



# International Journal of Agriculture Innovations and Cutting-Edge Research



## Enhancing Citrus Yield and Water Use Efficiency in Pakistan's Arid Zones: A Four-Year Evaluation of Low-Tech and High-Tech Irrigation Methods



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### Abstract

Water scarcity limits citrus production in arid areas of Pakistan. This study evaluated five irrigation techniques – basin irrigation (BI, control), surface drip irrigation (SDI), plastic bottle irrigation (BTI), pitcher irrigation (PI), and perforated plastic sleeves irrigation (PPSI) – for their effects on soil moisture, fruit yield, water productivity, and economic returns of five-year-old Kinnow mandarin trees over four growing seasons (2016–2019) at Fateh Jang. The experiment used a randomized complete block design with three replications. SDI significantly ( $p \leq 0.05$ ) increased fruit yield (16,416 kg ha<sup>-1</sup>) and water productivity (7.13 kg m<sup>-3</sup>) compared to BI (9,732 kg ha<sup>-1</sup> and 1.43 kg m<sup>-3</sup>, respectively). SDI also achieved the highest net return (Rs. 2,087,400 ha<sup>-1</sup>) despite higher installation costs. PI and BTI produced intermediate yields (11,969–12,301 kg ha<sup>-1</sup>) with water productivity 4–5 times higher than BI. PPSI showed the lowest performance among the water-saving techniques. We conclude that surface drip irrigation is the most effective technique for enhancing water productivity (83%) and citrus yield (51%) under arid conditions, though pitcher and bottle irrigation offer affordable alternatives for resource-limited farmers.

**Keywords:** Irrigation techniques; water productivity; high-value crops; sustainable production; citrus

DOI:	<a href="https://zenodo.org/records/20541660">https://zenodo.org/records/20541660</a>
Journal Link:	<a href="https://jai.bwo-researches.com/index.php/jwr/index">https://jai.bwo-researches.com/index.php/jwr/index</a>
Paper Link:	<a href="https://jai.bwo-researches.com/index.php/jwr/article/view/237">https://jai.bwo-researches.com/index.php/jwr/article/view/237</a>
Publication Process	Received: 22 April 2026/ Revised: 09 May 2026/ Accepted: 30 May 2026/ Published: 04 June 2026
ISSN:	Online [3007-0929], Print [3007-0910]
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Indexing:	     
Publisher:	BWO Research International (15162394 Canada Inc.) <a href="https://www.bwo-researches.com">https://www.bwo-researches.com</a>

## 1. Introduction

Arid regions receive less than 500 mm of average annual rainfall and consequently face water scarcity. Therefore, there is a threat of drought in the future in dry areas due to factors like climate change and increased population (Ullah et al., 2022; Elahi et al., 2023). Arid and semi-arid regions are experiencing increased evapotranspiration as rising temperatures enhance atmospheric water demand and soil moisture loss, leading to intensified drought and reduced water availability (Jin et al., 2017). Seventy percent of the agricultural sector depends on irrigation water, and increasing demand due to population growth heightens the risk of water scarcity (Knox et al., 2018; Ahmad et al., 2022; Hafeez et al., 2024). Citrus is a very important fruit in human nutrition, grown in over eighty countries with global per annum revenues of over US\$ 9.5 billion. Most of the citrus-producing nations like Italy, Greece, Egypt, Turkey, and Morocco have arid and semi-arid climates (Slamini et al., 2022). While drip irrigation is known to improve water productivity, its high initial cost limits adoption by smallholders. Low-cost alternatives such as pitcher, bottle, and perforated sleeve irrigation have been tested for vegetables but rarely for perennial fruit crops like citrus. Moreover, comparative field evaluations under the specific arid conditions of Pakistan's Pothohar region are lacking. Modern irrigation techniques, such as approaches that improve soil moisture retention and water use efficiency (WUE), will provide an effective measure to mitigate the impact of climate change (Ayling et al., 2021). Varying irrigation techniques and management ways do affect the yield and WUE of fruiting trees.

In comparison to surface irrigation, drip irrigation, which can be subdivided into

Surface Drip Irrigation and Underground Drip Irrigation, is capable of reclaiming more water (Martinez and Reza 2014). It has been observed in different research studies that both surface and subsurface drip irrigation techniques increase crop yields (Aydinsakir et al., 2021). Subsurface drip irrigation tends to minimize the evaporating water contents (Pramanik et al., 2024) and possesses a higher WUE as compared to surface drip irrigation (Cetin and Kara, 2019). Hence, it is the need of the hour to switch to the use of agricultural mechanization and automatic irrigation systems instead of traditional methods in irrigation activities (Al-Sammarraie et al., 2021). The common farming practice for irrigation in citrus orchards is flooding, furrows, and basins. Consequently, the world has faced an insufficiency of water in major citrus-grown areas (Singh and Srivastava 2004).

In Pakistan, citrus is grown on 0.195 million hectares with an annual yield of 2.27 million tons (Raza et al., 2020). Deficit irrigation in many crops has proven to be a tool for improving WUE. The supplemental irrigation at critical growth stages (flowering and fruit filling) using a limited amount of water by irrigation techniques resulted in higher fruit yield and WUE (Dimple et al., 2019). Consequently, to maximize water productivity and water saving in "water scarce areas" to avoid deficits and reduction in yield, the management of water has to be carried out effectively and efficiently using various irrigation techniques.

Irrigation water has two components, i.e., evapotranspiration (ET) and distribution of water to the area (Steduto et al., 2007). Therefore, advantages and disadvantages may be considered when choosing an irrigation technique for a particular area. Flood irrigation uses more water with greater losses but has lower

costs, while surface drip irrigation saves water and is more efficient but costs more to install and maintain. Overall, research focused on water productivity and efficiency for higher yield achievement. The current experiment was conducted 1) To quantify the effects of five irrigation techniques (basin, surface drip, plastic bottle, pitcher, and perforated plastic sleeves) on soil moisture retention, fruit yield, and yield attributes of Kinnow mandarin, 2) To compare the water productivity (kg fruit per m<sup>3</sup> water applied) and economic net returns of these irrigation techniques over four consecutive growing seasons, 3) To identify the most water-efficient and cost-effective irrigation method for citrus growers in water-scarce regions of Pakistan.

## 2. Materials and Methods

### 2.1 Experimental area

The study was conducted during 2016-2019 in the research area of the Soil and Water Conservation Research Station (SAWCRS) Fateh Jang at a latitude of 33.55°N, longitude 72.58°E, and an altitude of 402m above sea level to monitor the effect of different irrigation techniques applied to five-year-old citrus plants. i.e., Basin Irrigation (BI), Surface Drip Irrigation (SDI), Bottle Irrigation (BTI), drinking bottles (with multiple holes of 10 mm dia.), Pitcher Irrigation (PI), Perforated Plastic Sleeves Irrigation (PPSI) (3 mm dia. plastic pipe up to 3 feet depth with 12 holes of 10 mm were evaluated. Five plants of Mandarin sp. (*Citrus reticulata* Blanco cv. Pak-kinnow) were selected for each treatment. The research trial was planned using a Randomized Complete Block Design (RCBD) in three replications. Each set of plants received an equal amount of nutrients annually. Irrigation was carried out in the water deficit period every time, i.e., very low rainfall months (April-June and Oct-December), as shown in Figure 1.

A total of eight irrigation events were applied per year. Effective rainfall was not subtracted from gross irrigation applied in water productivity calculations. Rainfall during July-August (average 20-40 mm monthly) likely contributed to soil moisture, meaning the reported water productivity values may underestimate true efficiency. Future studies should compute net irrigation requirements using a water balance approach (Allen et al., 1998). Soil moisture content was determined by the gravimetric method. The mean monthly evapotranspiration during the study is presented in Table 1.

### Annexure (A)

### Annexure (B)

## 2.2. The soil analysis of the experimental site

The pre-sowing soil analysis results indicate that exchangeable potassium and available phosphorus were in the optimum range while the soil was deficient in organic matter. The texture of the soil was silt loam. The ECe was normal, while pH was found in the slightly alkaline range (Table 2)

**Table 2:** Soil Analysis of Experimental Site

Soil depth	PH	ECe (ds m-1)	O M (%)	Av. P (pp m)	Av. K (pp m)	Textu re
0-15	7.51	1.59	0.70	20.04	189	Silt loam
15-30	7.65	0.54	0.67	18.07	120	Silt loam
30-60	7.69	0.49	0.65	16.25	110	Silt loam
60-90	7.67	0.53	0.58	11.40	80	Silt loam

### 2.3 Irrigation Schedule

Irrigation scheduling for various irrigation systems, such as FI, SDI, BI, PI, and PPSI, was established at the experimental site by viewing the pit and pan-evaporation source from the SAWCRS observatory 1 cm from each treatment. Rainfall and temperature data were

recorded at the meteorological data station of the Soil and Water Conservation Research Station, Fateh Jang. Supplementary irrigation was applied according to the orchard design and crop water requirements. Irrigation was applied at the time of the critical growth stage (flowering and fruiting) period and during the dry spell. A rain gauge was also installed for the collection of rainfall data. Fruit yield and water productivity ( $\text{kg plant}^{-1} \text{m}^{-3}$ ) were tabulated at harvesting.

#### 2.4 Measurement of water discharge and installation of Tensiometers

Soil moisture was monitored using tensiometers at 30, 60, and 90 cm depth. The water was applied by flood irrigation (FI) to the basin of the plant, while 25 drippers were used for each plant of  $1.55 \text{ mm h}^{-1}$  discharge in surface drip irrigation (SDI), having 13 compensators in each drip line. The plant-to-plant distance was  $4.57 \text{ m} \times 4.57 \text{ m}$ . In BI 4, plastic bottles of 1.5 liters were installed around the canopy of a tree having a hole of 2 mm dia on the fourth side and buried in the soil. In pitcher irrigation (PI), three clay pitchers of a capacity of 5 liters were buried around the tree. In PPSI, four pipes were buried with a 10 mm diameter. The total operational hours of water of  $12.10 \text{ mm h}^{-1}$  was noted and, in each system, water applied was calculated as total operational hours  $\times$  discharge rate  $\text{mm h}^{-1}$ .

#### 2.5 Water Productivity $\text{kg m}^{-3}$ , fruit yield, and yield attributes measurement

Water productivity was calculated as total fruit yield / total water consumed (Allen et al., 1998). Fruit yield measurement and other characteristics, i.e., total fruit yield at maturity, were calculated from harvested fruits. Five fruits were selected for average fruit weight ( $\text{g fruit}^{-1}$ ).

#### 2.6 Statistical Analysis

A single-factor RCBD with 3 replications was used to get valid estimates

International Journal of Agriculture Innovation and Cutting-Edge Research 4(2) of treatment effect, having minimum experimental error. Statistical software was used for the analysis of data. ANOVA or the F test was used to determine the level of treatment effect, while the LSD test was applied to compare means after ANOVA. The data were subjected to analysis of variance using the methods given by Steel et al. (1997).

### 3. Results

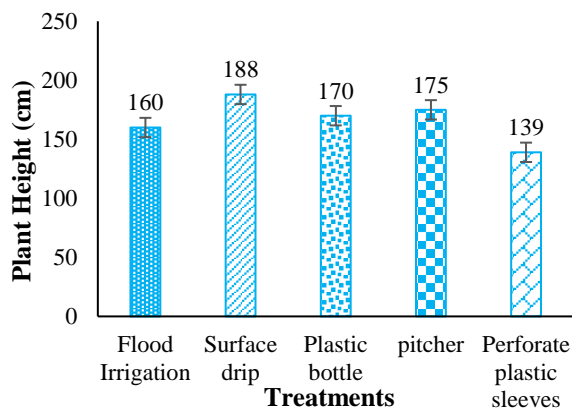
#### 3.1 Soil Moisture Percentage (%)

Soil moisture content was highest (13.20%) at 0-15 cm depth under surface drip irrigation followed by Plastic bottle (11.20 %), pitcher irrigation (10.60 %), perforated plastic sleeves (10.50%) and flood irrigation (7.80 %) while at 15-30 cm highest (14.60%) under surface drip irrigation followed by pitcher irrigation (13.40 %), Plastic bottle (12.70 %), perforated plastic sleeves (11.50%) and flood irrigation (9.30%) (Table 3). The higher wetted soil volume resulted in more water productivity. The variation in the moisture content was due to different irrigation techniques used. Overall, research focused on water productivity and efficiency for higher yield achievement. The soil moisture retention advantage of surface drip irrigation (13.2% at 0-15 cm depth) aligns with Kaushal et al. (2012), who reported 55% water savings with drip irrigation compared to conventional methods. Better water management and distribution are needed to improve citrus yield and water productivity in water-scarce areas of Punjab, Pakistan.

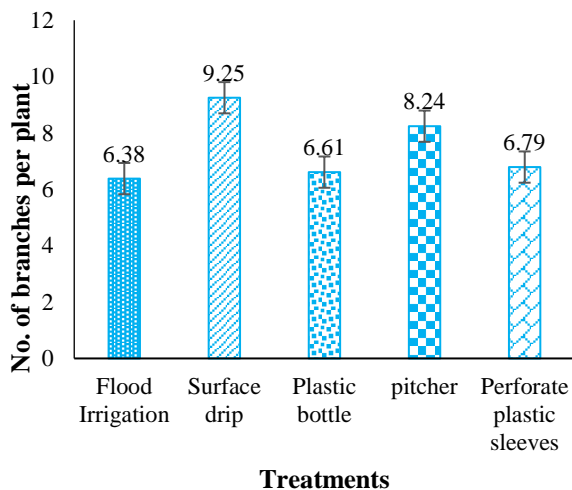
#### 3.2 Yield attributes of citrus

The results of the study revealed that different irrigation techniques significantly affected the yield attributes of kinnow. Results showed that plant height (188 cm), No. of branches (9.25), Plant periphery (343 cm), No. of fruits per plant (353) and fruit weight (170 g) significantly ( $p \leq 0.05$ ) increased by surface drip irrigation

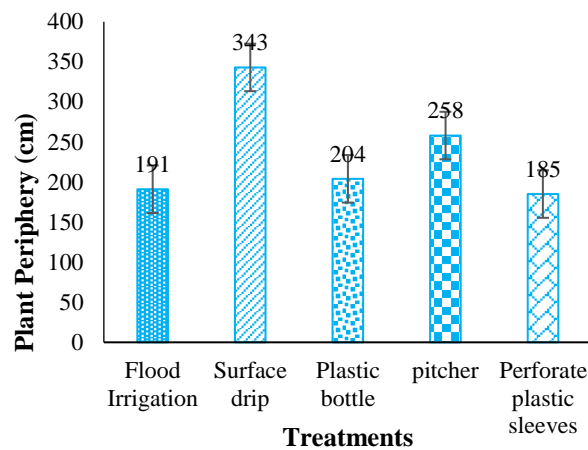
technique followed by pitcher irrigation (Figures 2 to 5). The plant height of pitcher irrigation and the plastic bottle was statistically similar compared to flood irrigation and the perforated plastic sleeve. No. of branches were also significantly affected by irrigation techniques, as shown in Figure 3.



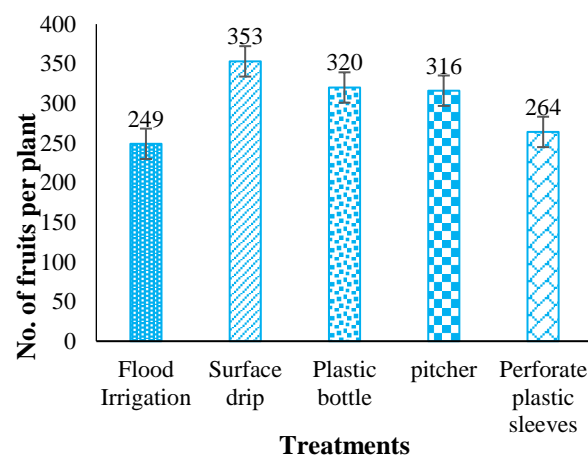
**Figure. 2:** Effect of different irrigation systems on the plant height (cm)



**Figure. 3:** Effect of different irrigation systems on the No. of Branches per plant



**Figure. 4:** Effect of different irrigation systems on the Plant Periphery (cm)



**Figure. 5:** Effect of different irrigation systems on the No. of Fruits per plant

### 3.3. Water Productivity ( $\text{kg m}^{-3}$ )

The results of the study showed that water productivity was significantly higher ( $7.13 \text{ kg m}^{-3}$ ) in the drip irrigation technique during the year 2019 compared to the lower water productivity of the flood irrigation technique ( $1.43 \text{ kg m}^{-3}$ ), with a similar trend during all other years of the experiment (Table 4). Surface drip irrigation showed 6.1 times more water productivity during the year 2016, followed by the pitcher (4.8 times), plastic bottles (4.4 times), and perforated plastic sleeves (4.1 times) (Table 4). Water productivity varied significantly across years ( $F = 3.24$ ,  $p = 0.042$ ), with the lowest values in 2017 (coinciding with higher May evaporation,  $4.56 \text{ mm day}^{-1}$ ) and the

highest in 2019. This suggests that inter-annual climate variation affects irrigation efficiency, supporting the need for adaptive irrigation scheduling. Reduction in water productivity observed due to variation in irrigation techniques efficiency, i.e., flood irrigation over surface Drip irrigation technique. The increase in water productivity may be due to the efficiency that results in more yield and ultimately more water productivity. In the long run, investment in drip irrigation systems to boost water productivity will reduce the cost of the application with time and ensure sustainability for food security compared to other irrigation techniques (Zhang et al., 2013). The 5-7 fold increase in water productivity under SDI (6.73-7.13 kg m<sup>-3</sup>) compared to flood irrigation (1.09-1.43 kg m<sup>-3</sup>) reflects reduced evaporative losses from direct root-zone application, a mechanism well-documented in arid-zone irrigation literature (Fereris & Soriano, 2007; Tejero et al., 2011).

#### 3.4. Fruit yield of citrus

Various irrigation techniques significantly impacted the fruit yield of citrus in surface drip irrigation technique during the year 2019, followed by pitcher irrigation. The fruit yield of 51% was significantly increased by using the surface drip irrigation (SDI) system, followed by PI (38%). The periodical increase in the yield was recorded during the experimental period in FI, SDI, PB, PI, and PPSI irrigation techniques (Table 6). In PPSI and FI techniques, citrus fruit yield did not improve significantly. The results showed that the maximum citrus yield (16416 kg ha<sup>-1</sup>) was recorded in the surface drip irrigation (SDI) technique (51% greater) associated with the pitcher irrigation technique (11969 kg ha<sup>-1</sup>) during 2019. The average increase in fruit yield under surface drip, plastic bottle, pitcher, and perforate plastic sleeves compared to flood

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irrigation was 86.6, 42.8, 48.9, and 21.3%, respectively (Table 6).

### 3.5. Economic analysis

#### 3.5.1. Cost of installation and fruit yield gross income

The data regarding the cost of installation and fruit yield are presented in Table 7. An economic analysis of the data showed that the highest cost of installation (Rs. 375000 ha<sup>-1</sup>) was recorded in surface drip irrigation, whereas the minimum cost of installation (Rs. 3500 ha<sup>-1</sup>) was observed in the flood irrigation technique (Table 7). The highest cost of installation of surface drip might be due to the higher rate of material and accessories compared to other irrigation techniques. On the other hand, the flood irrigation technique resulted in a lower cost of application (Rs. 3500 ha<sup>-1</sup>) due to less labor and the non-application of any material for an installation. Similarly, maximum gross income (Rs. 2462400 ha<sup>-1</sup>) was calculated in surface drip irrigation, and it was close to plastic bottle (Rs. 1845150 ha<sup>-1</sup>) and pitcher irrigation (Rs. 1795350 ha<sup>-1</sup>) (Table 7). Bottle and pitcher irrigation required manual refilling every 2-3 days, representing an estimated additional labor cost of 15-20 person-hours per hectare per month. While this study did not quantify these labor costs, they would substantially reduce the net returns for these techniques, making them less viable for large-scale orchards than the economic analysis suggests.

#### 3.5.2. Net return for fruit yield

Results of the study showed that the maximum net return (Rs. 2087400 ha<sup>-1</sup>) was obtained by the surface drip irrigation technique, followed by the plastic bottle (Rs. 1839750 ha<sup>-1</sup>), while the lowest net return (Rs. 979800 ha<sup>-1</sup>) may be due to the higher cost of installation material and the lowest fruit yield (Table 7). The yield of perforated plastic sleeves indicated that pores may be blocked with soil due to

Irrigation systems	2016	2017	2018	2019	% Increase of fruit yield over FI
Flood Irrigation	745 2 D	863 4 C	8294 D	9732 BC	-
Surface drip	154 84 A	144 12 A	13909 A	16416 A	51%
Plastic bottle	112 99 BC	113 18 B	11168 BC	12301 B	34%
Pitcher	120 96 B	113 48 B	12668 AB	11969 B	38%
Perforated plastic sleeves	103 89 C	940 4 BC	9622 CD	7900 C	28%
LSD	977 .39	236 6.9	2361. 6	2588. 5	
<b>Note.</b> Values followed by different letters are significantly different at $p \leq 0.05$ (LSD test).					

hardness and hinder the availability of moisture to the root zone, resulting in decreased fruit yield at the time of flowering and fruit formation. Low-cost irrigation technologies are economically viable in developing countries because they improve water efficiency, increase crop productivity, and reduce reliance on rainfall.

#### Annexure (C)

#### Annexure (D)

**Table 5:** ANOVA Summary Table for Fruit yield of citrus as affected by various irrigation techniques

Source	D F	SS	MS	F	P
Rep	2	40767 2	20383 6		
Year	3	35780 76	11926 92	1.56	0.29 27
Error Rep*Year	6	45727 43	76212 4		
Treat	4	3.149	7.872	59.2 6	0.00 00

Year*treat	12	3.061	25510 31	1.92	0.06 97
Error Rep*Year*treat	32	4.250	13282 56		
Total	59	3.965			

**Table 6:** Fruit yield of citrus as affected by various irrigation techniques

**Table 7:** Economic analysis of different irrigation techniques

Irrigation systems	Fruit yield (kg ha <sup>-1</sup> )	Gross Income (Rs.)	Cost Variations (Rs.)	Net Income (Rs.)
Flood Irrigation	9732	1459800	3500	1456300
Surface drip	16416	2462400	37500 0	2087400
Plastic bottle	12301	1845150	5400	1839750
Pitcher	11969	1795350	10125 0	1694100
Perforated plastic sleeves	7900	1185000	20520 0	979800

## 4. Discussion

### 4.1. Citrus fruit yield and yield attributes as affected by various watering techniques

Surface drip irrigation demonstrated yield benefits compared to FI (flood irrigation). Considering the irrigation techniques, pitcher and surface drip achieved more fruit yield as compared to other techniques of irrigation. The loss of nutrients due to leaching in the active root zone was minimized and resulted in higher fruit under the drip irrigation technique by the continuous supply of moisture (Martinez-Gimeno et al., 2018). Under the drip irrigation technique, higher fruit yield was recorded due to a reasonable supply of moisture to the citrus plant. Fruit yield increased in such irrigation systems gradually from the 1<sup>st</sup> year (2016) of the study, which may be attributed to weed suppression, zero tillage, and favorable moisture in the root zone, resulting in more

plant growth (Panigrahi et al., 2012). The increase in the yield of citrus may be due to a larger number of branches, plant periphery, and the number of fruits and fruit weight, which ultimately resulted in higher fruit yield of citrus. The results are in line with Raza et al. (2020), who reported that citrus yield increased under drip irrigation significantly. Drip irrigation is considered the most efficient and cost-effective method for rearing high-value crops specifically in the developed world (Asmon and Rothe 2006). While surface drip irrigation required higher installation costs (Rs. 375,000 ha<sup>-1</sup>), its water productivity gains (83% over flood irrigation) are consistent with the 60-200% water use efficiency improvements reported for trickle irrigation systems Kaushal et al., 2012. It was found by Sharma et al. (2024) that using drip irrigation in fruit orchards saved abundant water and resulted in better returns, irrespective of the initial higher cost incurred for its installation. Drip irrigation sustains an ample water supply to crops and improves water saving, crop yield, and fruit quality (Hanson et al., 2006). Kumar and Palanisami (2010) found that drip irrigation increased net sown and irrigated areas while improving cropping consistency and irrigation intensity.

#### 4.2. Water productivity of various irrigation techniques

The results of the study showed that 83% more water productivity was achieved using the drip irrigation technique compared to flood irrigation and other similar techniques of irrigation. The improved water productivity for various irrigation techniques, i.e., SDI (Surface Drip Irrigation), may be due to fewer water losses compared to the sprinkler irrigation technique. This finding is also supported by Fereres and Soriano (2007) that Surface drip irrigation is an excellent tool to achieve

maximum water productivity and profits by growing crops at ET levels below their maximum potential. Further studies on SDI and RDI, compared for irrigation water use, stated that irrigation water use significantly reduced without causing substantial losses in productivity, while RDI was especially effective when water stress was applied during less sensitive stages of fruit development (Tejero et al., 2011). The use of surface drip irrigation enhanced the instantly available moisture in the soil, and more uptake of nutrients from the soil resulted in enhanced fruit yield per hectare of citrus and high gross income. These results are in line with those of Wilde et al. (2009), water saving 20-60%, and a 7-25% yield increase compared to the farmer practice of irrigation using pitcher irrigation. Generally, water saving was high for drip irrigation due to the direct application of water to plants that is absorbed directly by roots, preventing excessive evaporation that is not possible with a trickle and other irrigation techniques used in the current study. Higher WUE was recorded in the surface drip irrigation technique, and 35% more water was saved in comparison to flood irrigation (Maisiri et al., 2005). Rosegrant and Cai (2000) reported that rainfed agriculture has lower water productivity than irrigated farming due to inefficient resource use and limited infrastructure investment. The maximum amount of irrigation water applied to fruit trees lost due to evapotranspiration using flooding without consideration of root zone targeting. The mean monthly evapotranspiration rate increased during May and June, resulting in more water use in these months. Surface drip irrigation used 21 to 29% water compared to the sprinkler technique of irrigation (Yin et al., 2011). Similarly, water savings of 28 to 35% were recorded under surface drip irrigation

in furrows compared to the flood irrigation technique and improved the productivity of water from 0.43 to 0.61 kg m<sup>-3</sup> (Darouich et al., 2014). Drip irrigation techniques can diversify and enhance crop production by reducing drought stress even under high-temperature regimes due to effective water management (Dany et al., 2016). The surface drip irrigation to olive trees increased fruit yield by 19.20% and saved water by 34.40% compared to flood irrigation with a ring of soil (Abbas and Fares 2009). (Khalifa & Mahmoud, 2020) evaluated the economics of a research study and concluded that fruit crops are most suitable for adopting drip irrigation as the technique provides a promising water economy and better crop productivity. The water productivity was also best in the treatments using the surface drip irrigation method (Li et al., 2024). Affordable systems such as drip irrigation and treadle pumps help smallholder farmers increase income and support sustainable agricultural development (Namara et al., 2005). The progressive yield increase observed from 2016 to 2019 under SDI (from 15,484 to 16,416 kg ha<sup>-1</sup>) suggests cumulative soil health benefits beyond immediate water savings, including improved nutrient availability and root development (Panigrahi et al., 2012)

### 5. Limitations of the Study

This research was conducted at a single location, which may not be representative of the larger arid region. The soil salinity data may be added to the study to provide a complete picture for the farmers in the salinity areas. The water application measurement may have underestimated deep percolation losses because soil moisture was monitored only to a depth of 90 cm. The study was conducted at a single location with silt loam soil; results may differ on sandy or clay soils. Bottle and pitcher irrigation systems require manual

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refilling every 2–3 days, which may not be practical for large orchards. Economic analysis considered only installation cost, not annual maintenance or labor costs for unconventional techniques.

### 6. Conclusions

This four-year field study demonstrates. Surface drip irrigation significantly improves water productivity, fruit yield, and net economic returns for Kinnow mandarin under arid conditions in Pakistan compared to conventional basin irrigation. Specifically, surface drip increased fruit yield by 51% (from 9,732 to 16,416 kg ha<sup>-1</sup>) and achieved 83% higher water productivity while reducing applied water by approximately 66%. Pitcher and plastic bottle irrigation also outperformed basin irrigation, offering intermediate benefits for farmers unable to invest in drip systems. Perforated plastic sleeves showed the least improvement among the water-saving techniques. This study provides the first empirical evidence that perforated plastic sleeves, despite their low cost, are unsuitable for citrus irrigation in silt-loam soils due to pore blockage. This negative result is valuable for extension services, preventing farmer investment in ineffective technologies. The intermediate performance of pitcher and bottle irrigation offers a viable pathway for resource-limited farmers who cannot afford drip systems. We recommend surface drip irrigation as the preferred technology for citrus growers in water-scarce regions, with subsidies to offset initial installation costs. Limitations include the absence of water quality monitoring and the single-location design; further studies across different soil types and climates are needed to validate these findings.

### 7. Future Research Prospects

Future research should investigate automation, deficit irrigation, and soil health to overcome labour shortages and

other limitations involved in irrigating large areas of citrus orchards, while initial soil ECe was within normal range (0.49-1.59 dS m<sup>-1</sup>). Drip irrigation systems can exacerbate salinity in the root zone over time due to limited leaching. Long-term monitoring of soil salinity is recommended for sites where SDI is adopted, particularly in arid regions with high evapotranspiration (Hanson et al., 2006)

### 8. Author Contributions

Rahina Kausar did conceptualization, methodology, formal analysis, and writing—original draft. Obaid ur Rehman did supervision, project administration, and data investigation. Muhammad Imran Akram conducted, analyzed, performed data curation, writing, review, editing, proof reading. Ayesha Malik did soil analysis, editing, and proofreading. Mashal Rehman, Muhammad Zubair, and Muhammad Usman did data curation, interpretation of data, and proofreading. Abid Ali, Qaisar Abbas, and Kashif Shabir did review, editing, and proofreading. Saima Jameel did data curation, interpretation, and verification of data. Mahreen Khalid did statistical analysis, editing, and proofreading. Faheem Altaf did the computational framework, editing, and proofreading. All authors have read and agreed to the published version of the manuscript.

### 9. Acknowledgements

This work was supported by the Government of Punjab, Pakistan, and the Soil and Water Conservation Research Station, Fateh Jang, Attock, Pakistan.

### 10. Conflict of Interest

The authors declare no conflicts of interest.

### 11. Data Availability Statement

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request. Soil moisture, yield, and water

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application data have been deposited in the Laboratory of Soil and Water Conservation Research Station, Fateh Jang.

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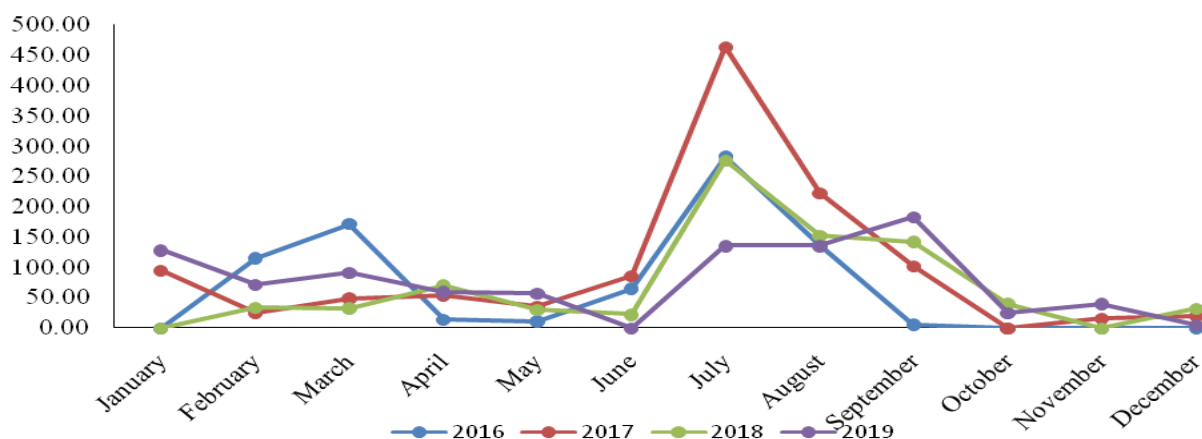
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## Annexure (A)

### Rainfall during 2016-2019 at experimental site\*



\*Soil and water conservation Research Station, Fateh

**Figure 1:** Monthly rainfall at experimental site during 2016-2019

## Annexure(B)

Month	2016	2017	2018	2019	Mean monthly evaporation (mm month <sup>-1</sup> ) (Average of four years)
January	0.710	0.516	0.782	0.558	0.64
February	1.241	0.750	0.661	0.511	0.79
March	1.219	0.968	1.098	1.306	1.15
April	3.117	0.883	1.313	1.283	1.65
May	3.565	4.555	4.0306	1.429	3.96
June	3.767	1.533	7.467	2.543	3.83
July	1.774	0.581	1.042	1.368	1.19
August	0.919	0.776	0.729	1.013	0.86
September	1.583	0.900	1.010	0.881	1.09
October	1.258	1.006	0.952	0.881	1.02

<b>November</b>	1.087	1.007	0.487	0.417	0.75
<b>December</b>	0.439	0.468	0.897	0.335	0.53

**Table 1:** Monthly Evaporation during 2016-2019**Annexure (C)**

Irrigation systems	2016		2017		2018		2019		Mean 0-15	Mean 15-30
	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30		
<b>Flood Irrigation</b>	7.53	8.64	6.89	8.76	6.75	7.34	9.89	12.35	<b>7.8</b>	<b>9.3</b>
<b>Surface drip</b>	12.35	13.63	11.11	10.19	10.34	11.16	19.04	23.45	<b>13.2</b>	<b>14.6</b>
<b>Plastic bottle</b>	9.89	11.11	9.8	11.11	9.8	11.05	15.23	17.64	<b>11.2</b>	<b>12.7</b>
<b>Pitcher</b>	7.52	9.89	9.11	12.35	9.68	10.96	16.27	20.48	<b>10.6</b>	<b>13.4</b>
<b>Perforated plastic sleeves</b>	9.26	10.11	8.89	9.46	7.86	9.05	16.02	17.44	<b>10.5</b>	<b>11.5</b>
<b>Mean</b>	<b>9.31</b>	<b>10.67</b>	<b>9.16</b>	<b>10.37</b>	<b>8.88</b>	<b>9.91</b>	<b>15.29</b>	<b>18.27</b>		

**Table 3:** Effect of different irrigation systems on the soil moisture % at different depths (0-15, 15-30 cm)**Annexure (D)**

Year	Treatments	Fruit yield (kg ha <sup>-1</sup> )	Gross water applied (m <sup>3</sup> ha <sup>-1</sup> )	Water productivity (kg m <sup>-3</sup> )	% increase of water productivity over FI
2016	Flood Irrigation	7452	6800	1.09	-
	Surface Drip	15484	2300	6.73	83%
	Plastic bottle	11299	2300	4.91	67%
	Pitcher	12096	2300	5.25	78%
	Perforated plastic sleeve	10389	2300	4.51	75%
2017	Flood Irrigation	8634	6800	1.26	-
	Surface Drip	14412	2300	6.26	79 %
	Plastic bottle	11318	2300	4.92	73 %
	Pitcher	11348	2300	4.93	73%
	Perforated plastic sleeve	9404	2300	4.08	65%
2018	Flood Irrigation	8294	6800	1.21	-
	Surface Drip	13909	2300	6.04	79 %
	Plastic bottle	11168	2300	4.86	74 %
	Pitcher	12668	2300	5.50	77%
	Perforated plastic sleeve	9622	2300	4.18	70%

2019	Flood Irrigation	9732	6800	1.43	-
	Surface Drip	16416	2300	7.13	80 %
	Plastic bottle	11969	2300	5.20	72 %
	Pitcher	12301	2300	5.34	73%
	Perforated plastic sleeve	7900	2300	3.43	58 %

**Table 4:** Water productivity of high-efficiency irrigation techniques