in first week of March before flowering,  $\frac{1}{3}$  nitrogen in mid-April after fruit formation and  $\frac{1}{3}$  nitrogen and  $\frac{1}{2}$  potash was applied in the end of August. Plants were closely monitored during the whole period. During the month of October, olive fruits were picked from each tree after ripening, yield parameters including fruit weight/tree, average weight/fruit and oil content of fruit were recorded for each treatment. Results showed that increasing N and P application rates significantly improved olive productivity and oil accumulation. Among the tested treatments, NPK application at 600-300-300 g tree<sup>-1</sup> (T<sub>6</sub>) produced the highest fruit yield and superior fruit quality attributes, indicating that adequate nutrient supply is critical for maximizing olive performance in Pothwar conditions. The results suggest that application of 600 g N, 300 g P, and 300 g K per tree represents the most effective nutrient combination for 'Arbequina' olive. These findings provide a locally validated fertilization strategy to enhance olive productivity and support the sustainable development of Pakistan's emerging olive industry.

## Introduction

Olive (*Olea europaea* L.) is one of the world's most economically important fruit crops, cultivated extensively in Mediterranean and semi-arid regions for its edible oil, table fruit, and environmental benefits. In addition to its economic value, olive cultivation contributes to environmental sustainability through carbon sequestration, soil conservation, and adaptation to climate variability. Although olive cultivation has a long history in Mediterranean countries, olive farming in Pakistan is a relatively recent development. The country's first olive harvest was recorded in 1991 in Chakwal, Punjab (Ali et al., 2024). Owing to its diverse agro-ecological conditions, Pakistan possesses considerable potential for olive cultivation, particularly in rainfed and semi-arid regions. Recognizing the future demand for olive oil and the crop's high economic returns, the Government of Punjab has designated the Pothwar region as the "Olive Valley" of Pakistan (Iqbal et al., 2023).

Several olive cultivars, including Ascolana, BARI Zaitoon-1, Earlik, Gemlik, Hamdi, Hojiblanca, Manzanilla, and Picual, have been introduced and promoted for commercial cultivation in Punjab (Iqbal et al., 2022). Despite the rapid expansion of olive plantations, achieving high fruit yield and oil quality remains a major challenge due to suboptimal orchard management practices, particularly nutrient management. Balanced fertilization is essential for optimizing olive tree growth, canopy development, flowering, fruit set, yield, and oil synthesis. Adequate nutrient supply not only enhances fruit productivity but also influences oil content and fatty acid composition, which are critical quality parameters for olive oil production.

Among essential nutrients, nitrogen is frequently considered the most limiting element in olive orchards because of its central role in vegetative growth, leaf development, photosynthetic activity, and fruit production. However, excessive nitrogen application may adversely affect oil quality and reduce production efficiency (Jan et al., 2021). Potassium is equally important, particularly for fruit development, oil accumulation, osmotic regulation, and drought tolerance under water-scarce conditions (Rohi et al., 2023). Recent studies have demonstrated that integrated nutrient management approaches, including the combined use of soil-applied NPK fertilizers and foliar applications of potassium and boron, can significantly improve fruit yield and oil quality in olive orchards (Çolak et al., 2024). Likewise, fertilizer application at critical growth stages has been reported to improve nutrient-use efficiency and stabilize productivity under Mediterranean-like environments (Iqbal et al., 2022).

The effectiveness of fertilization practices, however, is strongly influenced by soil and environmental conditions. The soils of the Pothwar Plateau are predominantly alkaline, calcareous, low in organic matter, and frequently deficient in essential plant nutrients (Shaheen, 2016). High soil pH, calcium carbonate content, moisture limitations, and nutrient interactions often restrict nutrient availability and uptake by olive trees. Consequently, fertilizer recommendations developed for Mediterranean regions may not be directly applicable to the edaphic and climatic conditions of Pothwar. Furthermore, many local growers apply fertilizers without prior soil or leaf analysis, leading to imbalanced nutrient use, reduced fertilizer efficiency, and inconsistent yields (Iqbal et al., 2022; Khan et al., 2022).

Although considerable research has been conducted on olive nutrition in traditional olive-growing countries, information regarding the optimum nutrient requirements of olive under the alkaline, calcareous, and rainfed conditions of the Pothwar Plateau remains limited. In particular, field-based evaluations of different nitrogen and phosphorus combinations for maximizing fruit yield and oil production in commercially cultivated olive varieties are scarce. The lack of region-specific fertilizer recommendations represents a significant knowledge gap that limits the productive potential of olive orchards in Pakistan.

Therefore, the present study was conducted to evaluate the response of olive trees to different nitrogen and phosphorus fertilization regimes under Pothwar conditions and to identify the optimum nutrient combination for maximizing fruit yield and oil production. The findings are expected to provide scientifically validated fertilizer recommendations that will enhance nutrient-use efficiency, improve orchard productivity, and support the sustainable expansion of Pakistan's emerging olive industry.

## Materials and Methods

### Site selection and Experimental Design

Field experiments were conducted for five consecutive years during 2020-21 to 2024-25 at Chakwal, Pothwar region of Pakistan. The climatic conditions of the region are semi-arid, heavily influenced by monsoon rainfall, mostly characterized by hot summers and cool winters. The soil texture of the experimental site ranges from sandy loam to loam. Soils are non-saline with low organic matter. Trials were executed on permanent layout following randomized complete block design (RCBD) consisting of total six treatments including, T<sub>1</sub> (400-200-300) NPK g/plant, T<sub>2</sub> (500-200-300) NPK g/plant, T<sub>3</sub> (600-200-300) NPK g/plant, T<sub>4</sub> (400-300-300) NPK g/plant, T<sub>5</sub> (500-300-300) NPK g/plant, and T<sub>6</sub> (600-300-300)NPK g/plant with three replications (Table 1).

**Table 1: Treatment Plan (g/plant)**

| Treatment | N   | P <sub>2</sub> O <sub>5</sub> | K <sub>2</sub> O |
|-----------|-----|-------------------------------|------------------|
| T1        | 400 | 200                           | 300              |
| T2        | 500 | 200                           | 300              |
| T3        | 600 | 200                           | 300              |
| T4        | 400 | 300                           | 300              |
| T5        | 500 | 300                           | 300              |
| T6        | 600 | 300                           | 300              |

**Fertilizer application, Data collection and analysis**

Olive plants of 10 years old age were selected for the experiment. Total 36 plants were selected with two plants in each treatment. Fertilizer application was completed according to treatment plan, all phosphorus,  $\frac{1}{3}$  nitrogen and  $\frac{1}{2}$  potash was applied in first week of March before flowering,  $\frac{1}{3}$  nitrogen in mid-April after fruit formation and  $\frac{1}{3}$  nitrogen and  $\frac{1}{2}$  potash was applied in the end of August. Plants were closely monitored during the whole period. During the month of October, olive fruits were picked from each tree after ripening, yield parameters including fruit weight/tree, average weight/fruit and oil content of fruit were recorded for each treatment.

**Soil analysis**

To record the changes in soil chemical characteristics and fertility dynamics, soil samples (0-15 and 15-30 cm) were collected in February every year before start of fertilization. The analysis was done by using standard analytical protocols at Soil and Water Testing Laboratory, Rawalpindi. Soil textural class was determined by hydrometer method (Gee and Bauder, 1986), available phosphorus was measured on spectrophotometer using Olsen's method (Olsen et al., 1982), and potassium was determined with flame photometer by ammonium acetate extraction (Ryan et al., 2001; Estefan et al., 2013). Soil organic matter was determined by using Walkley and Black titration method (Nelson and Sommers, 1996).

**Data analysis**

The data of all years was compiled and analyzed statistically using statistix 8.1 software. Treatment means were compared using the least significant difference (LSD) test at a 5% level of significance. The economic analysis of the olive yield data was also done to compare the cost of different fertilizer doses and find the best fertilizer recommendation.

**Results****Effect of variable rates of NPK on soil chemical characteristics**

Soil samples collected annually after fruit harvesting revealed noticeable variations in soil chemical properties across the study period (2020–21 to 2024–25) (Table 2). Overall, fruit production resulted in nutrient removal from the soil; however, the continuous application of balanced fertilizers combined with pruning residues returned to the orchard floor helped sustain soil fertility and prevented severe nutrient depletion.

Electrical conductivity (EC) remained within the non-saline range throughout the study, varying from 0.90 to 1.81 dS m<sup>-1</sup>. A gradual increase in EC was observed over the years, particularly during 2023–24, which may be attributed to the cumulative effect of fertilizer additions and nutrient cycling within the orchard system. Nevertheless, EC values remained below the threshold considered detrimental for olive growth, indicating that fertilizer management practices did not induce salinity problems.

Soil pH remained moderately alkaline throughout the experimental period, ranging from 7.31 to 8.03. Minor fluctuations among treatments and years were observed, but no consistent trend of acidification or alkalization occurred. The relatively stable pH suggests that fertilizer applications and orchard management practices maintained a favorable chemical environment for nutrient availability and root activity.

Soil organic matter (OM) exhibited considerable temporal variation. Initial OM contents ranged from 0.57 to 0.85% during 2020–21, declined in several treatments during 2021–22 and 2023–24, and subsequently increased during 2024–25. The recovery of OM in the final year, particularly under T2, T3, T5, and T6 (0.75–0.78%), indicates the beneficial contribution of leaf litter, pruned biomass decomposition, and root turnover to soil carbon accumulation. These results suggest that orchard residue recycling partially compensated for organic matter losses associated with crop production.

Available phosphorus ( $P_2O_5$ ) showed substantial year-to-year fluctuations, ranging from 6.13 to 11.30  $mg\ kg^{-1}$ . The highest phosphorus concentration was recorded in T3 during 2020–21 (11.30  $mg\ kg^{-1}$ ), whereas the lowest value was observed in T5 during 2022–23 (6.13  $mg\ kg^{-1}$ ). Despite annual nutrient removal through fruit harvest, phosphorus levels were generally maintained within a narrow range across treatments, indicating that fertilizer applications replenished a significant proportion of the phosphorus removed by the crop.

Exchangeable potassium ( $K_2O$ ) varied considerably during the study period. Potassium levels declined after the initial years, reflecting substantial uptake by olive trees during fruit development. However, a marked increase was recorded during 2024–25, when  $K_2O$  concentrations reached 108–117  $mg\ kg^{-1}$  across treatments. The highest potassium content was observed in T6 (117  $mg\ kg^{-1}$ ), followed by T3 (112  $mg\ kg^{-1}$ ) and T5 (111  $mg\ kg^{-1}$ ). This improvement suggests that continued fertilizer application and nutrient recycling from orchard residues effectively restored soil potassium reserves.

Overall, the findings demonstrate that although fruit production continuously removes nutrients from the soil, long-term application of balanced NPK fertilizers together with the incorporation of pruned biomass and leaf litter can maintain soil fertility, stabilize soil chemical properties, and support sustainable olive production. Among the treatments, T6 consistently maintained comparatively higher soil nutrient reserves in the later years of the study, indicating a greater capacity to sustain soil fertility under continuous orchard production.

**Table 2. Chemical characteristics of soil 2020-21 to 2024-25**

| Year    | Treatments | EC<br>( $dS\ m^{-1}$ ) | pH   | OM<br>(%) | $P_2O_5$<br>( $mg\ kg^{-1}$ ) | $K_2O$<br>( $mg\ kg^{-1}$ ) |
|---------|------------|------------------------|------|-----------|-------------------------------|-----------------------------|
| 2020-21 | T1         | 0.94                   | 7.71 | 0.71      | 10.03                         | 90                          |
|         | T2         | 0.95                   | 7.57 | 0.85      | 6.40                          | 90                          |
|         | T3         | 0.92                   | 7.51 | 0.71      | 11.30                         | 83                          |
|         | T4         | 0.90                   | 7.41 | 0.84      | 8.60                          | 88                          |
|         | T5         | 0.98                   | 7.31 | 0.74      | 8.30                          | 82                          |
|         | T6         | 0.92                   | 7.95 | 0.57      | 7.40                          | 77                          |
| 2021-22 | T1         | 0.97                   | 7.87 | 0.52      | 6.60                          | 65                          |
|         | T2         | 0.96                   | 7.84 | 0.52      | 7.40                          | 73                          |
|         | T3         | 1.02                   | 7.90 | 0.52      | 9.10                          | 60                          |
|         | T4         | 0.92                   | 7.85 | 0.51      | 6.80                          | 80                          |
|         | T5         | 1.01                   | 7.89 | 0.52      | 8.30                          | 77                          |
|         | T6         | 0.95                   | 7.88 | 0.54      | 9.60                          | 85                          |
| 2022-23 | T1         | 1.13                   | 7.75 | 0.72      | 7.03                          | 71                          |
|         | T2         | 1.21                   | 7.74 | 0.82      | 6.90                          | 71                          |
|         | T3         | 1.23                   | 7.74 | 0.83      | 8.07                          | 76                          |
|         | T4         | 1.11                   | 7.74 | 0.69      | 7.90                          | 73                          |
|         | T5         | 1.02                   | 7.75 | 0.72      | 6.13                          | 72                          |
|         | T6         | 1.05                   | 7.77 | 0.75      | 7.30                          | 69                          |
| 2023-24 | T1         | 1.81                   | 7.58 | 0.31      | 10.00                         | 77                          |
|         | T2         | 1.32                   | 7.64 | 0.41      | 9.14                          | 86                          |
|         | T3         | 1.35                   | 7.75 | 0.38      | 9.60                          | 80                          |
|         | T4         | 1.42                   | 7.42 | 0.59      | 9.00                          | 92                          |
|         | T5         | 1.40                   | 7.59 | 0.46      | 8.96                          | 75                          |
|         | T6         | 1.21                   | 7.61 | 0.30      | 9.63                          | 83                          |
| 2024-25 | T1         | 1.48                   | 7.85 | 0.67      | 6.92                          | 109                         |
|         | T2         | 1.44                   | 7.91 | 0.77      | 6.51                          | 109                         |
|         | T3         | 1.39                   | 7.89 | 0.78      | 6.84                          | 112                         |
|         | T4         | 1.44                   | 7.91 | 0.72      | 6.63                          | 108                         |
|         | T5         | 1.41                   | 7.94 | 0.75      | 7.07                          | 111                         |
|         | T6         | 1.35                   | 8.03 | 0.78      | 7.07                          | 117                         |

#### Effect of variable rates of NPK on Olive fruit yield

Overall results of five years study demonstrates that a continuous increase in the fruit yield of olive plants was observed with increasing doses of NPK. Graded doses of NPK significantly ( $\leq 0.05$ ) influenced the olive fruit yield.

The five years pooled data of fruit yield per tree (figure 1) demonstrates that during first year of experiment maximum fruit yield per tree (12.245 kg) was obtained with the application of NPK @600-300-300 g/plant. Critical findings of the data suggested that increasing the level of P from 200 to 300 g/plant performed better when compared to the sole grading of nitrogen while keeping P constant. Silva et al., 2023 also reported similar trends. Quantitative analysis of the data depicted that 23% increase in fruit yield per tree and was recorded in T6 (NPK@ when compared to T1. Year wise comparison of the data showed that highest fruit yield was obtained during second year of experiment giving 19.986 kg per plant fruit yield.

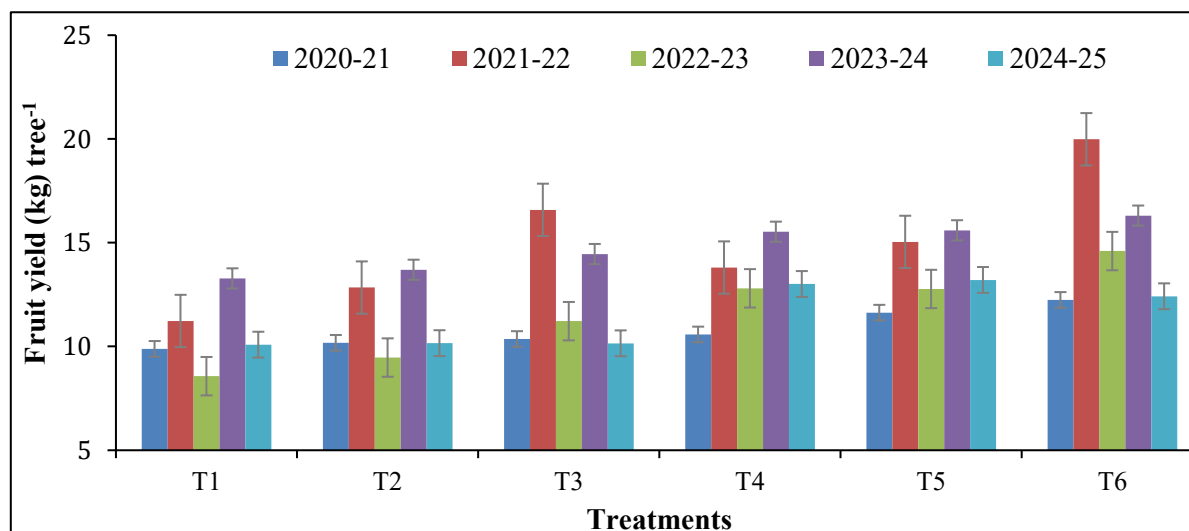


Fig 1. Effect of fertilizer treatments on fruit yield of olive. Error bars show standard error of mean of three replicates (n=3).

#### Effect of variable rates of NPK on Olive fruit quality

The data of average fruit weight showed a steady increase with the increasing levels of NPK concluding that experimental treatment positively influenced the quality of fruit. However maximum fruit weight was obtained with the application of NPK @600-300-300 kg/ha in T6. Elevating the level of P from 200 g/plant to 300 g/plant significantly boosted olive yield. These findings are in line with previous studies by Haberman et al., 2021.

As the experiment was continued for five consecutive years, in the first year of experiment there was 11% increase in fruit quality as average fruit weight was increased from 1.268 g in T1 to 1.413 g in T6. Although, a minor reduction in fruit size was observed in the subsequent year across all treatments, with values ranging from 1.021 to 1.291 g, however no effect was observed on overall yield. Maximum fruit size was picked during the year 2023-24. These yearly variation may be attributed to different rainfall pattern in each year.

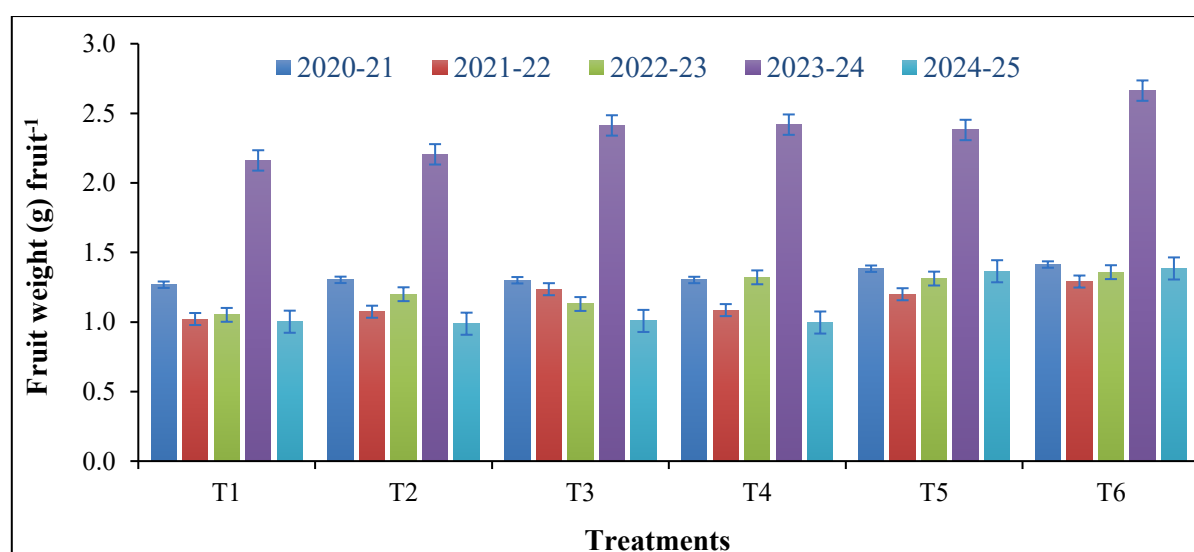


Fig 2. Effect of fertilizer treatments on per fruit weight of olive. Error bars show standard error of mean of three replicates (n=3).

### Effect of variable rates of NPK on olive fruit oil contents

Oil recovery from olive plants was significantly improved by increasing the dose of P, as 16% increase in oil content was observed in T<sub>6</sub> when compared with T<sub>3</sub>. Raising the sole nitrogen dose caused negligible impact on fruit oil content, however elevating the level of P significantly enhanced the oil recovery. The pooled data of long term study provided further evidences in the yield enhancement of olive plants with increasing levels of N and P. Tadayon et al., 2025 reported that application of balanced fertilization improved nutritional value, yield, and oil quality of olive fruit.

Maximum fruit oil content was observed with the application of NPK @600-300-300 g/plant. The experiment was concluded in 2024-25 by determining the best fertilizer recommendation for olive plants of age 10 years, giving maximum fruit oil recovery. Pairwise comparison of treatment means using Least Significant Difference (LSD) test also revealed significant difference in treatments means of different doses of N and P.

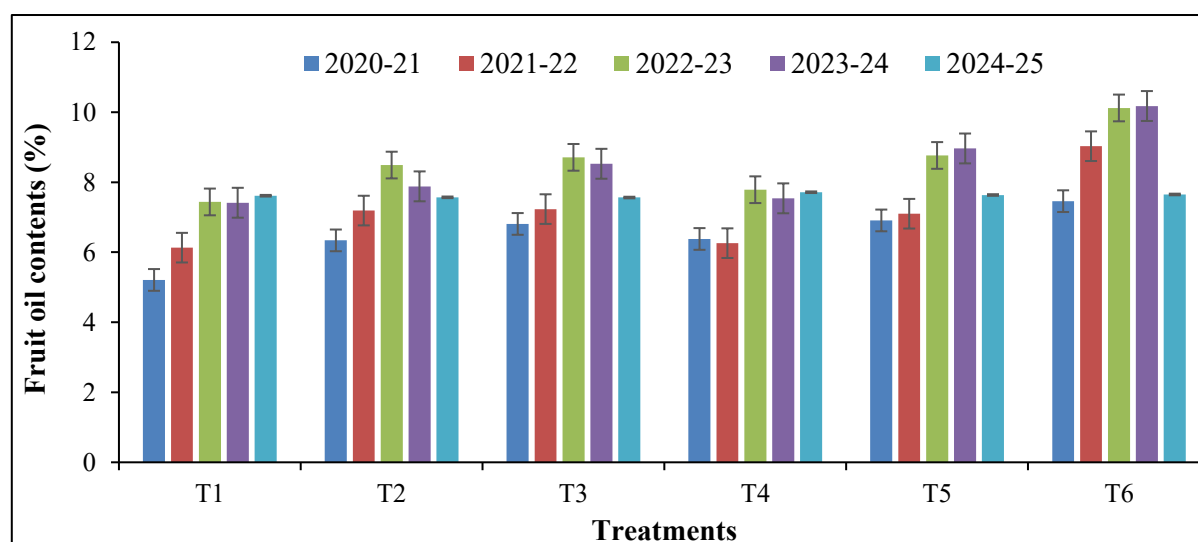


Fig 3. Effect of fertilizer treatments on fruit oil contents of olive. Error bar shows standard error of mean of three replicates (n=3).

### Discussion

The present study was carried out to determine the nutrient requirements of olive plants grown under semi-arid climatic conditions of pothwar region of Punjab. The results revealed that application of each nutrient significantly influenced all recorded yield parameters including average fruit weight, fruit yield per tree and oil content. Abdulqader and Shaymaa, 2024 also reported the similar trends. Application of different levels of nitrogen to olive plants caused significant variation in fruit yield in response to different nutrient levels. Maximum fruit yield was obtained by increasing the level of nitrogen from 400 to 600 g/plant which may be attributed to enhanced number of healthy and functional flower clusters. As reported by Silva et al., 2023 the boosted fruit yield may also be due to enhanced rate of photosynthesis, as nitrogen is a vital component of chlorophyll. Kotsias et al., 2023 and Pappas et al., 2023 also narrated the similar trends.

Application of phosphorus also contributed towards yield improvement of olive plants. As raising the level of phosphorus along with nitrogen caused more elevated yield as compared to sole increase in the nitrogen rate. According to Haberman et al., 2021 increase in yield may be supported by boosted rate of cell division, tissue development, inflorescence initiation, flower formation and ultimately developing into higher pulp to stone ratio fruit. These evidences have also been reviewed by Jan et al., 2021 through several studies.

Potassium plays a real support system for plants in osmoregulation and stomatal control, as narrated by Colak et al., 2024. Rohi et al., 2023 and Gowda et al., 2022 also reported the role of potassium in improving the fruit size and quality of fruit. Potassium also plays critical role in fatty acid synthesis which indirectly improves both oil content and overall quality of fruit pulp. Similar studies have also been reviewed by Isaac et al., 2020 stating that application of balanced fertilization increased fruit set and reduced fruit drop. Improvement in all yield parameters was observed with the application of NPK @ 600-300-300 gram per plants suggesting it an optimum recommended dose for the study area. On overall basis the increase in all yield components is supported by enhanced photosynthetic activity, fatty acid synthesis and improved sink strength due to sufficient supply of each essential nutrient as mentioned by Jan et al., 2021, Zipori et al., 2020 and Ferreira et al., 2020.

## Conclusion

This study evaluated the response of olive trees to different nitrogen and phosphorus fertilization regimes under the agro-climatic conditions of the Pothwar region. The results demonstrated that graded applications of NPK fertilizers significantly influenced fruit yield and oil content, highlighting the importance of balanced nutrient management for olive production. Among the evaluated treatments, the application of NPK at 600-300-300 g tree<sup>-1</sup> (T6) produced the highest fruit yield, fruit weight, and oil content, with differences confirmed as statistically significant by the LSD test at the 5% probability level.

The findings indicate that adequate and balanced supplies of nitrogen, phosphorus, and potassium are essential for maximizing olive productivity and improving fruit quality under the alkaline and calcareous soil conditions of the Pothwar Plateau. Based on the results of this study, the application of NPK at 600-300-300 g tree<sup>-1</sup> can be recommended as an effective fertilization strategy for enhancing yield and oil production in olive orchards of the region.

Furthermore, the study emphasizes that nutrient application at appropriate growth stages is critical for improving nutrient-use efficiency and sustaining orchard productivity. Balanced fertilization not only increases fruit yield but also contributes to enhance oil content, thereby improving the economic value of olive cultivation. Nevertheless, the present findings are limited to the conditions of this study and the evaluated cultivar. Future research should investigate the long-term effects of this fertilization regime on soil fertility, nutrient dynamics, and environmental sustainability, as well as validate its effectiveness across different olive cultivars, orchard ages, and agroecological conditions.

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