Optimizing Hass Avocado Production through Sustainable Irrigation Practices in the Arid Zone of Tacna, Peru

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Abstract. In the arid Tacna region of Peru, Hass avocado cultivation is constrained by limited water resources and the need for efficient irrigation practices. This study investigates the combined effects of soil characteristics and irrigation efficiency on Hass avocado yield and growth across diverse production zones in Tacna, Peru, to inform strategies for sustainable cultivation in arid environments. Field measurements were conducted in avocado orchards located in the districts of Cinto Valley, Hospicio Irrigation Area, La Yarada, Calana Valley, Pachía, and Higuerani in the Tacna region. Data included soil moisture at different depths, tree height, and stem diameter. Irrigation system performance was evaluated in each location, and a comparative analysis was carried out to assess the relationship between irrigation efficiency, tree growth, and fruit yield across the regions. Key results indicate that irrigation efficiency and uniformity critically affect avocado productivity. Zones such as Cinto Valley achieved high irrigation efficiency (up to 94%) and correspondingly higher soil moisture, resulting in significantly greater tree heights (up to 416 cm) and fruit yields (up to 195.8 fruits per tree). In contrast, Hospicio areas showed poor irrigation efficiency (as low as 13%), low soil moisture, and markedly reduced tree growth and fruit production. A statistically significant positive correlation was found between irrigation uniformity and yield (Spearman $\rho = 0.49$, $p = 0.006$), underscoring the direct impact of water management on productivity. Soil analyses revealed low organic matter (0.03%–0.89%) and high sand content (up to 95%), limiting water retention and nutrient availability across sites. Salinity was elevated in Pachía (EC up to 5.16 dS/m), indicating a need for salinity management in some areas. Cation exchange capacity varied, with Higuerani soils showing better nutrient retention. Overall, yields ranged widely, from below 1,000 kg/ha in less favorable zones (Hospicio, Yarada) to nearly 11,000 kg/ha in Valle de Cinto by the 2023–2024 season, highlighting strong spatial variability driven by irrigation performance and soil conditions. Orchard age also influenced productivity, with older orchards (>6 years) outperforming younger ones (<4.5 years). This study emphasizes that improving irrigation uniformity and

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soil management practices are essential for optimizing Hass avocado production and sustainability under the arid conditions of Tacna.

Keywords: Hass Avocado, Irrigation Efficiency, Irrigation Uniformity, Soil Moisture, Soil Salinity, Fruit Yield, Cation Exchange Capacity, Water Management, Arid Agriculture, Sustainable Cultivation.

1 Introduction

Avocado cultivation in Peru has undergone a significant transformation in recent decades, evolving from a small-scale local practice into an export-oriented industry [1]. This rapid expansion is driven by favorable climatic conditions, strategic investments in irrigation infrastructure, and a surge in global demand for avocados, particularly the Hass variety [2]. Avocado farming in Peru has witnessed a remarkable shift from a modest local activity to a growing export sector [3]. This development is attributed to favorable climatic conditions, strategic investments in irrigation infrastructure, and an increase in global demand for avocados [2]. However, challenges such as climate change, water resource management, and market competition pose potential threats to the sustainability of the industry [2]. This section provides an overview of avocado production in Peru, exploring its global significance, climatic impacts, and the key factors influencing its future growth.

Avocado (*Persea americana* L.) is a nutrient-dense fruit renowned for its high content of healthy fats, vitamins, and minerals [4]. It is widely consumed worldwide due to its health benefits, including promoting heart health, offering anti-inflammatory properties, and providing a high fiber content [5, 6]. The most commercially valuable variety is the Hass, which dominates global markets due to its rich flavor, creamy texture, and long shelf life [7]. Other significant varieties include Fuerte, Bacon, and Zutano, although their market shares are considerably smaller [8].

Climate change has significant effects on avocado cultivation in Peru. Despite the country being responsible for only 0.4% of global greenhouse gas emissions, it ranks as the third most vulnerable nation to climate risks [9]. Over the past 30 years, 22% of the glaciers in Peru have melted, with these glaciers accounting for 71% of the world's tropical glaciers [10]. Additionally, between 1964 and 2014, notable increases in monthly and annual temperatures have been observed across the country [11]. Climate projections for 2050 predict an increase in annual average temperatures ranging from 1.7 to 3.5°C, with regional variations, such as a 40% decrease in rainfall in the Amazon region and a more than 45% increase in precipitation on the northern coast [12]. These changes are having various negative impacts on avocado farming. Rising temperatures may affect flowering and fruit set processes, potentially reducing yields [13]. Moreover, the decreasing availability of water resources, especially in areas dependent on irrigation systems, makes production more challenging [14]. Extreme weather events, such as droughts and heavy rainfall, can threaten the health of avocado trees and lead to soil erosion, reducing agricultural productivity [15]. Additionally, pests and diseases may spread more rapidly in warmer and more humid climates, which could increase production costs and further decrease yields. To mitigate the effects of climate change, farmers are shifting towards more resilient avocado varieties and employing advanced irrigation techniques to conserve water. Furthermore, methods such as shading systems and agroforestry practices can offer protection against extreme temperatures [16]. Investments from both the government and the private sector are promoting the widespread adoption of sustainable agricultural techniques, playing a critical role in combating climate change [17].

Global demand for avocados has surged, making it one of the most profitable products in the fruit industry [4]. Leading producers include Mexico, the Dominican Republic, Peru, Colombia, and Indonesia [2]. Mexico, which accounts for over 30% of global production, is the largest supplier [18], followed by Peru, which has established itself as the second-largest exporter of Hass avocados [19]. Global avocado trade is highly dynamic, with key markets in North America, Europe, and an increasingly growing presence in Asia [2]. The seasonality of production in different regions allows for year-round availability, making international trade an essential aspect of the sector. Avocado production systems vary significantly depending on regional climatic conditions, water availability, and technological advancements [20]. Countries like Mexico benefit from traditional rain-fed production systems [14], while Peru relies heavily on advanced irrigation infrastructure to sustain its production [3]. The Dominican Republic and Colombia are also emerging as strong players in the avocado market, focusing on both export potential and domestic consumption [21]. The global increase in avocado consumption is largely driven by health trends and dietary shifts toward plant-based nutrition [22]. In response, major producing countries are investing in expanding planting areas, improving post-harvest technologies, and developing sustainable agricultural practices [23]. However, challenges such as deforestation, water use concerns, and carbon footprints are becoming increasingly important in discussions about the future of avocado production [18].

Peru has rapidly become a significant player in the avocado market, transitioning from small-scale local production to large-scale, export-oriented cultivation [24]. Favorable climatic conditions, investments in irrigation infrastructure, and strong global demand have fueled this transformation. The primary avocado-growing regions are located along the coastal strip, extending over 2,000 kilometers from the north in Chiclayo to the south in Arequipa [21]. Key production areas include Olmos, Chavimochic, and Ica, where extensive irrigation systems enable high-yield farming in otherwise arid environments [25]. Currently, Peru ranks among the largest avocado producers globally, with an annual production exceeding 550,000 metric tons [3]. The country's avocado yield averages between 15 to 20 metric tons per hectare, a competitive level compared to other major producers [2]. The sector's efficiency is largely attributed to modern agricultural techniques, extensive irrigation networks, and favorable climatic conditions [26]. Approximately 93% of Peru's avocado production is aimed at international markets, making the sector predominantly export oriented. Major export destinations include Europe, the United States, and more recently, the increasingly demanding Asian markets [27]. Peru’s ability to supply avocados during seasonal shortages faced by other large producers, such as Mexico, has further strengthened its position in the global market [2]. However, the sector’s expansion brings about several challenges. The reliance on irrigation, particularly in regions where water resources are already under stress, has raised concerns regarding long-term water sustainability [28]. Additionally, growing competition from emerging producers like Colombia and Kenya requires Peruvian growers to continuously improve production efficiency and quality standards to maintain their competitive edge [29].

While various avocado varieties are cultivated worldwide, the Hass variety dominates Peru's commercial production due to its superior marketability [23]. The thick skin of Hass avocados makes them more resistant to transportation and storage, factors crucial for export-oriented production [30]. Other varieties, such as Fuerte, Bacon, and Zutano, are primarily grown on a smaller scale for local consumption [8]. Hass avocados are preferred for large-scale cultivation in Peru due to their high yield potential, consistent fruit quality, and long shelf life [4]. These characteristics make them particularly suitable for export markets, where durability during long transit times is critical [31]. Furthermore, Hass avocados have high oil content and a creamy texture, factors that increase their demand in premium markets such as Europe and North America [21]. Peru's avocado industry has organized its production to meet international market demands, with approximately 95% of exports consisting of Hass avocados [32]. The other varieties, cultivated in smaller quantities, cater to niche markets and local consumption needs. The success of Hass avocados in Peru is also attributed to the country's coastal desert climate and the efficiency of large-scale irrigation systems that provide consistent, high-quality yields [33].

Despite its rapid growth, Peru's avocado industry faces various challenges that could impact its long-term sustainability. Climate variability, including prolonged droughts and sudden floods, is affecting both production volumes and fruit quality [34]. The availability of suitable land for new avocado plantations has reached its limit, making the sector more vulnerable to production fluctuations [2]. Additionally, the reliance on irrigation continues to be a significant concern, with water scarcity posing a major challenge and necessitating more efficient water management strategies. The expansion of avocado production in countries like Colombia and increasing competition in international markets have intensified market competition [24].

To ensure continued growth and sustainability, Peru must invest in climate-resilient agricultural practices, diversify its export markets, and explore value-added processing options. Research on the development of drought-resistant avocado varieties and the improvement of irrigation efficiency will be critical in addressing future challenges.

2 Materials and Methods

2.1 Experimental Design and Data Collection Methods

This study involves the technical and economic analysis of Hass avocado (*Persea americana* Mill) production in semi-arid regions of the Tacna province, Peru. The research was conducted in the main production areas of Tacna, including Cinto Valley, Hospicio Irrigation Area, La Yarada, Calana Valley, Pachía, and Higuerani (Figure 1). These study areas were selected because they exhibit different climate, soil composition, and irrigation system characteristics, allowing for a comparative analysis.

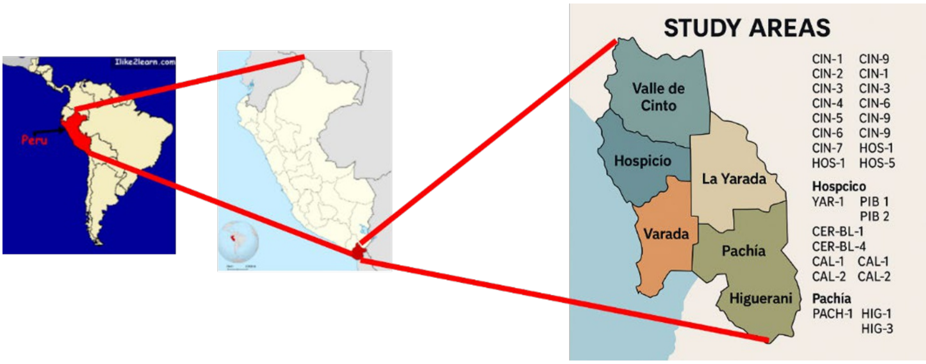

Fig. 1. Areas of avocado tree production where the research was conducted in Tacna Region, Peru

The research was conducted through the collaboration of various institutions to obtain scientific data on agricultural production processes. The Asociación de Frutas de Tacna (AFRUTAC), representing fruit producers in the Tacna region, played a significant role in conducting tests in avocado orchards and providing economic data (Figure 1). Data was collected and analyzed during the 2023-2024 growing season. The study focused on examining avocado plantations from a total of 30 producers across different regions.

2.2 Leaf Sampling and Analysis

To assess the nutritional status of the plants, leaf samples were collected from avocado trees one month before flowering. The sampling process included all leaf components (leaf petiole and leaf blade). The collected leaf samples were analyzed at the soil and plant laboratory of Universidad Nacional Agraria La Molina. The leaf analysis allowed for the determination of the optimal nutrient levels for avocado trees and the identification of any nutrient deficiencies.

2.3 Soil Sampling and Analysis

Soil sampling was performed across 30 avocado orchards located in the Tacna region during the 2023 and 2024 agricultural seasons. Samples were collected at two critical phenological stages: early in the season (approximately two months prior to flowering) and at the end of the production cycle. The collected samples were submitted to the Soil and Water Laboratory of the Universidad Nacional Agraria La Molina (Lima, Peru) for comprehensive physical and chemical analysis. The evaluations included quantification of macro- and micronutrient concentrations, as well as assessment of the soil's water retention capacity.

2.4 Soil Moisture Measurements

To evaluate the effectiveness of irrigation management, soil moisture levels were measured. Measurements were taken using the Moisture Meter HH2 device, and the moisture content at different soil depths was analyzed. The designated measurement depths were 20 cm and 30 cm, and 8 to 10 trees were selected from each plot, with two different points per tree being measured. Additionally, to allow continuous data recording, Utility Z12 sensors were used to log soil moisture levels at specified intervals. During the measurement process, 35 cm deep holes were dug on both sides of the selected trees to ensure more accurate results (Figure 2).

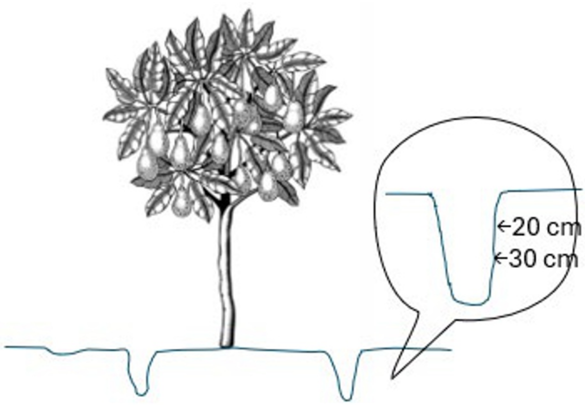

Fig. 2. Plot of pits and depth of moisture data collection

The equipment was installed in three intervention areas: Hospicio, Cinto Valley, and Calana Valley. The setup was carried out as follows: For each of the two trees in the selected plots, four detection terminals were used in parallel at two different soil depths. The first measurement was taken 10 cm from the surface, and the second one was taken 25 cm from the surface (Figure 3). This setup allowed for the monitoring of soil moisture at different soil depths to evaluate the irrigation system's performance more accurately.

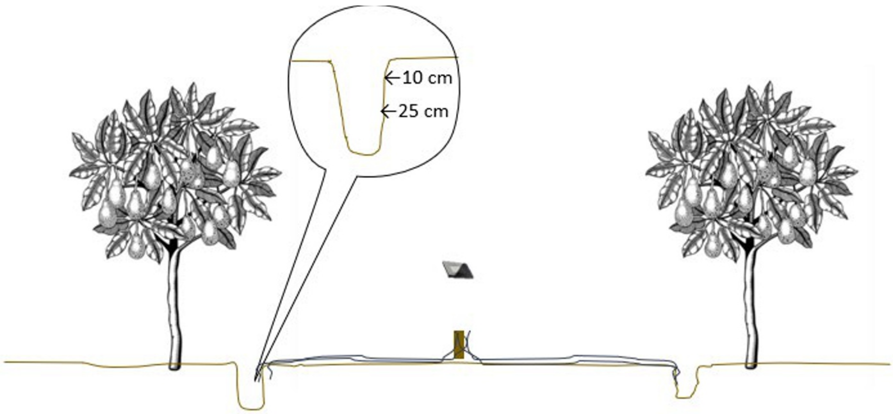

Fig. 3. Equipment installation

2.5 Irrigation Flow Rate Measurements

For the flow measurement within the plots, different irrigation zones within a single plot were separated. One irrigation zone, or "key zone," was selected, and four irrigation lines were evenly and fairly distributed within this zone based on their locations. Similarly, within each irrigation line, emitters were chosen at various points along the line: at the beginning, one-quarter, one-half, three-quarters, and the end (Figure 4). The irrigation system was activated by the landowner, and measurements were taken once the system reached full operating pressure, typically after 10 minutes. Water output from each selected emitter was collected using 500 ml graduated containers, and precise volumes were measured with a graduated cylinder. Each emitter was monitored for 60 seconds, and the resulting value was multiplied by the number of emitters per tree to estimate total discharge. To assess the efficiency of the drip irrigation systems, flow measurements were taken at four different points along each irrigation line: the start, middle, two-thirds, and end of the line. This setup allowed for an evaluation of the even distribution of irrigation water throughout the plot. The flow measurements were performed based on a standard of 60 ml/sec flow rate, and the results were analyzed to evaluate the overall performance of the irrigation system.

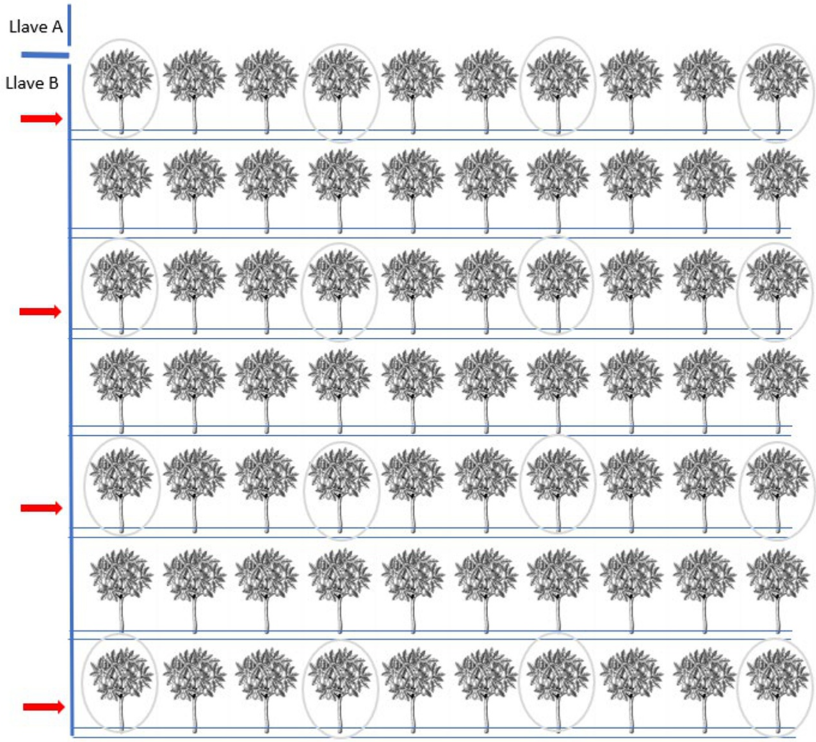

Fig. 4. Flow measurement in the parcel

2.6 Continuous Soil Moisture Monitoring During Irrigation

To evaluate moisture dynamics during irrigation, a continuous soil moisture monitoring device (Utility Z12) was used. This sensor recorded data at 5-minute intervals and was installed at strategic locations to assess evaporation, infiltration rates, and moisture retention. The device was deployed in three different areas: Hospicio, Valle de Cinto, and Valle de Calana. In each area, four probes were installed to monitor two trees simultaneously at two different depths: 10 cm and 25 cm from the soil surface.

2.7 Tree Growth Measurements

To track the development of the trees, both tree height and trunk diameter were measured. The trunk diameter measurements were taken at a height of 30 cm from the ground (Figure 3). Additionally, the plant spacing was calculated to determine the tree density, and the average growth rate per tree was analyzed. These measurements provided key insights into the growth patterns and overall health of the avocado trees under different irrigation and environmental conditions.

2.8 Fruit Yield and Productivity Analysis

To evaluate fruit yield, a fruit count was conducted on the selected trees. The counting process was performed by dividing each tree into two reference halves (Figure 5). The fruits were categorized into three groups: small, medium, and large. Based on the data collected, the average number of fruits per tree was calculated, and the productivity of avocado production was analyzed. This analysis provided valuable insights into the efficiency of different cultivation practices and irrigation systems in enhancing fruit production.

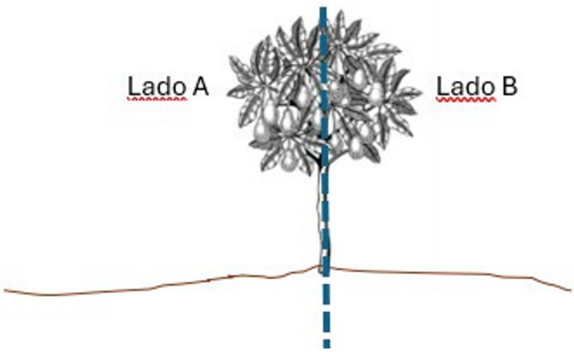

Fig. 5. Fruit counting by dividing each tree into two reference halves

2.9 The Uniformity of Water Distribution

The Uniformity Coefficient (CU) is a metric used to assess the evenness of water distribution in irrigation systems. It quantifies how uniformly water is applied across a field, which is crucial for efficient water use and optimal crop growth. The uniformity of water distribution was evaluated using the CU, calculated according to the following equation:

$$\mathrm{CU} = \left(\frac{\mathrm{q25}}{\mathrm{Qa}}\right) X\ 100$$

Where:

- q_{25} is the average discharge rate of the 25% of emitters with the lowest flow (i.e., the average of the 4 lowest-emitting emitters).
- Q_a is the average discharge rate of all sampled emitters (i.e., the average of 16 emitters evaluated per irrigation unit).

Flow measurements were taken using a standardized method under controlled pressure conditions. Each sampling point included 16 emitters per irrigation zone, from which the four with the lowest flow rates were used for the q_{25} calculation. This method allows for assessing distribution uniformity and identifying inefficiencies within the irrigation system.

By focusing on the lowest 25% of irrigation volumes, this method highlights deficiencies in water application but overlooks the overall distribution pattern and any beneficial higher volumes near low-volume zones [35].

2.10 Data Collection

This study was conducted using field data from 30 agricultural plots distributed across various irrigation zones. For each plot, two key variables were recorded: the irrigation uniformity coefficient (C.U.), expressed as a percentage, and the crop yield, measured in kilograms per hectare (kg/ha). The uniformity coefficient was calculated based on irrigation distribution measurements and reflects the consistency of water application across the field.

2.11 Data Preprocessing

All entries were compiled into a structured dataset for statistical analysis. A natural logarithmic transformation was applied to the yield variable to reduce skewness and stabilize variance, using the formula:

$$Y=\log(1+\text{yield (kg/ha)})$$

This transformation helps normalize the distribution and improves the interpretability of linear modeling results.

2.12 Statistical Analysis

To evaluate the association between irrigation uniformity and yield, two complementary statistical analyses were conducted:

Spearman's Rank Correlation Coefficient (ρ): A nonparametric test was used to assess the strength and direction of the monotonic relationship between the uniformity coefficient and raw crop yield. Spearman's method is particularly suitable for data that may not follow a normal distribution or exhibit a strictly linear trend.

Log-Transformed Linear Regression: A simple linear regression model was applied using the log-transformed yield as the dependent variable and the uniformity coefficient as the predictor. This model was selected to better capture nonlinear tendencies and reduce the influence of extreme values in the yield data.

All analyses and visualizations were performed in Python (v3.11), utilizing the libraries pandas, numpy, scipy.stats, matplotlib, and seaborn. The statistical significance level was set at $\alpha = 0.05$.

3 RESULT

This study evaluated the technical and economic aspects of Hass avocado production in the Tacna region of Peru. The obtained data revealed the relationship between water management, soil conditions, and production efficiency, providing key insights into sustainable farming practices. Due to the inability to establish a control group analysis, the results were examined using a comparative analysis approach.

3.1 Soil Analyses

The analysis of soil samples collected from different avocado-growing locations in Tacna (Peru) during the years 2023 and 2024 revealed notable spatial and temporal variations in both chemical and physical soil properties, as well as agronomically relevant parameters (Table 1). Soil pH values ranged from slightly acidic to neutral across the sites, with the highest pH observed in Yarada (7.43 ± 0.00) in 2023 and the lowest in Calana (5.90 ± 0.23) in 2024. Electrical conductivity (EC) values indicated elevated salinity levels in Pachia for both years, with the highest EC measured in 2023 (5.16 ± 0.00 dS/m). These findings suggest the need for salinity management practices, particularly in Pachia (Table 1).

Organic matter content was consistently low across all sites (ranging from 0.27% to 0.89%), reflecting poor organic fertility and indicating the potential benefit of organic amendments to enhance soil quality. Potassium (K) concentrations were notably high in Calana during 2023 (1025.45 ± 80.24 ppm), although a decrease was recorded in 2024, implying possible nutrient depletion or variability in fertilizer application (Table 1).

From a physical standpoint, the soils were generally characterized by high sand content (e.g., Calana: 69.27% in 2023), suggesting low water-holding capacity (Table 1). This trend was consistent with relatively low moisture content values, particularly in sandier soils, which could affect crop water availability and productivity (Table 1).

Overall, the findings emphasize the importance of site-specific soil management strategies tailored to local edaphic conditions. Enhancing organic matter content and addressing salinity-related constraints could significantly improve soil health and support sustainable avocado production in the region (Table 1).

Table 1. Chemical properties of soil, physical properties of soil, and agronomically relevant parameters in avocado-growing areas of Calana, Hospicio, Pachía, Higuerani, Yarada, and Valle de Cinto (Tacna, Peru) during the years 2023 and 2024. Values are expressed as mean ± standard error. Sample sizes ranged from 3 to 9 for Calana, Hospicio, Higuerani, and Valle de Cinto, and were limited to a single observation (n = 1) for the Pachía and Yarada locations.

		Chemical Properties of Soil					
		pH	**Electrical Conductivity (ds/m)**	**$CaCO_3$ (%)**	**Organic Matter Content (%)**	**P (ppm)**	**K (ppm)**
2023	**CALANA**	6.80±0.18	3.92±0.56	0.25±0.07	0.78±0.15	28.70±2.94	1025.45±80.24
	HOSPICIO	7.05±0.05	6.74±2.23	0.00±0.00	0.09±0.06	12.94±2.54	411.80±28.86
	PACHIA	6.30±0.00	5.16±0.00	0.27±0.00	0.82±0.00	21.00±0.00	860.00±0.00
	HIGUERANI	7.46±0.11	3.34±0.28	0.21±0.03	0.46±0.02	21.90±9.12	1420.00±85.05
	YARADA	7.43±0.00	1.75±0.00	0.09±0.00	0.03±0.00	15.00±0.00	330.00±0.00
	VALLE DE CINTO	7.58±0.13	2.56±0.39	1.66±0.22	0.71±0.17	22.93±4.49	591.44±58.21
2024	**CALANA**	6.90±0.23	2.60±0.41	0.16±0.07	0.44±0.13	14.99±2.85	684.81±71.46
	HOSPICIO	7.01±0.072	1.84±0.69	0.00±0.00	0.038±0.01	5.96±1.19	208.40±13.45
	PACHIA	6.96±0.00	3.80±0.00	0.36±0.00	0.53±0.00	51.6±0.00	1350±0.00
	HIGUERANI	7.42±0.07	2.20±0.80	0.06±0.06	0.25±0.12	11.97±9.07	825±183.87
	YARADA	7.09±0.00	0.60±0.00	0.00±0.00	0.07±0.00	2.70±0.00	189±0.00
	VALLE DE CINTO	7.45±0.10	2.18±0.27	1.59±0.21	0.89±0.14	14.4±2.60	489.22±29.40
		Physical Properties of Soil				**Agronomically Relevant Parameters**	
		Sand (%)	**Silt (%)**	**Clay (%)**	**Bulk Density (g/cc)**	**Field Capacity (%)**	**Moisture Content (%)**
2023	**CALANA**	69.27±3.80	26.36±6.04	11.36±1.32	1.28±0.03	13.54±1.26	6.86±0.79
	HOSPICIO	90.00±1.26	6.60±1.17	3.40±0.40	1.50±0.03	7.24±0.28	2.91±0.18
	PACHIA	56.00±0.00	29.00±0.00	15.00±0.00	1.25±0.00	19.78±0.00	10.78±0.00
	HIGUERANI	75.33±2.91	17.00±1.15	7.67±1.76	1.36±0.05	14.61±1.36	7.53±0.85

	YARADA	86.00±0.00	9.00±0.00	5.00±0.00	1.44±0.00	8.46±0.00	3.67±0.00
	VALLE DE CINTO	65.56±3.12	23.89±1.98	10.56±1.23	1.32±0.02	7.47±2.39	7.21±0.57
2024	**CALANA**	72.36±4.27	21.36±2.82	6.27±1.46	1.31±0.03	14.01±1.59	7.16±0.10
	HOSPICIO	92.60±1.29	7.00±1.10	0.40±0.24	1.45±0.01	6.94±0.25	2.71±0.16
	PACHIA	74.00±0.00	21.00±0.00	5.00±0.00	1.28±0.00	12.36±0.00	6.12±0.00
	HIGUERANI	84.67±2.40	12.33±1.33	3.00±1.15	1.37±0.09	12.09±1.61	5.95±1.01
	YARADA	95.00±0.00	5.00±0.00	0.00±0.00	1.45±0.00	7.19±0.00	2.87±0.00
	VALLE DE CINTO	68.44±3.07	24.78±2.25	6.78±0.91	1.25±0.03	15.24±0.99	7.93±0.62

Table 2. Cation exchange capacity and exchangeable cations in avocado-growing areas of Calana, Hospicio, Pachía, Higuerani, Yarada, and Valle de Cinto (Tacna, Peru) during the years 2023 and 2024. Values are expressed as mean ± standard error. Sample sizes ranged from 3 to 9 for Calana, Hospicio, Higuerani, and Valle de Cinto, and were limited to a single observation (n = 1) for the Pachía and Yarada locations.

		Cation Exchange Capacity and Exchangeable Cations								
		Cation Exchange Capacity	**Exchangeable Cations (meq/100g)**					**Sum of Cations**	**Sum of Bases**	**% Base Saturation**
			Ca^{2+}	**Mg^{2+}**	**K^{+}**	**Na^{+}**	**$Al^{3+} + H^{+}$**			
2023	**CALANA**	9.85±0.79	5.90±0.58	1.80±0.27	1.50±0.09	0.34±0.03	0.01±0.01	9.56±0.77	9.55±0.77	97.18±1.93
	HOSPICIO	3.87±0.20	2.34±0.25	0.60±0.15	0.65±0.05	0.28±0.1	0.00±0.00	3.87±0.20	3.87±0.20	100±0.00
	PACHIA	10.24±0.00	7.66±0.00	1.04±0.00	1.30±0.00	0.23±0.00	0.00±0.00	10.24±0.00	10.24±0.00	100±0.00
	HIGUERANI	12.59±1.41	6.43±0.76	2.24±0.48	2.92±0.35	0.99±0.14	0.00±0.00	12.59±1.41	12.59±1.41	100±0.00
	YARADA	5.12±0.00	3.63±0.00	0.86±0.00	0.61±0.00	0.03±0.00	0.00±0.00	5.12±0.00	5.12±0.00	100±0.00
	VALLE DE CINTO	9.97±0.63	6.978±0.59	1.83±0.07	1.02±0.08	0.15±0.05	0.00±0.00	9.97±0.63	9.97±0.63	100±0.00
2024	**CALANA**	8.00±0.95	4.91±0.54	1.49±0.42	1.14±0.12	0.17±0.03	0.01±0.01	7.73±0.95	7.71±0.95	96.82±2.36
	HOSPICIO	3.52±0.10	2.41±0.15	0.52±0.13	0.44±0.06	0.13±0.04	0.00±0.00	3.50±0.11	3.50±0.11	99.60±0.40
	PACHIA	8.00±0.00	4.33±0.00	1.81±0.00	1.76±0.00	0.10±0.00	0.00±0.00	8.00±0.00	8.00±0.00	100±0.00
	HIGUERANI	10.27±2.45	5.44±1.30	1.81±0.94	2.28±0.21	0.72±0.18	0.00±0.00	10.27±2.45	10.27±2.45	100±0.00
	YARADA	3.40±0.00	2.27±0.00	0.66±0.00	0.39±0.00	0.09±0.00	0.00±0.00	3.40±0.00	3.40±0.00	100±0.00
	VALLE DE CINTO	9.89±0.74	7.01±0.74	1.95±0.12	0.823±0.05	0.11±0.02	0.00±0.00	9.89±0.74	9.89±0.74	100±0.00

The results from 2023 and 2024 indicate significant spatial variability in cation exchange capacity (CEC) and exchangeable cation concentrations across the avocado-growing regions of Tacna, Peru (Table 2). The Higuerani site consistently exhibited the highest CEC values (2023: 12.59±1.41, 2024: 10.27±2.45), likely due to higher clay content and organic matter levels contributing to greater cation retention capacity (Table 2).

Regarding exchangeable bases, Ca^{2+} and Mg^{2+} levels were generally aligned with CEC values, with notably higher concentrations in Higuerani and Calana. In 2023, Pachia recorded the highest K^{+} concentration (1.50 meq/100g), while Na^{+} levels remained low across all sites, suggesting minimal risk of sodium-induced salinity issues (Table 2).

Base saturation percentages were close to 100% in most locations, indicating favorable soil fertility conditions (Table 2). However, a slightly lower base saturation was observed in Calana in 2023 (97.18±1.93%), potentially pointing to the presence of acidic cations (H^+, Al^{3+}) affecting overall saturation (Table 2).

Overall, the variation in CEC and exchangeable cation composition provides essential insight into soil fertility status (Table 2). Targeted soil amendments are recommended in areas with lower CEC to enhance nutrient-holding capacity and sustain crop productivity (Table 2).

3.2 Soil Moisture Level Comparison

Graphical analysis showed that regions with higher moisture levels generally had more efficient irrigation systems. The highest moisture levels at a 20 cm depth were found in the Cinto 06, Cinto 08, and Cinto 09 areas, while the lowest moisture levels were observed in the Hospicio 05, Hospicio 04, and Cinto 07 regions. As a general trend, moisture levels at 30 cm depth were lower compared to 20 cm depth, indicating that the surface layer loses water more rapidly and deeper soil layers have higher water retention capacity (Figure 6).

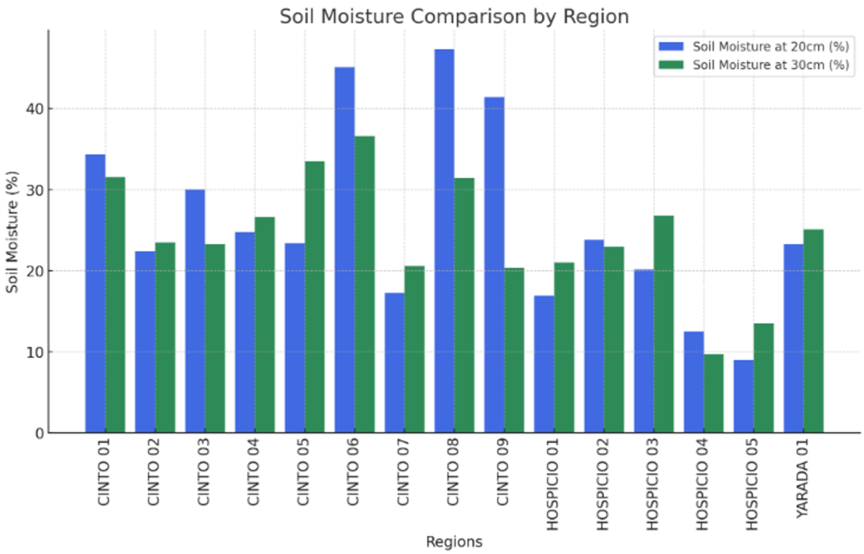

Fig. 6. Comparison of soil moisture levels between regions

3.3 Irrigation Efficiency and Flow Rate Comparison

According to the graphical analysis, the highest irrigation efficiency was observed in the Cinto 01 and Cinto 06 areas, both reaching 94%. The system in these regions performed highly due to regular maintenance and the use of appropriate irrigation equipment. On the other hand, the irrigation efficiency in the Cinto 07 (13%), Hospicio 01 (44%), and Hospicio 02 (50%) areas was significantly low. In the Hospicio 03 and 04 regions, the irrigation efficiency remained at 50%, indicating that improvements are needed in these areas. The low irrigation efficiency in certain regions suggests high water losses and that the irrigation systems are not functioning effectively (Figure 7).

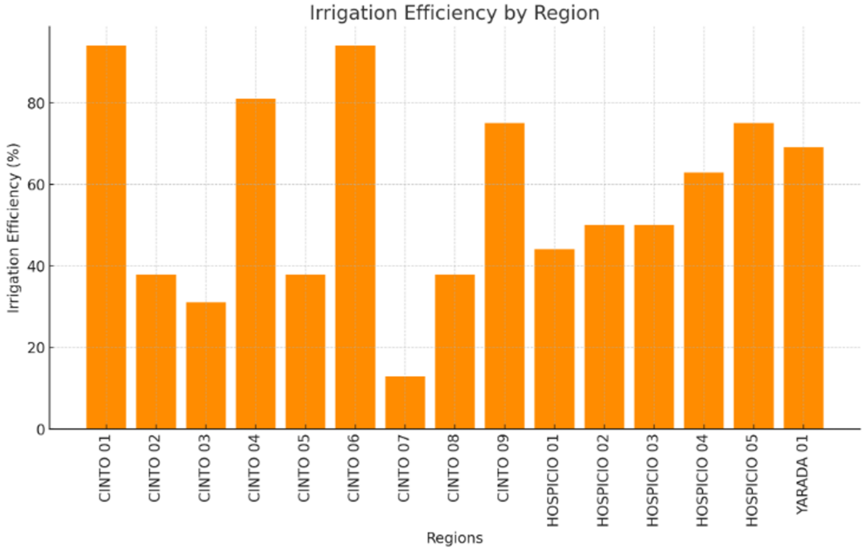

Fig. 7. Comparison of irrigation efficiency across regions

3.4 Tree Height and Stem Diameter Comparison

When examining the tree heights measured in different regions, the areas with the tallest average tree heights were Cinto 06 (416.3 cm), Cinto 05 (345.4 cm), and Cinto 04 (311.6 cm). Generally taller trees in these regions are likely associated with optimal irrigation conditions, sufficient soil moisture, and adequate plant nutrients. On the other hand, the shortest trees were found in the Hospicio 03 (179 cm), Hospicio 04 (184.4 cm), and Hospicio 02 (202.4 cm) regions. The low irrigation efficiency and challenges in accessing water in these regions may have negatively impacted tree growth, limiting their development. Additionally, inadequate soil structure and organic matter content could also be contributing factors. In conclusion, it was observed that trees in areas with high irrigation efficiency and suitable soil moisture levels exhibited healthier growth, while trees in regions with lower irrigation efficiency had relatively shorter heights (Figure 8).

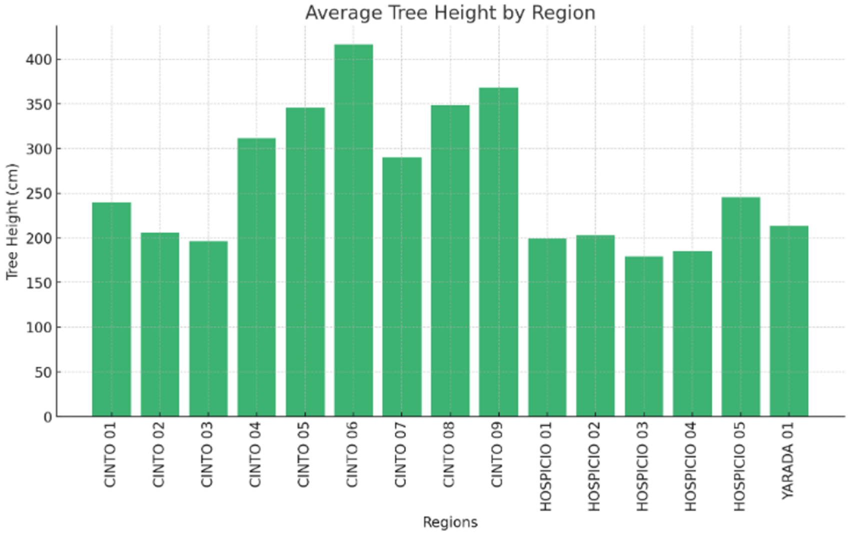

Fig. 8. Comparison of tree heights between regions

According to the data, the regions with the widest stem diameters were Cinto 06 (17.1 cm) and Cinto 04 (14.4 cm), while the trees with the narrowest stem diameters were found in Hospicio 04 (7.2 cm) and Cinto 03 (6.6 cm). These findings highlight that irrigation efficiency and soil moisture levels directly impact plant growth and productivity. In regions with high irrigation efficiency, trees were taller and more productive, while in areas with lower irrigation efficiency, tree development and fruit production were adversely affected. In this context, it is crucial to improve systems and review water management strategies, particularly in regions with low irrigation efficiency (Figure 9).

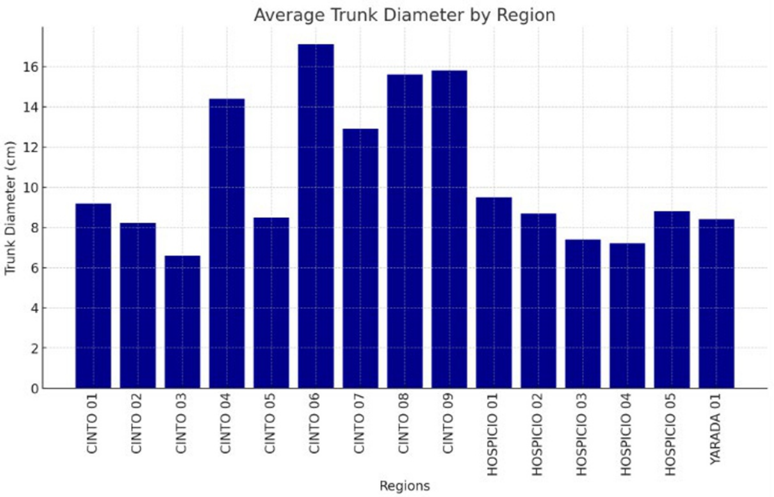

Fig. 9. Comparison of trunk diameter between regions

3.5 Plant Growth and Fruit Yield Comparison

In terms of fruit yield, the highest average fruit numbers were observed in Cinto 06 (195.8 fruits), Cinto 04 (183.3 fruits), and Cinto 09 (161.6 fruits). The high productivity in these areas is generally associated with appropriate irrigation management, high soil moisture, and healthy plant development. Particularly in the Cinto 06 region, where both high irrigation efficiency and optimal soil moisture levels were observed, this may have positively influenced fruit production.

On the other hand, the lowest fruit yield was recorded in the regions of Hospicio 01 (0 fruits), Hospicio 03 (2 fruits), and Hospicio 02 (10 fruits). The absence of fruit in Hospicio 01 suggests significant issues in tree development and potential shortcomings in agricultural management strategies. Furthermore, the low efficiency of irrigation systems and high-water stress in these regions may have limited the trees' ability to retain fruit. Overall, a strong relationship between fruit yield, irrigation efficiency, and plant growth was observed. In this context, it is recommended to improve irrigation strategies in low-performing regions and to enhance agricultural practices that support tree health (Figure 10).

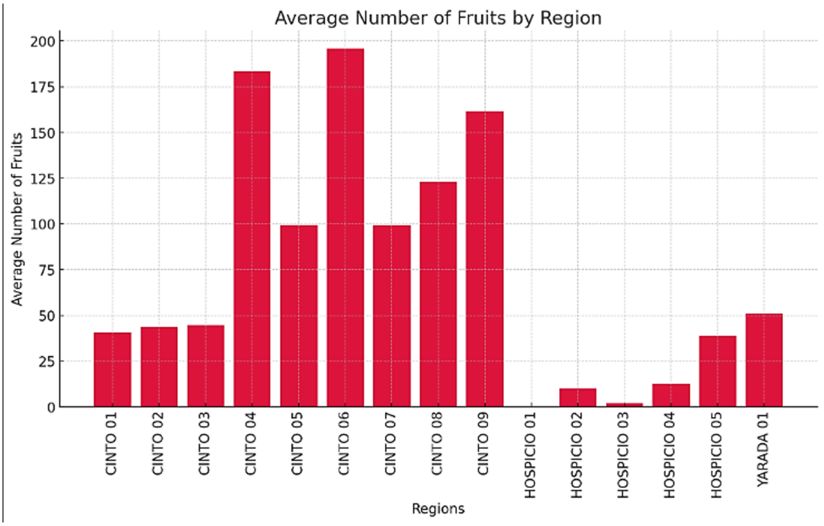

Fig. 10. Comparison of fruit yields between regions

In terms of regional productivity differences, considerable variation was observed across the avocado-growing zones of Tacna during the two consecutive seasons (Figure 11). Valle de Cinto consistently recorded the highest production values, with yields increasing from approximately 7,000 kg/ha in 2022–2023 to nearly 11,000 kg/ha in 2023–2024. This marked improvement, albeit with notable standard errors, may be attributed to more favorable environmental conditions or enhanced management strategies implemented during the second season. Pachía also exhibited high productivity, particularly in 2023–2024, though the low sample size (n = 1) for this site warrants cautious interpretation. Conversely, Hospicio and Yarada remained the lowest-yielding areas across both years, producing less than 1,000 kg/ha, suggesting persistent limitations in site-specific factors such as soil fertility or water availability. Calana and Higuerani showed intermediate levels of productivity with slight year-to-year increases. The observed variability between and within sites highlights the importance of localized agronomic interventions and underscores the need for more uniform data collection across sites to improve the reliability of regional yield comparisons.

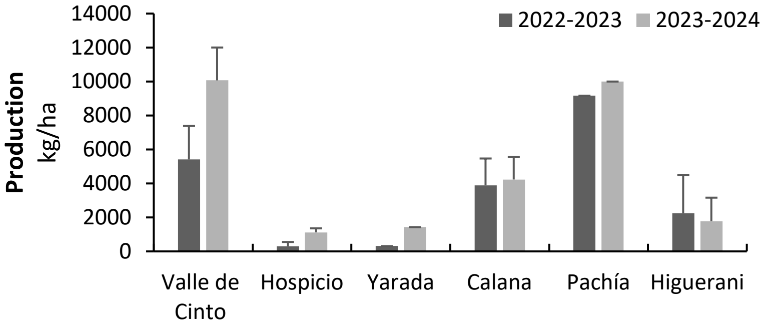

Fig. 11. Production (kg/ha) in avocado-growing areas of Calana, Hospicio, Pachía, Higuerani, Yarada, and Valle de Cinto (Tacna, Peru) during the years 2023 and 2024. Values are shown as mean ± standard error (n=3–9, except for Pachía and Yarada (n = 1)).

The average age of avocado orchards also varied across the studied locations in Tacna, potentially influencing yield performance and management practices (Figure 12). Calana had the oldest orchards, with a mean age exceeding 6.5 years, followed by Valle de Cinto, where orchards averaged approximately 6 years. These two locations, which also demonstrated higher yield levels (Figure 11), suggest a possible link between orchard maturity and productivity. In contrast, Hospicio and Yarada had the youngest orchards, averaging below 4.5 years, which may partially explain their lower production levels. Intermediate orchard ages were observed in Pachía and Higuerani, with mean values around 5–5.5 years. However, as noted previously, the limited sample size in some sites (e.g., Yarada and Pachía) necessitates cautious interpretation. Overall, the distribution of orchard age across sites underscores the heterogeneous development stages of avocado cultivation in the region and may have implications for future site-specific agronomic interventions.

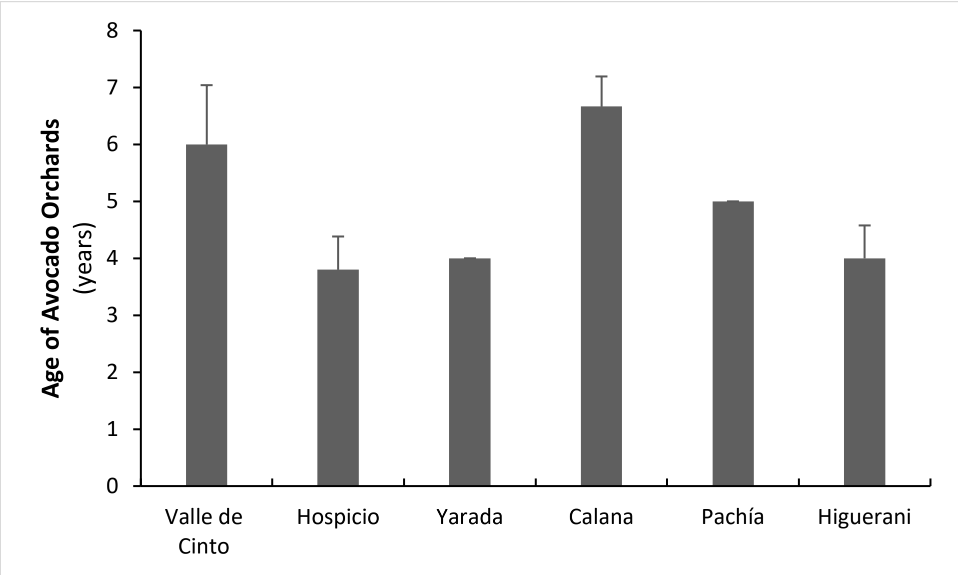

Fig. 12. Age of avocado orchards (years) in avocado-growing areas of Calana, Hospicio, Pachía, Higuerani, Yarada, and Valle de Cinto (Tacna, Peru) during the years 2023 and 2024. Values are shown as mean ± standard error (n=3–9, except for Pachía and Yarada (n = 1)).

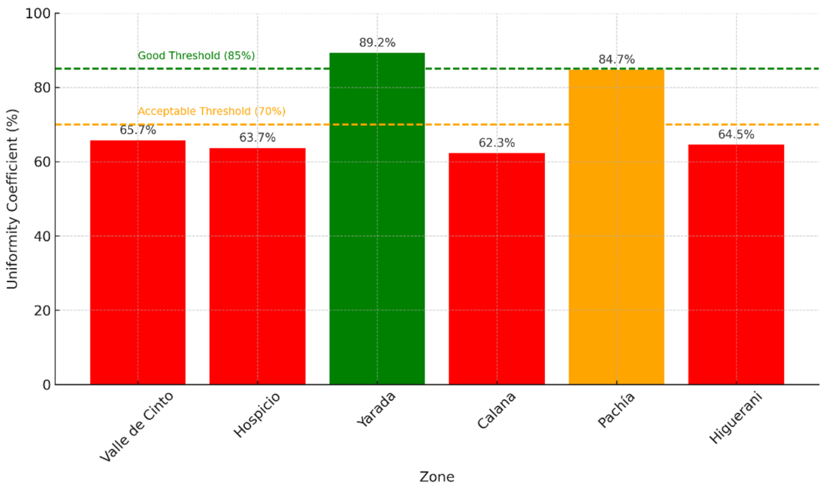

Fig. 13. Uniformity coefficient values across different irrigation zones. The orange and green dashed lines indicate the thresholds for acceptable (70%) and good (85%) performance, respectively. According to the classification, coefficients below 70% are considered unacceptable, values between 70% and 80% are poor, 80% to 86% acceptable, 86% to 94% good, and above 94% excellent. The color of each bar corresponds to its respective classification. Values are shown as mean ± standard error (n=3–9, except for Pachía and Yarada (n = 1)).

The Coefficient of Uniformity (CU) was assessed for six irrigation zones to quantify the spatial distribution efficiency of applied water. CU values represent the percentage uniformity in irrigation water application, with higher values indicating more homogeneous distribution and thus greater system performance (Figure 13). The measured CU values for Valle de Cinto (65.73%), Hospicio (63.68%), Calana (62.28%), and Higuerani (64.54%) fall below the critical threshold of 70%, thereby classifying these zones as "Unacceptable" in terms of irrigation uniformity (Figure 13). Such low CU values are indicative of significant spatial variability in water application, which may be attributed to factors including hydraulic deficiencies, improper system design, or operational malfunctions. This non-uniform water distribution potentially leads to under-irrigation and over-irrigation zones, negatively impacting crop water use efficiency, promoting stress conditions, and reducing overall yield potential (Figure 13). Pachía exhibited a CU of 84.70%, categorized as "Acceptable," reflecting moderate irrigation uniformity (Figure 13). This value suggests improved system functionality compared to the previously mentioned zones but still indicates non-negligible heterogeneity in water distribution that may warrant system optimization. Yarada demonstrated the highest CU value of 89.20%, classified as "Good." This indicates a relatively high level of uniform water application, which is critical for optimizing water use efficiency and maintaining agronomic productivity. None of the zones achieved the "Excellent" category (CU > 94%), underscoring the opportunity for performance enhancement across all areas (Figure 13). To address the observed deficiencies, it is recommended to conduct detailed hydraulic audits, assess emitter performance, and implement corrective maintenance and design adjustments. Enhancing uniformity in these irrigation systems is essential for sustainable water management and maximization of crop yield and quality.

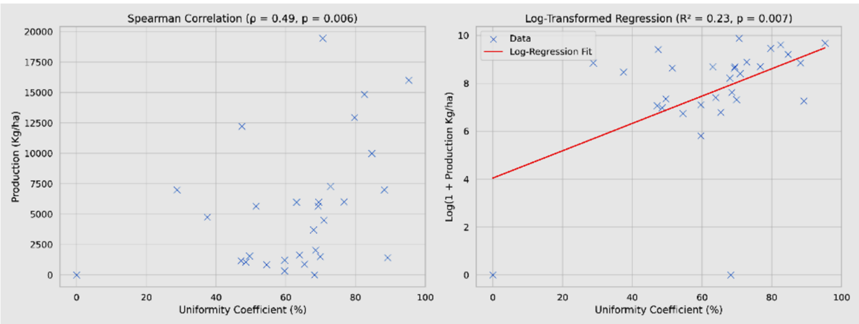

Fig. 14. Relationship between irrigation uniformity coefficient (%) and avocado yield (kg/ha). The left panel shows the Spearman correlation analysis, and the right panel displays a log-transformed linear regression model based on log(1 + yield).

3.6 Relationship Between Uniformity Coefficient and Yield

To explore the association between irrigation uniformity and crop yield, a series of statistical analyses were performed using the uniformity coefficient (C.U.) and production in kg/ha as variables. Figure 14 (left) presents the Spearman rank correlation analysis, which evaluates the monotonic relationship between the two variables. The results indicate a moderate and statistically significant positive correlation ($\rho = 0.49$, $p = 0.006$), suggesting that higher irrigation uniformity tends to be associated with increased yield. Figure 14 (right) shows a linear regression performed on the log-transformed yield data (log(1 + kg/ha)) to stabilize variance and account for skewness. This model produced a stronger correlation than the linear regression on raw yield data, with an R^2 value of 0.23 and a statistically significant slope ($p = 0.007$). These results suggest that the relationship between irrigation uniformity and yield may follow a nonlinear trend that is better captured using a logarithmic transformation. Taken together, these findings highlight that irrigation uniformity has a meaningful impact on yield, especially when analyzed using robust statistical techniques like nonparametric correlation and log-transformed modeling.

4 DISCUSSION

The present study investigated the interaction between soil characteristics, irrigation system performance, and agronomic outcomes in Hass avocado orchards across multiple locations in the Tacna region of Peru. The results underscore the complexity of managing avocado production in arid and semi-arid conditions, where soil fertility, water availability, and irrigation infrastructure directly influence productivity.

4.1 Soil Properties and Management Implications

The analysis of soil chemical and physical properties revealed significant spatial and temporal heterogeneity across sites. Particularly low organic matter content and high sand fractions in most soils point to limited water-holding capacity and poor fertility, which can restrict nutrient availability and root development. These findings align with earlier studies that highlight organic matter depletion and sandy soils as common constraints in arid agricultural systems [36, 37]. The elevated electrical conductivity values in Pachía suggest localized salinity issues that may impair plant growth if not addressed, consistent with known salinity challenges in semi-arid horticulture [38]. Hence, targeted soil management such as organic amendments and salinity mitigation practices are essential.

4.2 Cation Exchange Capacity and Nutrient Dynamics

Variability in CEC and exchangeable bases correspond with soil texture differences; clay-rich soils like those in Higuerani demonstrated higher nutrient retention, supporting improved avocado growth, as also reported by Brady et al. (2008) [39]. While base saturation was generally high, the slightly lower values in Calana may indicate acidic cation presence affecting nutrient availability [40].

4.3 Irrigation Efficiency and Its Agronomic Impact

A key finding was the significant relationship between irrigation system performance and avocado productivity. Regions with efficient and uniform irrigation exhibited superior tree growth and fruit yields, confirming the critical role of optimized water management in avocado production [28]. The positive correlation between irrigation uniformity coefficient and yield aligns with previous research highlighting yield penalties due to uneven water application [41].

4.4 Influence of Orchard Age and Developmental Stage

Orchard age appeared to influence yield potential, consistent with the literature showing mature trees generally achieve higher productivity [42]. Younger orchards in lower-yield zones may not have reached full productive capacity, with management and environmental factors also playing roles.

4.5 Limitations and Future Directions

Limitations include the absence of a formal control group and limited sample sizes in some areas, restricting the ability to draw definitive causal conclusions. Future research incorporating larger, balanced sampling and advanced tools like remote sensing and precision agriculture would strengthen understanding and provide actionable insights [43, 44].

In summary, this study reaffirms the importance of integrated soil and water management for improving avocado yield and sustainability in arid regions. Addressing irrigation inefficiencies and soil fertility constraints through localized agronomic strategies can enhance productivity and resource-use efficiency in Tacna and similar environments.

5 CONCLUSION

This study provided a comprehensive evaluation of the agro-environmental and technical factors influencing Hass avocado production in the Tacna region of Peru. The findings emphasize the crucial interplay between soil characteristics, irrigation performance, and plant productivity. Notable spatial and temporal variability was observed in key soil parameters, including pH, salinity, organic matter content, and cation exchange capacity, underscoring the need for site-specific soil management strategies.

Irrigation system performance varied significantly across regions, with some zones demonstrating high efficiency and uniformity, while others showed critical deficiencies. These discrepancies directly impacted tree growth parameters such as height and stem diameter, as well as fruit yield. Regions with higher irrigation efficiency and better soil moisture retention, particularly Valle de Cinto and parts of Cinto, consistently outperformed others in terms of growth and productivity.

Statistical analysis confirmed a positive and significant relationship between irrigation uniformity and yield, highlighting the importance of hydraulic optimization for sustainable production. Furthermore, the correlation between orchard age and productivity suggests that developmental stage also plays a role in yield potential.

Overall, the results stress the necessity of integrated water and soil management practices, targeted infrastructure improvements, and localized agronomic interventions to enhance yield and resource-use efficiency. Addressing these challenges can contribute to the long-term sustainability and profitability of avocado cultivation in arid and semi-arid environments like Tacna.

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Competing Interests. The authors declare that they have no competing interests.

Ethical Approval. This study did not involve any experiments on humans or animals, and therefore, ethical approval was not required.

Consent to Participate. Not applicable.

Consent to Publish. All authors have reviewed the final manuscript and consent to its publication.

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