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## Research Article

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**Soil Moisture Partitioning and Water Productivity in Pomegranate-Based Agroforestry Systems in Semi-Arid Agro ecosystems**

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## Abstract

Pomegranate-based intercropping systems provide a viable approach for improving water-use efficiency and productivity in semi-arid agro ecosystems. A long-term field study (2016 to 2020) was conducted at ICAR–CAZRI, Regional Research Station, Pali-Marwar, Rajasthan, to evaluate soil moisture extraction patterns, crop water use (CWU), system yield, and water productivity (WP) under different pomegranate-based intercropping systems. Treatments included green gram, cluster bean, and okra during kharif, and mustard, fenugreek, and cabbage during rabi, along with sole pomegranate as control. Results revealed that soil moisture extraction was highest in the surface layer (0–15 cm), followed by 15–30 cm and 30–45 cm across all treatments, with intercropping systems exhibiting greater surface water utilization and reduced deep soil moisture extraction compared to sole pomegranate. Total CWU was highest under pomegranate + okra–cabbage (2366.7 mm) and lowest under sole pomegranate (1877.9 mm). Despite higher water consumption, intercropping systems significantly enhanced system yield, with pomegranate + okra–cabbage recording the highest productivity (23.10 t ha<sup>-1</sup>). Similarly, water productivity peaked under pomegranate + okra–cabbage (82.57 kg ha<sup>-1</sup> mm<sup>-1</sup>), compared to sole pomegranate (30.51 kg ha<sup>-1</sup> mm<sup>-1</sup>). The results demonstrate that complementary water use between deep-rooted pomegranate and shallow-rooted intercrops improves soil water utilization efficiency and system productivity. Overall, pomegranate-based intercropping systems, particularly with vegetable intercrops, substantially enhance water productivity and resource-use efficiency under water-limited semi-arid conditions. These findings highlight their potential as a climate-resilient strategy for sustainable intensification of dryland agriculture.

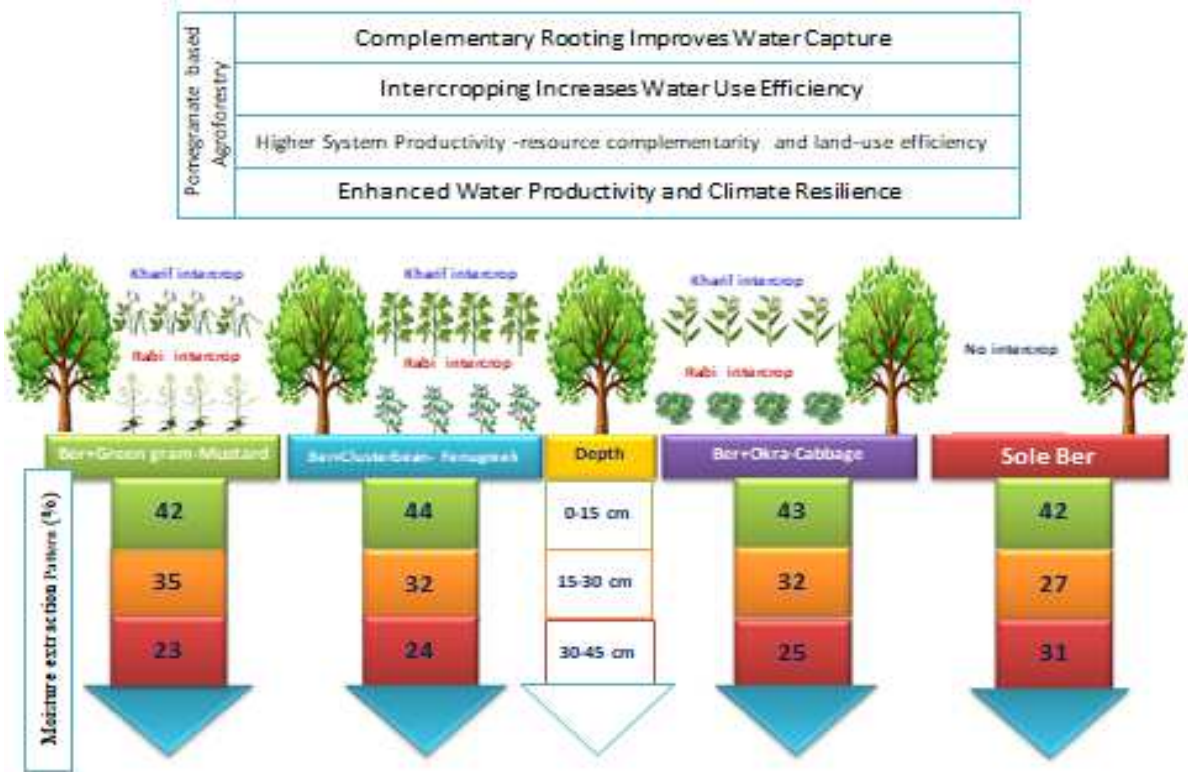
**Keywords:** Pomegranate; Agroforestry systems; Arid and Semi-arid region; Soil moisture dynamics; Water productivity; Western Rajasthan.

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### Highlights

- Soil moisture extraction was complementary across soil depths in intercrops.
- Pomegranate + okra–cabbage produced the highest system yield (23.1 t ha<sup>-1</sup>).
- Intercropping enhanced resource-use efficiency over sole pomegranate.
- Water productivity was greatest in the pomegranate + okra–cabbage system.
- Pomegranate-based intercropping improved sustainability in semi-arid areas.

Graphical Abstract



## 1. Introduction

Arid and semi-arid regions are expanding globally, with more than one-third of the Earth's land area now affected by drought stress Vries et al., 2024. Agricultural production in these regions is severely constrained by erratic rainfall, high evaporative demand, declining soil fertility, and limited freshwater resources Liu, 2022; Ma et al., 2024). These constraints are particularly critical in western Rajasthan, India, where rainfall (300–500 mm) is highly variable and concentrated within a short monsoon period, leading to frequent soil moisture deficits and unstable crop productivity. Under such conditions, conventional monocropping systems exhibit low resilience and high yield variability Soni et al., 2020; Santra et al., 2017).

Pomegranate (*Punica granatum* L.) is an important fruit crop of arid and semi-arid regions due to its high economic value, nutritional quality, and strong adaptability to harsh environments (Prasad, 2000; Sharma and Maity, 2010). Its drought tolerance and ability to perform under marginal conditions make it suitable for dryland farming systems (Meshram et al. 2024). However, orchard interspaces remain largely underutilized during the initial years of establishment, resulting in low land-use efficiency. Intercropping in these spaces offers an opportunity to enhance productivity, improve farm income, and maintain ecological stability (Awasthi et al., 2008).

Agroforestry-based intercropping systems have emerged as a promising strategy for enhancing resource-use efficiency and climate resilience in dryland agriculture. Pomegranate, being a deep-rooted perennial fruit species, can access subsoil moisture and partially buffer seasonal water stress. When combined with annual intercrops, these systems improve land-use efficiency, enhance microclimatic regulation, reduce evaporation losses, and stabilize farm income. Earlier studies have reported improved water-use efficiency, reduced environmental degradation, and higher economic returns in fruit-based intercropping systems compared with sole cropping under arid and semi-arid regions (Awasthi et al., 2009; Pal and Tarai, 2015; Yadava et al., 2017; Soni et al., 2020). Despite the documented advantages of pomegranate-based agri-horti systems, most previous studies conducted in arid and semi-arid regions, have primarily focused on crop productivity, economic returns, land-use efficiency, and overall water productivity (Soni et al., 2020; Yadava et al., 2017; Pal and Tarai, 2015). While these studies demonstrated the benefits of integrating annual crops with fruit trees, they provided limited information on the underlying soil–plant water relations governing system performance. In particular, quantitative assessments of soil moisture distribution across different soil depths, root-zone water extraction patterns, and the contribution of intercrops to seasonal water partitioning remain largely unexplored. Such process-based understanding is essential for identifying complementary resource-use mechanisms and designing water-efficient intercropping systems under moisture-limited environments.

The present study advances beyond earlier investigations by simultaneously evaluating soil moisture dynamics, crop water use, and system-level water productivity in pomegranate-based intercropping systems under the semi-arid conditions of western Rajasthan. This integrated approach provides mechanistic insights into how intercrops differing in rooting characteristics and growth habits influence water-use complementarity

and resource-use efficiency within pomegranate orchards. Furthermore, increasing climate variability, land degradation, and growing pressure on freshwater resources necessitate the development of resilient and resource-efficient production systems (Coulibaly et al., 2020; Liu and Dai, 2020; Khanal et al., 2021). Agroforestry systems are widely recognized for their role in conserving soil and water resources, reducing erosion, and enhancing productivity and profitability (Kuyah et al., 2019; Yadav et al., 2021b). However, their success in dryland regions depends on the selection of compatible intercrops that efficiently utilize available soil moisture without intensifying competition with perennial components.

Therefore, the present study was conducted at ICAR–Central Arid Zone Research Institute (CAZRI), Regional Research Station, Pali-Marwar, Rajasthan, to evaluate the effects of integrating different intercrops with pomegranate on soil moisture extraction patterns, crop water use, water productivity, and overall system performance under semi-arid conditions. We hypothesized that intercrops differing in rooting depth and growth habit would modify soil moisture extraction across soil layers, promote complementary water use with pomegranate, and consequently enhance system water productivity and overall resource-use efficiency compared with sole pomegranate cultivation.

## **2. Materials and Methods**

### **2.1. Experimental Site**

The experiment was conducted during 2016-17 to 2022-23 at the ICAR–Central Arid Zone Research Institute (CAZRI), Regional Research Station, Pali-Marwar, Rajasthan, India (25°47'–25°49' N latitude and 73°17'–73°18' E longitude; 217–220 m above mean sea level). The region is characterized by a hot semi-arid climate with a mean annual rainfall of approximately 460 mm and high inter-annual variability. The mean maximum temperature during summer reaches about 42°C, while the minimum temperature during winter falls to nearly 7°C. The experimental soil was shallow (30–45 cm depth) with sandy clay loam to sandy loam texture. Soil bulk density ranged from 1.35 to 1.50 Mg m<sup>-3</sup>, soil pH varied between 7.7 and 8.4, and electrical conductivity ranged from 0.15 to 0.55 dS m<sup>-1</sup>. A dense murrum layer consisting of highly calcareous weathered granite fragments coated with lime was present beneath the soil profile.

### **2.2. Experimental Design and Treatments**

The pomegranate orchard was established with six month old plants in 2015 in the month of July. Experimental period is five years (2015-16 to 2019-20). Land preparation involved ploughing during April–May followed by pit digging (1 m<sup>3</sup>). The pits were refilled with a mixture of soil, sand, and farmyard manure (FYM). Six-month-old rooted air-layered pomegranate variety 'Bhagwa' plants were planted in pits at a spacing of 6 m × 3 m, and the 6 m inter-row spaces were used for cultivating intercrops, providing a planting density of approximately 555 plants ha<sup>-1</sup>. Each experimental plot consisted of 138 pomegranate plants, of which the central plants were used for observations to avoid border effects. The experiment was laid out in a Randomized Block Design (RBD) with three replications. Intercrops were grown in the inter-row spaces between pomegranate plants. During the kharif season, green gram (*Vigna radiata*), cluster bean (*Cyamopsis tetragonoloba*), and okra (*Abelmoschus esculentus*) were cultivated as intercrops. During the rabi season, mustard (*Brassica juncea*),

fenugreek (*Trigonella foenum-graecum*), and cabbage (*Brassica oleracea* var. *capitata*) were grown. No intercrops were cultivated during the first year to ensure proper establishment of the pomegranate orchard.

### 2.3. Irrigation Management and Experimental Setup

Irrigation was provided through a flood irrigation system. During the rabi season, irrigation water was applied at intervals, whereas kharif crops were primarily dependent on rainfall. The experimental plot utilized a structured irrigation schedule tailored to the specific crop types, including a main fruit crop and two intercrops. Water application depth was strictly controlled across all treatments, with a uniform depth of 15 cm applied per irrigation event. The total number of irrigation events and cumulative water applied for each crop during the experimental period were given in table 1. Meteorological observations were recorded regularly during the experimental period are given in Figure 1.

### 2.4. Soil Moisture Extraction Pattern, Crop Water Use, Water and System Productivity:

Soil samples were collected at fixed points in each plot immediately before irrigation and 24 h after irrigation throughout the crop growth period.

#### Soil Sampling and Spatial Design

To capture the spatial variability of soil moisture dynamics under the influence of tree-crop interactions, a systematic transect-based sampling approach was deployed within each experimental plot. Three parallel linear transects were established perpendicular to the tree rows at equal intervals of 6 meters within each treatment and replication. Along each transect, undisturbed soil core samples were collected at fixed, distinct horizontal distances of 1.0 m and 2.0 m from the base of the tree trunk on both the left and right sides. This spatial configuration yielded a total of 12 distinct sampling points per replication plot (3 transects × 2 distances × 2 sides). At each designated sampling point, soil cores were extracted at stratified depth intervals (e.g., 0–15, 15–30, and 30–45 cm) to account for vertical variations in root water uptake.

#### Sample Handling and Moisture Analysis

To prevent evaporative water loss during handling, the extracted soil samples from each point and depth were immediately transferred into heavy-duty polyethylene bags, tightly sealed, and transported in insulated containers to the laboratory. Soil moisture was determined using the thermogravimetric method. The fresh weight of each sample was recorded immediately upon arrival. The samples were then oven-dried at 105°C for 24 hours or until a constant mass was achieved. The gravimetric soil water content ( $\theta_g$  g g<sup>-1</sup>) was calculated using the formula:

$$\theta_g = [(\text{Mass of wet soil}) - (\text{Mass of dry soil})] / \text{Mass of dry soil}$$

(Equation 1)

To accurately calculate the soil water storage, separate undisturbed core samples were collected from each zone using standard 100 cm<sup>3</sup> core rings to determine the soil bulk density ( $\rho_b$ , g cm<sup>-3</sup>). The gravimetric data was subsequently converted to volumetric water content ( $\theta_v$ , cm<sup>3</sup>cm<sup>-3</sup>) as follows:

$$\theta_v = \theta_g \times \rho_b / \rho_w$$

(Where  $\rho_w$  is the density of water, assumed to be 1.0 g cm<sup>-3</sup>)

(Equation 2)

Moisture depletion from each soil layer was calculated and summed over the crop season to estimate total soil water extraction. The relative contribution of each soil layer to total moisture depletion was used to characterize the soil moisture extraction pattern within the effective root zone.

$$\text{Soil moisture depletion from } i\text{th layer (cm)} = \frac{M_{ai} - M_{bi}}{100} \times A_{si} \times D_i$$

Where,

$M_{ai}$  = Moisture percentage after irrigation in  $i$ th layer

$M_{bi}$  = Moisture percentage before irrigation in  $i$ th layer

$A_{si}$  = Apparent specific gravity of  $i$ th layer (Mg/m<sup>3</sup>)

$D_i$  = Depth of  $i$ th layer in cm

(Equation 3)

Seasonal crop water use (CWU) was estimated separately for kharif and rabi seasons. During the kharif season, CWU was computed using the soil water balance approach under rainfed conditions by considering rainfall, runoff, and changes in soil moisture storage within the effective root zone. During the rabi season, CWU was estimated as the sum of irrigation water applied and effective rainfall, assuming negligible runoff and deep percolation losses.

Runoff was estimated using standard runoff coefficients recommended for semi-arid sandy loam soils under cultivated conditions. The quantity of water applied was measured using irrigation discharge rate and duration of application. Effective rainfall was estimated using the rainfall received during the crop season after accounting for runoff losses. Owing to the shallow soil profile (30–45 cm depth) and the presence of an underlying dense murrum layer restricting downward water movement, deep percolation losses were assumed negligible and were therefore omitted from the water balance calculations.

Water productivity (WP) was calculated as the ratio of economic yield to total crop water use (crop evapotranspiration). The following equation was used:

$$\text{Water productivity (WP) (kg ha}^{-1}\text{mm}^{-1}\text{)} = \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Total consumptive use of water (mm)}} \quad (\text{Equation 4})$$

System yield was expressed in terms of Green Gram Equivalent Yield (GEY) during kharif and Mustard Equivalent Yield (MEY) during rabi season based on prevailing market prices. Equivalent yield was calculated using the following equation (Erythrina et al. 2022):

$$\text{GEY} = Y_i \times \frac{P_i}{P_g} \quad (\text{Equation 5})$$

where,  $Y_i$  = yield of component crop ( $\text{kg ha}^{-1}$ ),  $P_i$  = market price of component crop ( $\text{₹ kg}^{-1}$ ), and  $P_g$  = market price of green gram ( $\text{₹ kg}^{-1}$ ).

Mustard equivalent yield (MEY) for the rabi season was calculated as (Erythrina et al. 2022):

$$\text{MEY} = Y_i \times \frac{P_i}{P_g} \quad (\text{Equation 6})$$

where,  $Y_i$  = yield of component crop ( $\text{kg ha}^{-1}$ ),  $P_i$  = market price of component crop ( $\text{₹ kg}^{-1}$ ), and  $P_g$  = market price of green gram ( $\text{₹ kg}^{-1}$ ).

### 3. Results and Discussion

#### 3.1. Soil Moisture Extraction Pattern

The soil moisture extraction pattern under different pomegranate-based intercropping systems and sole cropping treatments is presented in Table 2. Moisture extraction was predominantly concentrated in the surface soil layer (0–15 cm) across all treatments, followed by the 15–30 cm and 30–45 cm layers. This trend indicates greater root activity and moisture utilization in the upper soil horizons, where root density, nutrient availability, and microbial activity are generally higher.

Among the pomegranate-based intercropping systems, pomegranate + cluster bean–fenugreek recorded the highest moisture extraction from the 0–15 cm soil layer (43.45%), closely followed by pomegranate + okra–cabbage (43.33%). In contrast, sole pomegranate exhibited comparatively lower moisture extraction from the surface layer (42.09%). The greater utilization of topsoil moisture under intercropping systems may be attributed to enhanced root proliferation in the surface layer, improved soil cover, and increased canopy shading, which collectively reduce direct soil evaporation and promote efficient use of available moisture. Agroforestry and intercropping systems have been reported to enhance water retention and utilization in the upper soil profile (Anderson et al., 2009; Zhu et al., 2019; Chaudhary and Ghaley, 2025). Moisture extraction from the 15–30 cm

soil layer varied considerably among treatments, ranging from 27.34 to 35.30%. The highest moisture depletion at this depth was observed in the pomegranate + green gram–mustard system (35.30%), suggesting greater exploitation of subsurface moisture by the associated intercrops. Conversely, sole pomegranate recorded the lowest extraction (27.34%) from this layer. These differences may be attributed to variations in rooting depth, crop growth duration, and water demand among the intercrop species. At the deeper soil layer (30–45 cm), sole pomegranate showed the highest moisture extraction (30.57%), reflecting the ability of perennial pomegranate plants to access deeper soil water through their extensive root systems. In comparison, moisture extraction by intercropping systems ranged from 23.26 to 24.46%, with pomegranate + okra–cabbage recording the maximum value (24.46%). The relatively greater extraction at deeper depths in this treatment may be associated with the deeper rooting characteristics of okra, which can utilize moisture from lower soil horizons more effectively than shallow-rooted intercrops.

The results demonstrate clear differences in soil water-use patterns among the evaluated cropping systems. Annual intercrops primarily exploited moisture from the upper soil layers, whereas pomegranate relied more heavily on deeper soil moisture reserves. Consequently, intercropping systems exhibited a more balanced distribution of moisture extraction across soil depths, indicating complementary utilization of available water resources. Such complementary water use is particularly advantageous under arid and semi-arid conditions, where efficient exploitation of soil moisture is critical for sustaining productivity. Similar patterns of soil water depletion have been reported in agroforestry systems involving *Eucalyptus tereticornis* (Kombra et al., 2022), *Eucalyptus urograndis* (Pezzopane et al., 2015), *Brachiaria decumbens* (Bosi et al., 2020), and loblolly pine (Tian et al., 2017). The observed stratification of water uptake is consistent with reports from wheat–maize intercropping (Li et al., 2021), apple–soybean and apple–oilseed rape systems (Zhao et al., 2022), and apple–rye intercropping (Wei et al., 2024), where complementary root distribution enhanced overall water-use efficiency while minimizing competition between component crops.

### 3.2. Crop Water Use in Pomegranate-Based Production Systems

The total and mean crop water use (CWU) of different pomegranate-based intercropping systems and sole pomegranate cropping system during kharif, rabi, and total system period is presented in Table 3 and Fig. 2. Significant variations in crop water use were observed among the different production systems due to differences in crop duration, canopy cover, rooting pattern, and seasonal water requirements of intercrops. During the kharif season, the highest total crop water use was recorded under sole pomegranate (1340.4 mm), followed by pomegranate + okra (1286.2 mm), while pomegranate + green gram and pomegranate + cluster bean recorded the lowest and comparable water use (1252 mm). In the rabi season, pomegranate + cabbage exhibited the highest crop water use (1080.5 mm), significantly exceeding other treatments, whereas sole pomegranate recorded the lowest value (537.5 mm). The higher water consumption under cabbage-based systems may be attributed to the longer crop duration, higher biomass accumulation, and greater moisture demand of cabbage compared with mustard and fenugreek. Considering the total production period, the pomegranate + okra–cabbage system recorded the maximum crop water use (2366.7 mm), followed by pomegranate + cluster bean–fenugreek (2125 mm), whereas sole pomegranate showed the minimum water use (1877.9 mm). The higher water use observed under intercropping systems indicates greater utilization of available soil moisture and irrigation water due to increased plant population and complementary root

distribution. Despite higher water consumption, intercropping systems achieved superior productivity, suggesting more efficient conversion of water into economic yield. The results indicate that integration of intercrops, particularly okra and cabbage, enhances resource capture and overall system performance by utilizing soil moisture more effectively across the growing period. Similar trends have been reported in fruit-based intercropping systems (Birbal et al., 2013; Yadava et al., 2017; Soni et al., 2020), where increased crop diversity improved water utilization, resource-use efficiency, and productivity under arid and semi-arid environments.

### 3.3. System Yield and System Productivity (Kg ha<sup>-1</sup>) of Pomegranate-Based Production Systems

The system yield of different pomegranate-based intercropping systems varied significantly during kharif, rabi, and across the total production period (Table 4 and Fig. 3). Separate pomegranate (table 5) and intercrop yields (table 6) also given. During kharif, the pomegranate + okra system recorded the highest total yield (7259.5 kg ha<sup>-1</sup>) with a mean productivity of 1814.8 kg ha<sup>-1</sup>, followed by pomegranate + cluster bean (5654.9 kg ha<sup>-1</sup>). The lowest kharif yield was observed under pomegranate + green gram (4048.9 kg ha<sup>-1</sup>). In the rabi season, pomegranate + cabbage produced the highest yield (15839.7 kg ha<sup>-1</sup>), significantly surpassing all other treatments, owing to the high yield potential and marketable biomass of cabbage. The pomegranate + green gram–mustard and pomegranate + cluster bean–fenugreek systems recorded statistically comparable yields, whereas sole pomegranate produced the lowest yield (3662.2 kg ha<sup>-1</sup>). Considering total system productivity, the pomegranate + okra–cabbage system achieved the highest yield (23099.2 kg ha<sup>-1</sup>) with a mean productivity of 5774.7 kg ha<sup>-1</sup>, followed by pomegranate + cluster bean–fenugreek (13355.5 kg ha<sup>-1</sup>).

System productivity varied significantly among the pomegranate-based intercropping systems during the study period (Fig. 3). The Pomegranate + Cabbage–Okra system recorded the highest productivity, with a mean productivity of 6,560.55 kg ha<sup>-1</sup>, significantly outperforming all other treatments. The superior performance of this system may be attributed to the high yield potential, greater biomass production, and efficient resource utilization of cabbage and okra under orchard conditions. The Pomegranate + Cluster bean–Fenugreek system ranked second, recording a mean productivity of 2,480.3 kg ha<sup>-1</sup>. The Pomegranate + Green gram–Mustard system showed moderate productivity (2,041.0 kg ha<sup>-1</sup> mean), likely due to the comparatively lower yield potential of the component crops. In contrast, the sole pomegranate system recorded the lowest productivity, with a mean productivity of 1,831.1 kg ha<sup>-1</sup>. The results indicate that intercropping, particularly with high-yielding vegetable crops, substantially enhances overall system productivity and resource-use efficiency in pomegranate orchards.

The substantially higher productivity under intercropping systems compared with sole pomegranate demonstrates the efficient utilization of inter-row space, solar radiation, soil moisture, and nutrients. The inclusion of high-yielding vegetable and market valued crops such as okra and cabbage contributed significantly to total biomass production and overall system productivity. Intercropping also enhanced land-use efficiency and reduced production risks through crop diversification. Similar improvements in productivity under fruit-based intercropping systems have been reported in pomegranate, citrus, sweet orange, aonla, and ber, where complementary resource use and improved microclimatic conditions enhanced overall system performance (Awasthi et al., 2009; Arya et al., 2011; Pal and Tarai, 2015; Yadava et al., 2017; Soni et al., 2020).

Furthermore, legume-based intercrops may have contributed to improved productivity through biological nitrogen fixation and better soil moisture conservation, as reported by Birbal et al. (2013) and More et al. (2012). Moreover, diversification through intercropping minimized the risk associated with sole cropping and improved land-use efficiency under arid and semi-arid conditions.

### 3.4. Water Productivity of Pomegranate-Based Production Systems

Water productivity (WP) of different pomegranate-based production systems varied significantly during kharif, rabi, and across the total production system (Table 7 and Fig. 2). The results clearly indicated that intercropping systems improved water productivity compared to sole pomegranate cultivation under arid and semi-arid conditions.

During kharif, the pomegranate + okra system recorded the highest water productivity ( $24.00 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ), followed by pomegranate + cluster bean ( $19.30 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ), whereas pomegranate + green gram exhibited comparatively lower water productivity ( $13.70 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ). Sole pomegranate recorded negligible seasonal water productivity due to the absence of intercrop yield. The higher water productivity of the pomegranate + okra system may be attributed to its higher biomass production, greater marketable yield, and efficient utilization of available soil moisture. During rabi, pomegranate + cabbage recorded the highest water productivity ( $58.57 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ), followed by pomegranate + mustard ( $47.30 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ), while sole pomegranate recorded the lowest value ( $30.51 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ). Despite its relatively higher water consumption, the cabbage-based system achieved greater water productivity due to substantially higher yield output. Considering the total production system, pomegranate + okra–cabbage recorded the highest overall water productivity ( $82.57 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ), followed by pomegranate + green gram–mustard ( $61.00 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ) and pomegranate + cluster bean–fenugreek ( $54.73 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ), whereas sole pomegranate exhibited the lowest water productivity ( $30.51 \text{ kg ha}^{-1} \text{ mm}^{-1}$ ).

In fruit-based agroforestry systems, water productivity generally ranges from  $35$  to  $70 \text{ kg ha}^{-1} \text{ mm}^{-1}$  depending on tree species, intercrop combination, and irrigation management. Higher water productivity in such systems has been attributed to complementary utilization of water, nutrients, and solar radiation by component crops, resulting in greater overall biomass and economic yield. Similar trends have been reported in citrus-based intercropping systems, where integration of vegetables and legumes significantly improved water-use efficiency compared with sole orchards. Studies in sweet orange and citrus orchards have shown that vegetable intercrops such as cabbage, onion, and okra produced greater returns per unit of water consumed than monocropping systems due to their high marketable yields and efficient utilization of available soil moisture.

The results clearly demonstrate that intercropping enhanced water-use efficiency by improving productivity per unit of water consumed. Higher water productivity in vegetable-based systems indicates more efficient conversion of available water into economic yield, particularly under water-limited conditions. These findings suggest that integration of suitable intercrops with pomegranate can substantially improve resource-use efficiency, productivity, and sustainability of orchard systems in arid and semi-arid regions. Similar results have been reported by Soni et al., 2020, Kumar et al. (2023), who observed higher water productivity in vegetable-based cropping systems compared with cereal- and legume-based systems. Enhanced water productivity in fruit-

based intercropping systems has been linked to improved canopy management, reduced soil evaporation, better ground cover, and efficient resource sharing among component crops. Similar observations were reported by Awasthi et al. (2009), Arya et al. (2011), Pal and Tarai (2015), and Yadava et al. (2017) in citrus, aonla, and ber-based systems, where intercropping improved overall system productivity and resource-use efficiency.

#### **4. Conclusion**

Pomegranate-based intercropping significantly improved soil moisture utilization, system productivity, and water productivity compared with sole pomegranate cultivation under semi-arid conditions. The complementary use of soil water by pomegranate and intercrops enhanced resource-use efficiency and reduced moisture-related stress. Among the evaluated systems, pomegranate + okra–cabbage followed by pomegranate + green gram–mustard recorded the highest yield and water productivity, demonstrating its superiority in converting limited water resources into economic output. The results highlight the potential of pomegranate-based intercropping as a sustainable and climate-resilient production strategy for water-scarce regions. These findings suggest that pomegranate-based intercropping offers a viable strategy for maximizing productivity per unit of water and sustaining agricultural production in semi-arid regions. Adoption of suitable intercrop combinations can therefore contribute to improved farm income, efficient water management, and climate-resilient orchard production systems in areas facing increasing water limitations.

#### **CRedit authorship contribution statement**

MB Noor mohamed: Writing – review & editing, Writing – original draft, Visualization, Project administration, Supervision, Methodology, Data curation; A.K. Shukla: Writing – original draft, Writing – review & editing, Investigation; R.S. Mehta: Conceptualization, Writing – review & editing, Methodology; D.K. Gupta: Soil sampling and analysis; Arvind Singh Tatarwal: Writing – review & editing, Statistical Analysis; P.L. Regar: Conceptualization, Writing – review & editing, Analysis of data; Daya Shankar Misra: Writing – review & editing

#### **Declaration of competing interest**

There are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### **Data availability**

Data will be made available on reasonable request.

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**Table 1. Details of crop components, Irrigation and weed management and under ber-based agri-horti intercropping systems**

| S.N. | Main and Intercrops<br>(Common Name) | Botanical Name                                | Variety         | Spacing    | Irrigation scheduling and<br>management.                                                                                                                                                                                                                                                            | Weed management                                                                                                                                                                            |
|------|--------------------------------------|-----------------------------------------------|-----------------|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | Ber                                  | <i>Ziziphus mauritiana</i> Lam.               | Gola            | 12x6 m     | <ul style="list-style-type: none"> <li>Irrigation is provided at an interval of 3-4 weeks from October (fruit set) through February (fruit growth).</li> </ul>                                                                                                                                      | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> </ul>                                                                                                              |
| 2    | Green gram                           | <i>Vigna radiata</i>                          | GM -4           | 30 cm      | <ul style="list-style-type: none"> <li>Rainfed</li> </ul>                                                                                                                                                                                                                                           | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> <li><b>Frequency:</b> 25 days after sowing</li> </ul>                                                              |
| 3    | Clusterbean                          | <i>Cyamopsis tetragonoloba</i>                | RGC 936         | 30 cm      | <ul style="list-style-type: none"> <li>Rainfed</li> </ul>                                                                                                                                                                                                                                           | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> <li><b>Frequency:</b> 25 days after sowing</li> </ul>                                                              |
| 4    | Okra                                 | <i>Abelmoschus esculentus</i>                 | Parbhani Kranti | 45 cm      | <ul style="list-style-type: none"> <li>Rainfed</li> </ul>                                                                                                                                                                                                                                           | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> <li><b>Frequency:</b> 30 days after sowing</li> </ul>                                                              |
| 5    | Mustard                              | <i>Brassica juncea</i>                        | Bio-902         | 45 cm      | <ul style="list-style-type: none"> <li>The agronomic intercrop received 4 irrigation events, equating to a total water input of 60 cm.</li> </ul>                                                                                                                                                   | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> <li><b>Frequency:</b> 20 days after sowing</li> </ul>                                                              |
| 6    | Fenugreek                            | <i>Trigonella foenum-graecum</i>              | RMT 305         | 30 cm      | <ul style="list-style-type: none"> <li>The agronomic intercrop received 4 irrigation events, equating to a total water input of 60 cm.</li> </ul>                                                                                                                                                   | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> <li><b>Frequency:</b> 20 days after sowing</li> </ul>                                                              |
| 7    | Cabbage                              | <i>Brassica oleracea</i> var. <i>capitata</i> | Pusa Drumhead   | 60 × 45 cm | <ul style="list-style-type: none"> <li>Light irrigation immediately after transplanting, followed by regular intervals of 10-15 days, totalling 180 cm of applied water.</li> <li>Maintain steady moisture during head formation, but reduce watering near harvest to prevent splitting.</li> </ul> | <ul style="list-style-type: none"> <li><b>Method:</b> Hand weeding</li> <li><b>Frequency:</b> Shallow and frequent weeding and Earth up the plants 35 days after transplanting.</li> </ul> |

**Table 2. Soil moisture extraction pattern in pomegranate based production systems under different crop combinations (1 ha)**

| S.N. | Intercropping systems               | Soil horizon depth (cm) and Moisture Percentage (%) |                          |                          |
|------|-------------------------------------|-----------------------------------------------------|--------------------------|--------------------------|
|      |                                     | 0-15                                                | 15-30                    | 30-45                    |
| 1    | Pomegranate +Green Gram-Mustard     | 41.44± 2.87                                         | 35.30± 2.44 <sup>a</sup> | 23.26± 1.61 <sup>b</sup> |
| 2    | Pomegranate +Cluster bean-Fenugreek | 43.45 ± 3.76                                        | 32.22± 2.79 <sup>a</sup> | 24.33± 2.10 <sup>b</sup> |
| 3    | Pomegranate +Okra-Cabbage           | 43.33±1.98                                          | 32.21± 1.47 <sup>a</sup> | 24.46± 1.12 <sup>b</sup> |
| 4    | Sole Pomegranate                    | 42.09±3.64                                          | 27.34± 2.36 <sup>b</sup> | 30.57± 2.64 <sup>a</sup> |

Data are presented as mean ± standard deviation (SD). Differences among treatment means were analyzed using Tukey's Honest Significant Difference (HSD) test at P < 0.001. Means followed by different superscript letters within a column differ significantly according to Tukey's HSD test.

**Table 3. Seasonal crop water use (mm) of pomegranate-based production systems and sole cropping systems (1 ha)**

| S.N. | Intercropping systems               | Kharif        |             | Rabi                      |                          | In total system            |                           |
|------|-------------------------------------|---------------|-------------|---------------------------|--------------------------|----------------------------|---------------------------|
|      |                                     | Total         | Mean        | Total                     | Mean                     | Total                      | Mean                      |
| 1    | Pomegranate +Green gram - Mustard   | 1252± 86.74   | 313±21.68   | 688±47.66 <sup>c</sup>    | 172±11.91 <sup>c</sup>   | 1940±134.40 <sup>b</sup>   | 485±33.60 <sup>b</sup>    |
| 2    | Pomegranate +Cluster bean-Fenugreek | 1252±108.42   | 313±27.10   | 873±75.60 <sup>b</sup>    | 218.2±18.89 <sup>b</sup> | 2125±184.03 <sup>a</sup>   | 531.2±46.00 <sup>a</sup>  |
| 3    | Pomegranate +Okra-Cabbage           | 1286.2±58.94  | 321.5±14.73 | 1080.5±49.51 <sup>a</sup> | 270.1±12.37 <sup>a</sup> | 2366.7±108.45 <sup>a</sup> | 591.65±27.11 <sup>a</sup> |
| 4    | Sole Pomegranate                    | 1340.4±116.08 | 335.1±29.02 | 537.5±46.54 <sup>d</sup>  | 134.3±11.63 <sup>d</sup> | 1877.9±162.63 <sup>b</sup> | 469.4±40.65 <sup>b</sup>  |

Data are presented as mean ± standard deviation (SD). Differences among treatment means were analyzed using Tukey's Honest Significant Difference (HSD) test at P < 0.001. Means followed by different superscript letters within a column differ significantly according to Tukey's HSD test.

**Table 4. System yield (kg ha<sup>-1</sup>) of pomegranate-based production systems and sole cropping systems (1 ha)**

| S.N. | Intercropping systems               | Kharif                     |                            | Rabi                        |                            | In total system              |                            |
|------|-------------------------------------|----------------------------|----------------------------|-----------------------------|----------------------------|------------------------------|----------------------------|
|      |                                     | Total                      | Mean                       | Total                       | Mean                       | Total                        | Mean                       |
| 1    | Pomegranate +Green gram - Mustard   | 4048.9± 350.6 <sup>c</sup> | 1012.2± 87.65 <sup>c</sup> | 7854.4± 680.2 <sup>b</sup>  | 1963.6± 170.0 <sup>b</sup> | 11903.3± 276.4 <sup>c</sup>  | 2975.8± 257.7 <sup>c</sup> |
| 2    | Pomegranate +Cluster bean-Fenugreek | 5654.9± 195.9 <sup>b</sup> | 1413.7± 48.97 <sup>b</sup> | 7700.6± 266.7 <sup>b</sup>  | 1925.15±66.68 <sup>b</sup> | 13355.5± 462.6 <sup>b</sup>  | 3338.8± 115.6 <sup>b</sup> |
| 3    | Pomegranate +Okra-Cabbage           | 7259.5± 125.7 <sup>a</sup> | 1814.8± 31.43 <sup>a</sup> | 15839.7± 274.2 <sup>a</sup> | 3959.9± 68.58 <sup>a</sup> | 23099.2± 400.2 <sup>a</sup>  | 5774.7± 100.0 <sup>a</sup> |
| 4    | Sole Pomegranate                    | 0.00± 0.0 <sup>d</sup>     | 0.00± 0.0 <sup>d</sup>     | 3662.2± 276.4 <sup>c</sup>  | 915.55± 69.12 <sup>c</sup> | 3662.2± 1,030.8 <sup>d</sup> | 915.55± 69.12 <sup>d</sup> |

Data are presented as mean ± standard deviation (SD). Differences among treatment means were analyzed using Tukey's Honest Significant Difference (HSD) test at P < 0.001. Means followed by different superscript letters within a column differ significantly according to Tukey's HSD test.

**Table 5. Effect of different intercropping systems on average yield, total yield, and mustard equivalent yield of pomegranate**

| Treatment                            | Average yield (kg plant <sup>-1</sup> ) | Mustard equivalent yield (kg ha <sup>-1</sup> ) |
|--------------------------------------|-----------------------------------------|-------------------------------------------------|
| Pomegranate+ Green gram- Mustard     | 6.42 a                                  | 1869.5 a                                        |
| Pomegranate+ Cluster bean- Fenugreek | 5.89 a                                  | 1717.0 a                                        |
| Pomegranate+ Okra -Cabbage           | 5.40 a                                  | 1571.8 a                                        |
| Sole Pomegranate                     | 6.28 a                                  | 1831.1 a                                        |
| SE (m)                               | 0.25                                    | 73.1                                            |
| CD (5%)                              | 0.87                                    | 253.1                                           |

Means followed by the same superscript letter within a column are not significantly different at  $p \leq 0.05$  according to Tukey's HSD test under a linear mixed-effects model. SE(m) = standard error of mean; CD = critical difference at 5% level.

**Table 6.** Yield performance of component crops and their equivalent yield under pomegranate-based intercropping systems (Mean Yield (kg ha<sup>-1</sup>)).

| Intercropping system       | Kharif          |                                | Rabi            |                             |
|----------------------------|-----------------|--------------------------------|-----------------|-----------------------------|
|                            | Intercrop yield | Green gram<br>Equivalent Yield | Intercrop yield | Mustard<br>Equivalent Yield |
| Pomegranate + Green gram   | 1012.2 c        | 1012.2 d                       | 917.0 c         | 1028.8 d                    |
| Pomegranate + Cluster bean | 1033.1 c        | 1413.7 c                       | 933.3 c         | 1066.6 d                    |
| Pomegranate + Okra         | 2758.6 b        | 1814.8 b                       | 18515.4 b       | 3174.0 b                    |
| Sole Green gram            | 1055.2 c        | 1055.2 d                       | 1144.0 c        | 1144.0 c                    |
| Sole Cluster bean          | 1246.7 c        | 1706.0 b                       | 1408.1 c        | 1609.2 c                    |
| Sole Okra                  | 7014.7 a        | 4614.9 a                       | 35845.0 a       | 6144.8 a                    |
| SE (m)                     | 109.2           | 105.4                          | 567.2           | 143.7                       |
| CD (5%)                    | 344.3           | 332.3                          | 1787.5          | 452.9                       |

Means followed by the same superscript letter within a column are not significantly different at  $p \leq 0.05$  according to Tukey's HSD test under a linear mixed-effects model. SE(m) = standard error of mean; CD = critical difference at 5% level.

**Table 7.** Water productivity (kg ha<sup>-1</sup> mm<sup>-1</sup>) of pomegranate-based production systems and sole cropping systems

| S.N. | Intercropping systems               | Kharif                  |                         | Rabi                     |                          | In total system          |                           |
|------|-------------------------------------|-------------------------|-------------------------|--------------------------|--------------------------|--------------------------|---------------------------|
|      |                                     | Total                   | Mean                    | Total                    | Mean                     | Total                    | Mean                      |
| 1    | Pomegranate +Green gram - Mustard   | 13.7± 0.23 <sup>c</sup> | 3.42± 0.05 <sup>c</sup> | 47.30± 0.81 <sup>b</sup> | 11.82± 0.20 <sup>b</sup> | 61±1.05 <sup>b</sup>     | 15.24± 0.26 <sup>b</sup>  |
| 2    | Pomegranate +Cluster bean-Fenugreek | 19.3± 1.67 <sup>b</sup> | 4.84± 0.41 <sup>b</sup> | 35.43± 3.06 <sup>c</sup> | 8.858± 0.76 <sup>c</sup> | 54.73±4.74 <sup>c</sup>  | 13.698± 1.18 <sup>c</sup> |
| 3    | Pomegranate +Okra-Cabbage           | 24.0± 1.1 <sup>a</sup>  | 6.00± 0.27 <sup>a</sup> | 58.57± 2.68 <sup>a</sup> | 14.64± 0.67 <sup>a</sup> | 82.57± 3.78 <sup>a</sup> | 20.64± 0.94 <sup>a</sup>  |
| 4    | Sole Pomegranate                    | 0.00± 0.0 <sup>d</sup>  | 0.00± 0.0 <sup>d</sup>  | 30.51± 2.64 <sup>d</sup> | 7.62± 0.66 <sup>d</sup>  | 30.51±2.64 <sup>d</sup>  | 7.62± 0.66 <sup>d</sup>   |

Data are presented as mean ± standard deviation (SD). Differences among treatment means were analyzed using Tukey's Honest Significant Difference (HSD) test at  $P < 0.001$ . Means followed by different superscript letters within a column differ significantly according to Tukey's HSD test.

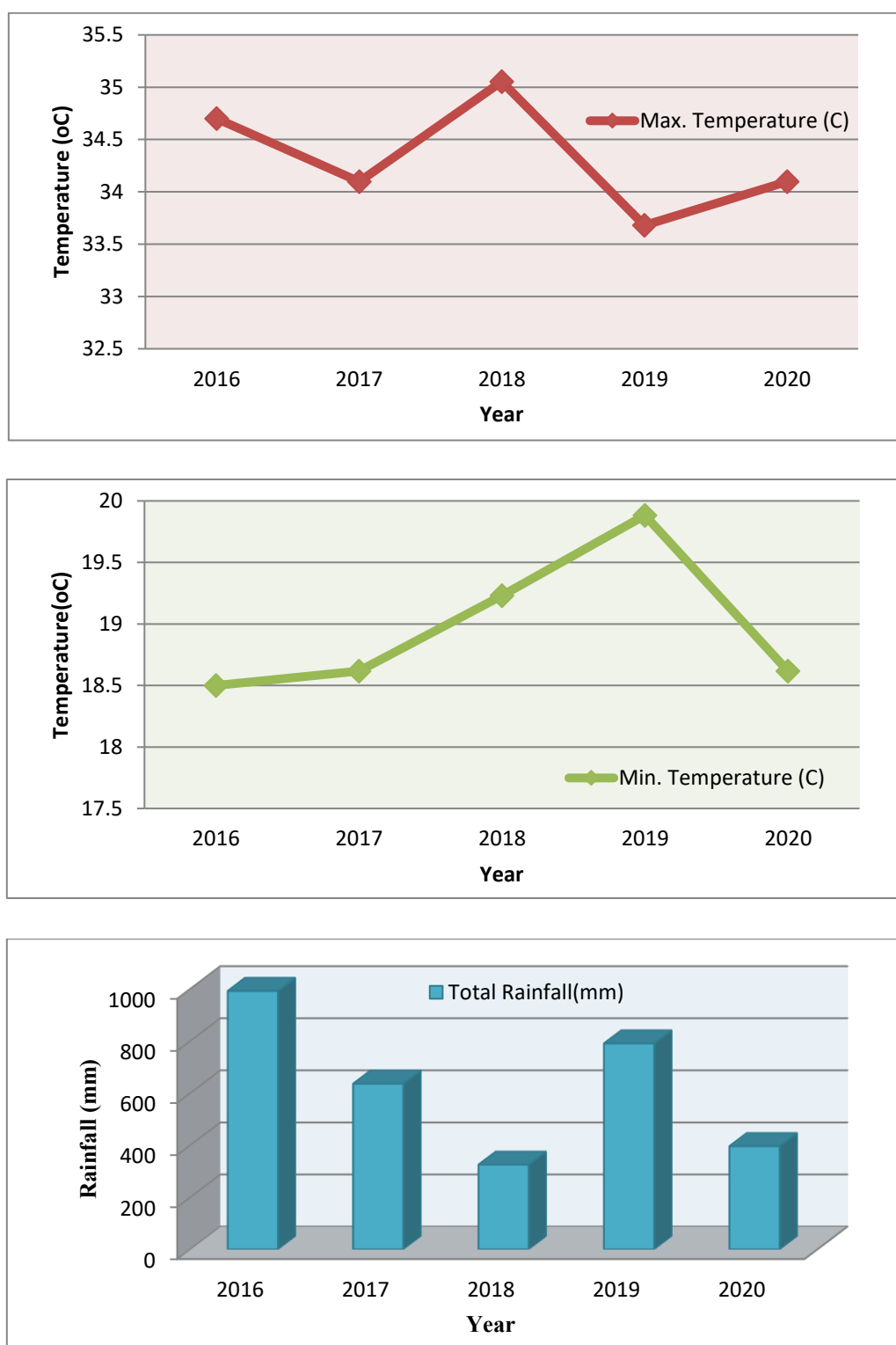


**Figure 1. Climatic conditions during the study period.**

Graph depicting pooled mean maximum temperature (°C), minimum temperature (°C), and total rainfall (mm) recorded throughout the experimental period under the pomegranate-based intercropping systems.

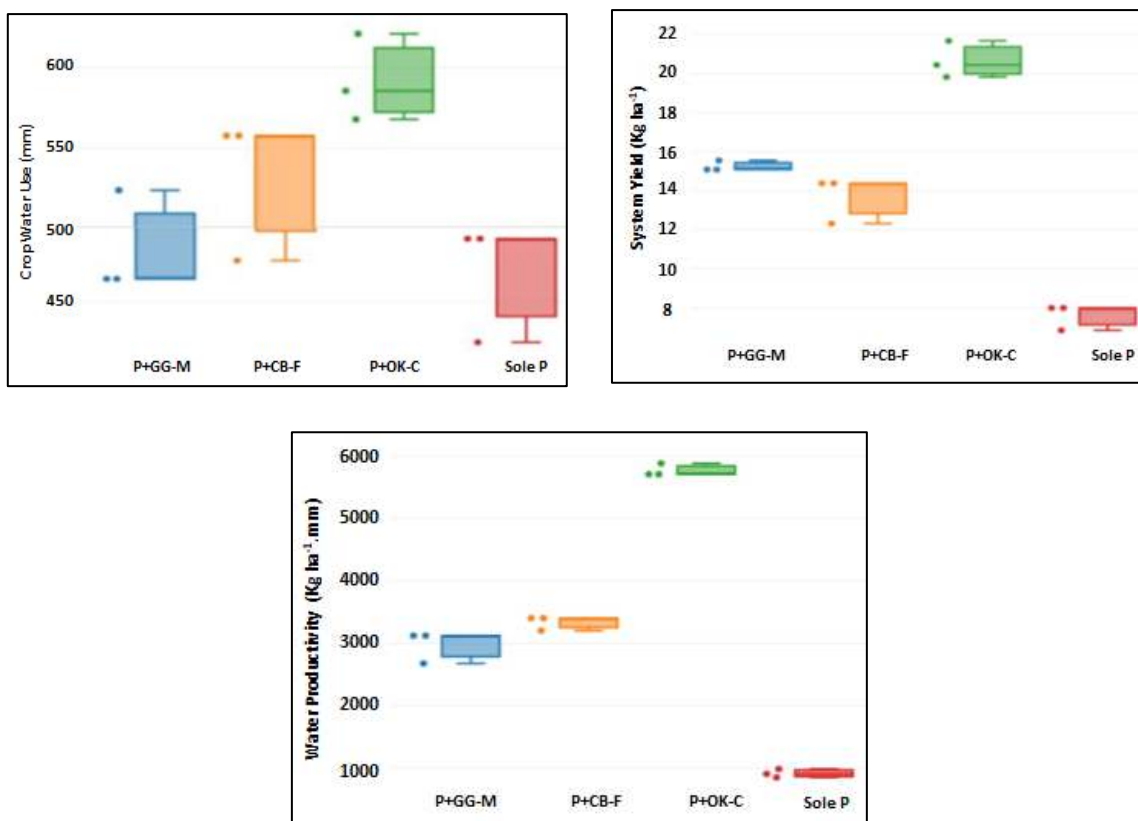


**Figure 2. Crop water use, system yield, and water productivity under pomegranate-based intercropping systems.**

Box-and-whisker plots illustrating the distribution of crop water use (mm), system yield ( $\text{kg ha}^{-1}$ ), and water productivity ( $\text{kg ha}^{-1} \text{mm}^{-1}$ ) across different intercropping combinations. Boxes represent the interquartile range (IQR), the central line indicates the median, whiskers denote the range, and points represent outliers. Values are pooled across study years. Treatments differing significantly at  $P < 0.05$  are indicated.

P+GG-M: Pomegranate+Greengram-Mustard, P+CB-F: Pomegranate+Clusterbean-Fenugreek, P+OK-C; Pomegranate+Okra-Cabbage, Sole P: Sole Pomegranate

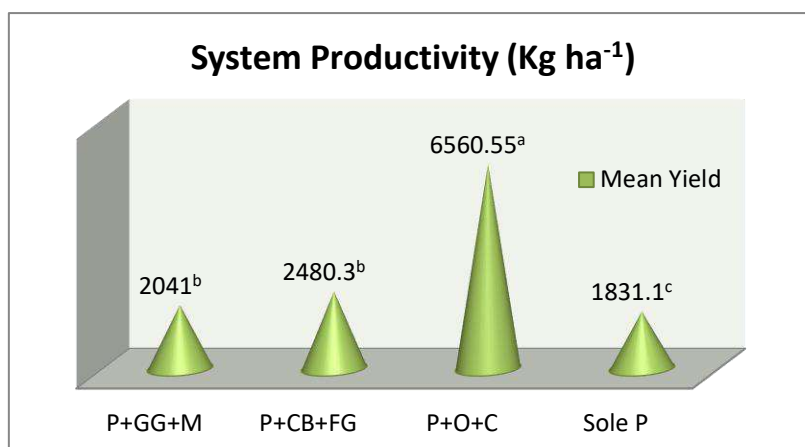


**Figure 3. System productivity of pomegranate-based intercropping systems.**

Mean system productivity (kg ha<sup>-1</sup>) recorded under different pomegranate-based intercropping combinations. Different letters above bars denote significant differences among treatments at  $P < 0.05$ .

P+GG-M: Pomegranate+Greengram-Mustard, P+CB-F: Pomegranate+Clusterbean-Fenugreek, P+OK-C; Pomegranate+Okra-Cabbage, Sole P: Sole Pomegranate