Research Article

Multi-Location Assessment of Harvesting Time Effects on Olive Oil Yield in Pakistan

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Abstract | In Pakistan, commercial olive cultivation has been initiated recently, with 20,459 hectares currently under cultivation and 6.314 million olive plants established. Olive oil, a historically significant and highly valued commodity, has served as an essential culinary and medicinal ingredient for centuries. The quantity of extracted olive oil is influenced by multiple factors, among which harvesting date and geographical location are critical. This study employed multi-environment trials to evaluate genotype-by-environment interactions (GEI) and optimize harvest timing for oil yield. A randomized complete block design was implemented across five districts in Punjab and Baluchistan over three consecutive years (2019–21). Fruits were harvested at seven intervals (30 September to 30 November), and oil was extracted using a cold press unit at the Barani Agricultural Research Institute, Chakwal. Maximum oil recovery (28.53%) was recorded on 20 October 2019 in Musakhel, while the minimum (3.82%) occurred in Attock on 30 September 2019. ANOVA confirmed significant effects of harvest time and location on oil yield. To dissect the complex interaction between harvest dates and environments, GGE biplot analysis was applied, which is a novel approach in olive research to identify stability and optimal growing conditions. The "Which-won-where" polygon delineated two mega-environments: Musakhel-Chakwal (highest yield potential) and Loralai-Rawalpindi. Findings demonstrate that Musakhel and Loralai (Baluchistan), followed by Chakwal (Punjab), are optimal for olive cultivation, with 20 October–30 November as the ideal harvest window for maximizing oil recovery.

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Introduction

The olive (*Olea europaea* L.) is a member of the Oleaceae family. This fruit tree is being cultivated in all the Mediterranean countries, as well as in other parts of the world, including Australia, Asia, the United States of America, and the Southern parts of Africa. Moreover, the cultivated olive groves are found in many other regions of the world having similar Mediterranean agro-climates (Torres *et al*., 2017). Olive cultivation is a significant agricultural activity in these regions, supporting local economies and playing a vital role in the production of olive oil, vegitable olives, and other olive-based products. The world area under olive cultivation is estimated to be around 10 million hectares, with production of 23.054 million metric tons and average yield of 2230 kg ha^{-1} (FAOSTAT, 2023).

Mediterranean countries are the largest producers of olive oil worldwide. The world's olive oil production is estimated to be around three million metric tons annually (USDA, 2023). Olive oil is a common ingredient in the diets of Mediterranean people owing to its dietary health benefits for humans. Due to the health benefits and enriched nutrition status of olive oil, its use has increased in recent years, even in non-olive-growing countries like USA, Japan and Canada (Sohaimy *et al*., 2016). In the world, cold-press units are used to extract premium quality olive oil from freshly harvested olives. This oil is the healthiest vegetable oil, which is among the rare vegetable oils that can be used in its raw state directly (Taluri *et al*., 2019).

Pakistan has recently initiated commercial olive cultivation, with 20,459 hectares of land now under olive groves and over six million plants established, yielding a current production of 861 metric tons. The government has actively promoted sectoral expansion through policy incentives supporting orchard establishment and management.

Mele, *et al*. (2018) reported that olive oil quality and quantity are influenced by the selection of the optimum harvesting period. However, due to variations in tree response at different locations and prevailing season, the selection of optimum harvest date is always challenging (Sohaimy *et al*., 2016). There are many other factors, like growing area, environmental conditions, fruit ripening, and harvest time should also be considered for getting optimum oil recovery. The environmental conditions are critical factors that can affect the quality and quantity of olive oil from one area to another area and from one harvest season to another (Mansouri *et al*., 2018). Qarnifa *et al*. (2019) updated that olive oil yield has a prime economic significance to the growers and would be linked along with other quality parameters for harvest scheduling. Likewise, the effect of harvest timing on the oil recovery is a very important factor to consider by the growers (Mele *et al*., 2018).

Despite the growing importance of olive cultivation in Pakistan, there remains a critical research gap regarding the optimal harvesting time for maximizing olive oil yield and quality under local agro-climatic conditions. While previous studies (Mele *et al*., 2018; Sohaimy *et al*., 2016) have established that harvest timing significantly influences oil recovery and quality, most of this research has been conducted in Mediterranean regions, which differ substantially from Pakistan's climate, soil, and olive cultivars. Furthermore, although Pakistan has rapidly expanded its olive cultivation, limited localized studies have systematically evaluated how harvesting dates affect oil yield and biochemical properties in different growing regions of the country. Recent localized studies from Pakistan have begun to address these challenges. Research by Alam *et al*. (2024) demonstrated that both olive oil yield and quality are highly sensitive to harvest dates and regional climatic conditions, particularly in the Pothohar Plateau and Balochistan regions. Findings showed that semi-ripe harvesting stages produced higher-quality extra virgin olive oil with elevated phenolic content and lower acidity, while delayed harvesting reduced oil quality significantly.

Additionally, while international research (Qarnifa *et al*., 2019; Mansouri *et al*., 2018) highlights the economic importance of harvest scheduling, there is a lack of region-specific data to guide Pakistani farmers on the best harvesting window to balance yield and quality. Given that environmental factors such as temperature, rainfall, and altitude vary significantly across Pakistan's olive-growing regions (e.g., Pothwar, Balochistan, and Khyber Pakhtunkhwa), a uniform harvesting recommendation may not be applicable. This study aims to address this gap by investigating the effects of harvesting time and geographical location on olive oil recovery and quality, providing locally validated insights to optimize harvest schedules for Pakistani olive growers. The findings will contribute to enhancing the economic viability and sustainability of Pakistan's emerging olive oil industry.

Materials and Methods

This study was conducted during the 2019-21 olive harvesting season at the Center of Excellence for Olive Research & Training (CEFORT) at Barani Agricultural Research Institute (BARI), Chakwal, located in North Punjab, Pakistan. Olive fruit samples from five different locations of Punjab (Attock, Chakwal, and Rawalpindi) and Baluchistan (Loralai and Musakhel) were harvested at various stages as given in the Table 1.

Fruit sampling was conducted at seven different dates; the initial harvest date was fixed by the end of September, and succeeding harvest dates were exactly ten days apart. The experimental trees were 6 years old during 1st year of this study. Only healthy fruits without any physical damage were collected for oil extraction. A representative sample of 100 kg of fruit was taken from twenty-five trees within each of three replicates. Single trees were harvested only once so as not to change the natural conditions, which may affect a succeeding harvest. After harvest, the olives were extracted into oil within 24 hours according to the Pieralisi (Fattoria, 2016) system as explained below.

The oil milling process begins with the careful selection and thorough washing of olives to remove any impurities. The cleaned olives are then crushed into a paste using hammer mills or traditional stone grinders, a step essential for maximizing oil extraction. This paste is subsequently transferred to a horizontal decanter, where centrifugal force separates the oil from the solids and water through a continuous process. The result is a high yield of pure olive oil. Following extraction, the oil undergoes clarification and filtration to eliminate any remaining impurities, ensuring high quality and purity.

Statistical analysis

The data was examined by analysis of variance with a 5% probability level by using R-Studio (GGE biplot) version 3.5.1 to identify significant differences for olive oil recovery. Principal component analysis was performed to analyze the harvesting dates on oil recovery percentage and environmental effects at diverse locations in Pakistan. Which-won-where analysis was also performed to identify the suitable environment for olive cultivation and its interaction with harvesting date, along with basic biplot, mean performance vs stability, and Discriminative-ness vs Representativeness analysis.

Results and Discussion

The olive oil recovery rate is closely tied to the timing of fruit harvesting, which represents one of the most critical and costly factors influencing overall yield. Proper scheduling of the harvest allows growers to maximize both the quantity and quality of the crop in

Table 2: *Agro-climatic characteristics of study locations in punjab and baluchistan, pakistan*

Region	Location	Altitude (m)	Annual rainfall (mm)	Average temperature (°C)	Soil type	Climate type
Punjab	Attock	350–520	600–800	18–26	Sandy loam to clay loam	Semi-arid to sub-humid
	Chakwal	450–600	500–700	17–25	Loamy to clayey	Semi-arid
	Rawalpindi	500–700	750–1200	16–24	Silt loam	Sub-humid
Balochistan	Loralai	1200–1500	250–400	15–22	Sandy loam	Semi-arid to arid
	Musakhel	1100–1400	200–350	16–23	Sandy to sandy loam	Arid to semi-arid

Pakistan meteorological department (PMD)

Table 3: *Analysis of variance for olive oil recovery data of five different locations and seven harvesting dates for three years*

Source	DF	SS	MS	F	P
Replication	2	3.4	1.70		
Year	2	25.3	12.66		
Replication*year	4	9.0	2.24		
Location	4	8128.2	2032.05	304.88	0.000
Treatment	6	423.5	70.58	10.59	0.000
Location*treatment	24	455.3	18.97	2.85	0.000
Error	272	1812.9	6.67		
Total	314	10857.5			

Coefficient of variance (CV) = 19.69 Grand mean = 13.113, DF = Degree of freedom, SS = Sum of squares, MS = Mean square, Significant at $p \leq 0.05$, 0.000 Significant at $p < 0.01$

Table 4: *Impact of harvesting dates on olive oil recovery percentage.*

Treatment	Date of harvesting	% Mean oil recovery	% Max. Recovery	% Min. Recovery
T_1	30-Sep	10.92 C	17.96	3.82
T_2	10-Oct	11.98 BC	21.86	4.81
T_3	20-Oct	13.42 AB	28.53	4.38
T_4	30-Oct	14.43 A	27.89	4.38
T_5	10-Nov	13.88 A	24.17	5.59
T_6	20-Nov	13.09 AB	23.22	4.23
T_7	30-Nov	14.04 A	25.48	4.42

Standard error = 0.54
Means followed by the same letter are not significantly different at p<0.05

a given year. Therefore, the choice of harvesting date is vital to achieving optimal production efficiency and oil quality (Lopez-Villalta, 1996).

The results of the ANOVA (Table 3) reveal significant effects of both location and harvesting dates on oil recovery. The F-values for location (304.88, df = 4) and harvesting dates (10.59, df = 6) were statistically significant ($p \leq 0.05$), indicating considerable variability influenced by these factors.

Post-hoc comparisons (Tables 4 and Table 5) demonstrated that oil yield progressively increased from late September through the end of November, with the highest recovery recorded when olives were harvested in late October and November. Notably, among the study sites, Musakhel District in Balochistan consistently achieved the highest oil yield compared to other locations ($p \leq 0.05$).

Table 5: *Evaluation of multi-location on olive oil recovery percentage*

Location	% Mean oil recovery	% Max. Recovery	% Min. Recovery
Musakhel	20.20 A	28.53	13.00
Loralai	18.29 B	25.48	13.50
Chakwal	9.96 C	19.03	4.17
Rawalpindi	8.98 CD	15.04	4.38
Attock	8.13 D	15.00	3.82

Standard error = 0.46
Means followed by the same letter are not significantly different at p<0.05

This trend of increasing oil content with delayed harvesting likely reflects the accumulation of synthesized oil during fruit ripening, coupled with a reduction in fruit moisture content as the season progresses. Although differing from Youssef *et al.* (2010), who found no significant variation in oil recovery during fruit maturation stages.

Across locations, the mean oil content ranged from 8.13% in Attock District to 20.20% in Musakhel District, with maximum and minimum individual sample values of 28.53% and 3.82%, respectively (Table 5). The observed regional differences are likely attributed to variations in climatic and environmental conditions, as previously noted by Hannachi *et al.* (2007). While previous studies (e.g., Alowaiesh *et al.*, 2016) have suggested that both environmental factors and crop year can influence oil yield, in the current study, the effect of crop year was found to be non-significant.

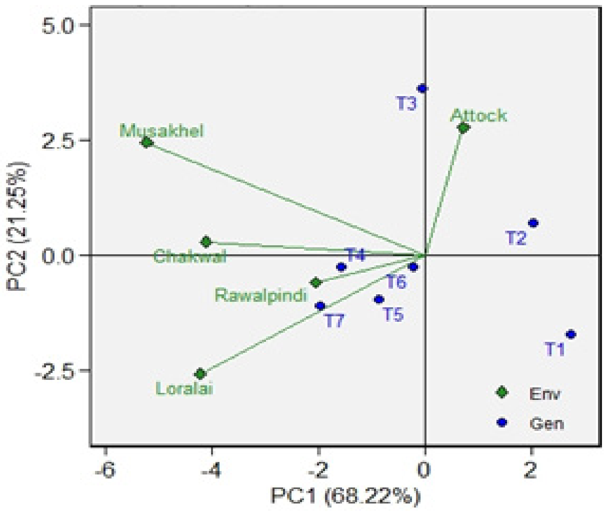

Figure 1: *Biplot analysis results*

An additional statistical analysis was carried out if there is a significant interaction between treatments (harvesting dates) and multi-location / environment to determine the stability level among the 07 treatments across the environment. GGE biplot permits the multi-location evaluation based on the discerning factor and representation of the GGE view (Sharma *et al.*, 2020).

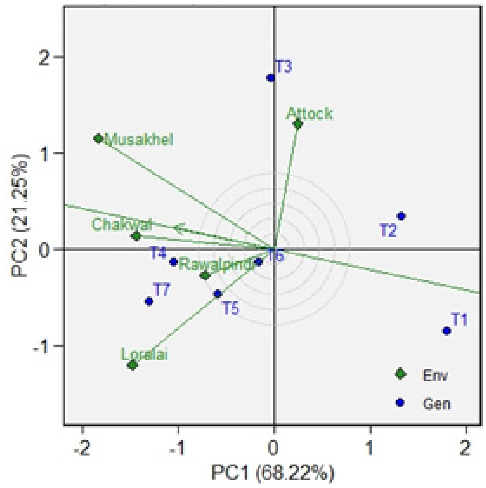

Figure 2: *Discriminativeness and representativeness of the harvesting dates with the locations*

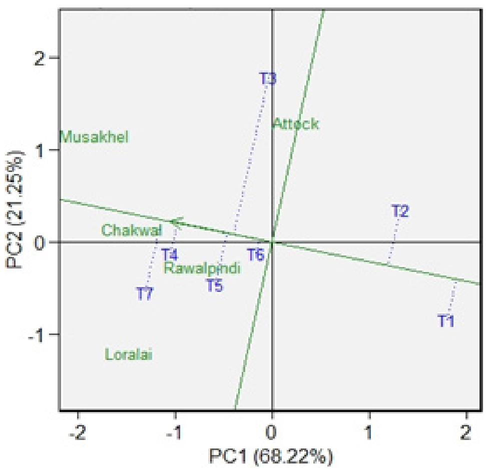

Figure 3: *Stability analysis of the harvesting dates with the locations*

The GGE biplot analysis was used to find out the most suitable harvesting date for every single location and to evaluate their steadiness as reported by Yan and Tinker (2006). They developed a correlation amongst the tested environments with a centered-based modelled on a centered and metric preserving environment without scaling. The biplot described 89.47% of the total differences recorded, of which 68.22% was explained by the first component (X-axis), while the second component (Y-axis) described 21.25%. The stretch of the multi-location vectors is comparable to the standard deviation within each biplot's environment and demonstrated the location's ability to classify. From this analysis (Figure 1) and illustration of the harvesting dates in multi-locations (Figure 2), Musakhel and Loralai stand out best among other locations.

The effect of harvesting dates on olive oil recovery at each location is shown in Figure 3. For the five locations, most of the harvesting dates are clustered away from the origin, especially at 20 October and 30 October. However, 10-November and 20-November are clustered close to the origin but have a clearer distinction than the other harvesting dates. In GGE biplot analysis "which-won-where" graph is the most important module, which supports recording the interaction patterns between harvesting dates and multi-location. The harvesting dates, 20 October, 30-October, and 30-November were all positioned at the corners of the shape (Figure 4), demonstrating that these dates were most suitable in terms of olive oil recovery in these locations. These dates were the best to extract maximum oil from Musakhel District fruit samples, followed by Loralai samples. Whereas 10-November and 20-November were positioned near to GGE biplot center. This specifies that these dates recorded a steady behavior among the locations. The result shown in Figure 4 presents three-location sets for olive cultivation; Musakhel and Chakwal together form the 1st one, while Loralai and Rawalpindi together form the 2nd one, last of all the Attock as 3rd set.

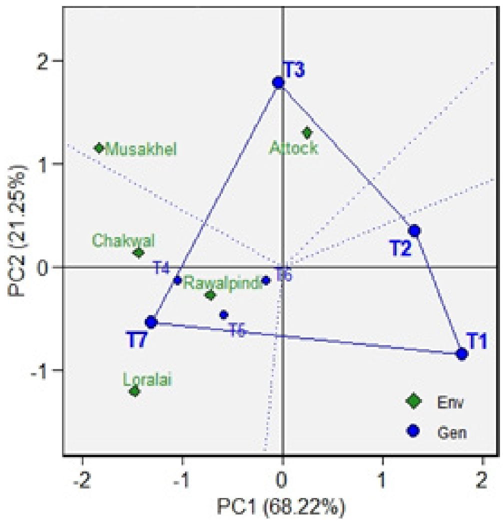

Figure 4: *Which-won-where analysis of harvesting dates identifying the best dates suitable for each location*

The superior performance of Musakhel can be attributed to several factors, including its favorable climatic conditions characterized by optimum temperatures and low humidity during fruit maturation, ideal soil properties that support olive cultivation, and possibly the selection of better-adapted olive varieties. These environmental and varietal advantages likely contributed to the higher oil recovery rates observed in this location compared to others.

Table 1: *Treatments showing harvest dates and locations for three consecutive years*

Treat-ments	Harvest date	Location														
		Attock			Chakwal			Loralai			Musakhel			Rawalpindi		
		2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	**2021**
T_1	30-Sep															
T_2	10-Oct															
T_3	20-Oct															
T_4	30-Oct															
T_5	10-Nov															
T_6	20-Nov															
T_7	30-Nov															

The non-significant year effect observed in this study can be attributed to the stability of environmental conditions and consistent orchard management practices across the different years of data collection. While previous research has indicated that crop year can influence oil yield, the lack of significant variation in this study suggests that the environmental consistency, such as climate and soil properties, likely played a larger role than fluctuations between years. In particular, environmental control through consistent orchard management, including practices like irrigation, pest management, and pruning, may have minimized annual variation in the olive fruit's physiological development and maturation process.

The GGE biplot analysis further supports this interpretation by showing that harvesting dates had a more pronounced impact on oil yield than the year of cultivation. Locations like Musakhel, with favorable climatic conditions and optimal soil for olive cultivation, consistently performed better in terms of oil recovery, indicating that these factors were more influential than annual variations. Additionally, the grouping of specific harvesting dates (such as 20 October and 30 October) near the corners of the GGE biplot suggests that the consistency in environmental conditions across years allowed for the identification of optimal harvest times, resulting in more reliable and higher yields. Therefore, the combination of favorable environmental factors and careful orchard management likely contributed to the lack of significant year-to-year variation in the oil recovery rates observed in this study. Moreover, the Agro-climatic characteristics of study locations in punjab and baluchistan, Pakistan are mentioned in Table 2.

Conclusions and Recommendations

The findings of this research conclude that harvesting date and environmental conditions play a significant role in olive oil recovery. In Pakistan, the regions of Musakhel and Loralai in Balochistan, followed by Chakwal in Punjab, are the most suitable for olive cultivation. The optimal harvesting period for maximum oil recovery is from 20 October to 30 November.

Future researchers should explore the impact of varying climatic conditions on olive oil quality and yield across different regions of Pakistan, including potential new cultivation zones. Further studies could investigate the effects of advanced harvesting techniques and post-harvest processing methods on oil recovery efficiency. Additionally, long-term monitoring of olive orchards in Musakhel, Loralai, and Chakwal is recommended to assess sustainability and productivity trends under changing environmental conditions

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Novelty Statement

This study uniquely identifies the optimal olive harvesting window (20 October–30 November) and the most suitable regions (Musakhel, Loralai, and Chakwal) for maximizing oil recovery under Pakistan's agro-climatic conditions.

Author's Contribution

Inam Ul Haq: Conceived the idea and conducted research.

Humara Umar: Wrote results and discussion, and provided technical input at every step.

Attiq-Ur-Rehman: Wrote abstract, introduction, methodology and references.

Muhammad Adnan: Data entry, analysis, wrote conclusion and literature review.

Muhammad Ramzan Anse: Overall management of the study.

Generative AI or AI assisted technology statement

The authors declare that no generative AI or AI-assisted technology was used in the writing or editing of this manuscript.

Conflict of interest

The authors have no conflict of interest.

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