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Transformation of Terraces with Irrigation Systems: Profitability and Water Savings in Potato Crop (*Solanum tuberosum* L.)

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Abstract: In recent decades, climate change has intensified the challenges in agriculture, increasing the incidence of water and heat stress during critical stages of the crop cycle. It includes the exacerbation of the seasonality of rainfall and temperature. This significantly affects their development and yield. In addition, climate change has reduced irrigation water availability, highlighting the need to evaluate joint strategies to increase water productivity. These strategies include the implementation of irrigation systems, the use of terraces, and the application of deficit irrigation (DI). In this context, the present research aims to evaluate the irrigation water productivity (WP_{irri}) and the economic water productivity (EWP) of the combined use of DI through a pressurized irrigation system in terraces of the southern highlands of Peru for a potato crop. The treatments included L0: traditional surface irrigation with irrigation depth equivalent to 100% ETc, L1: drip irrigation with irrigation depth equivalent to 100% ETc, L2: drip irrigation with DI at 75% ETc, and L3: drip irrigation with DI at 50% ETc. The DI treatments (L2 and L3) were implemented by forming stolons (60 DAS). As a result, L2 allows saving irrigation water of 3930 $m^3\ ha^{-1}$ compared to L0 and 1164 $m^3\ ha^{-1}$ compared to L1. It means a WP_{irri} of 6.15 ± 0.35 $kg\ m^{-3}$ allowing a commercial yield (CY: 27.15 ± 1.47 $t\ ha^{-1}$) statistically similar to L1 (WPirri: 5.45 ± 0.34 $kg\ m^{-3}$; CY: 30.14 ± 1.83 $t\ ha^{-1}$) and higher than the traditional surface irrigation (WP_{irri}: 2.63 ± 0.23 $kg\ m^{-3}$; CY: 21.62 ± 1.99 $t\ ha^{-1}$). This water saving meant a net income of 3097.04 ± 435.52 USD ha^{-1} for L2, close to L1 (4421.12 ± 724.24 USD ha^{-1}), and much higher than L0 (1664.50 ± 834.24 USD ha^{-1}). The results suggest that using drip irrigation systems in terraced crops optimizes water savings, maintains yields and profitability, and could promote the modernization of terraces in rural environments.

Keywords: deficit irrigation; water productivity; terraces; economic water productivity

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1. Introduction

Potato (*Solanum tuberosum* L.), a native species from the high Andean region of South America [1], is currently produced in various latitudes, and it is considered the fourth most produced staple product in the world [2,3]. Its nutritional characteristics and widespread consumption are why it is considered an important crop that underpins food security in several countries [2]. In 2022, Peru produced more than 6 million tons of potatoes, covering 1.61% of the world's production volume and establishing itself as the leading potato producer in Latin America [4]. Although an estimate of 4000 varieties can be found in Peru [5], most of the commercial production prioritizes conventionally bred white-fleshed cultivars and native yellow-fleshed varieties [6], reaching 61.9% of the cropping area of this country [7]. In a complementary and small-scale manner, the cultivation of native colored-fleshed potatoes has been developed, standing out for its high biodiversity but weak connection to the national and regional market [8]. Historically, these varieties have been grown and preserved in family and subsistence farming systems, forming an essential part of the Andean population's diet [3]. In recent years, their nutritional, aesthetic, and cultural potential has been unlocked, stimulating the growth of their demand and price in the market [6]. However, on a small scale, technological and institutional limitations persist. This situation has prevented the offer from meeting the demand for this product. Apart from that, the environmental vulnerabilities of dryland agriculture have not been properly reduced (climate, edaphic, and topography risks) [6].

In response to terrain challenges, Andean settlers developed technological alternatives such as constructing terraces (called 'Andenes' in pre-Hispanic cultures) [9]. These allowed the expansion of cropping areas in hillside environments, reducing the effects of erosive processes and generating microclimates, which helped cultivated species adapt to higher areas [10]. However, changes in demographic and climate patterns since colonial times led to the abandonment and lack of maintenance of vast terraced areas in the Andes [10]. It was estimated that Peru could have around 500 thousand hectares of terraces. Around 259 thousand ha are used, cultivating mainly alfalfa, starchy corn, and potatoes [11]. Production occurs mostly between November and May following the rainy season [3]. In cases where water is available for irrigation, it is complementarily applied by surface irrigation techniques [12].

The current context of climate change determines the exacerbation of seasonal patterns such as extreme precipitation events and reaching historical high and low temperatures. For the southern part of Peru, a decrease in annual precipitation volumes is expected, with more intense rains and shorter wet seasons [13]. This would aggravate the vulnerability of dryland agricultural systems to water erosion during the wet season [14] and to water stress during dry periods [15]. Given this, terrace use can be considered a local adaptive measure to improve water productivity by allowing the preservation of biodiversity in different altitudes and improving the ecosystem services that promote erosion control [16]. These interventions must be conceived and developed considering a basin management approach to guarantee their articulation with the whole hydrological system [11]. Therefore, utilizing irrigation patterns that enhance productivity and employing water distribution techniques to minimize unused water in terraces could alleviate demographic pressure in areas with physical vulnerabilities [16], ensuring the ongoing use and maintenance of terraces.

The sustainable management of resources implies their rational use in a manner that ensures the conservation of the associated ecosystems. In this context, the sustainable use of water resources in agriculture involves achieving higher crop yields while minimizing water usage, thereby positively impacting the farmer's economic outcomes. Consequently, Water Productivity ($kg \cdot m^{-3}$) and Economic Water Productivity (EWP, $USD \cdot m^{-3}$) are crucial indicators for evaluating the sustainability of agricultural water use [17]. These metrics facilitate improved planning in water-scarce regions by highlighting the relationship between output and resource use. Therefore, their analysis must account for the spatial and temporal variability of water availability, particularly in environments where irrigation is the primary factor influencing crop yield [18]. In response to these challenges, various technologies have been developed to enhance the management of irrigation systems, including the conveyance, distribution, and application of water, as well as optimizing the timing and frequency of irrigation. Thus, pressurized irrigation systems are presented as a reliable alternative to improve water productivity [19–21]. It allows the conduction of water without losses due to evaporation or infiltration, the application of water in a localized manner in the root zone of the crop, work with fertigation, reducing losses due to surface runoff, and the control of application volumes [22].

However, among the main limitations are the costs of the initial investment required, management and operation costs, etc. [23]. In addition, research and methodological proposals have been developed around water-saving strategies to control irrigation times, such as deficit irrigation (DI) [24]. DI applies water during crop growth stages that are most susceptible to water stress. Shifting the focus to reducing or omitting irrigation during non-critical growth stages provided that rainfall supplies the minimum water requirements [24]. Implementing deficit irrigation can bring potential reductions in crop yield, but this can be offset by increased water productivity, thus allowing a potential increase in irrigated crop areas [25]. Operationally, its application may incur increased operating costs linked to the management of the irrigation system or investment costs linked to the automation of the irrigation system [26]. Therefore, it is necessary to conduct performance evaluations of these technologies, including the optimization of irrigation depths and the farmer's profitability, which implies market considerations in terms of commercial yields and operating costs [18].

Although extensive literature supports the benefits of using deficit irrigation through the management of pressurized irrigation systems, it is necessary to evaluate the technical-economic viability of its implementation at the local level [22]. In addition, to ensure the success of these technologies, it is crucial to implement farmer-oriented training and technology transfer programs focused on the design, operation, and maintenance of irrigation systems and efficient management of water and nutrients [27]. This would allow validating the adaptability of these technologies to the production of promising crops in terms of their market demand and their importance for food security. In this sense, the objective of the research is to evaluate the effect of the joint use of deficit irrigation applied through a pressurized drip irrigation system implemented on a terrace system for the cultivation of native potatoes, considering water productivity and economic profitability.

2. Materials and Methods

2.1. Study Area

The research was developed at the Cuyay Experimental Center of the National Institute of Agrarian Innovation (INIA) located in the Cuyay hamlet, Chuquibamba district, Condesuyos province, Arequipa region, Peru. The experimental plot was installed at 15°50′0.3″ S, 72°37′5.2″ W, at 2800 m above sea level (Figure 1). The study area has an average annual rainfall of 199.1 mm. Most precipitation events occur between January and March (179.9 mm accumulated), while the rest of the year is dry and cold. Minimum temperatures vary between 4.4 °C and 7.8 °C, and maximum temperatures range between 21.8 °C and 22.4 °C. Historical averages were calculated from data from the Chuquibamba meteorological station (15°50′45.65″ S, 72°39′2.32″ W, 2859 m.a.s.l.) of the National Meteorological and Hydrological Service of Peru (SENAMHI). To obtain daily meteorological records during the research (September 2023–March 2024), a Davis Vantage Pro 2 meteorological station (15°49′58.80″ S, 72°37′47.42″ W) was installed adjacent to the experimental plot (Figure 2). The geography of the study area is rugged, so agriculture is mainly developed on terraces with shallow soils. The terraces of Chuquibamba usually have widths between 3–7 m and lengths of up to 50 m, managed with surface irrigation or dry land systems depending on water availability. The predominant crops are corn, potato, alfalfa, barley, quinoa, squash, and kiwicha. It is not known precisely when and by whom they were built; however, they could be an inheritance of the Huari culture from the beginning of the Middle Horizon (615–695 AD) and perfected or reused by the Incas during the late stage of the Late Intermediate Period (1200–1400 AD) [28]. Today, the locals use them frequently as part of their agricultural practices, and their maintenance is part of local cultural work.

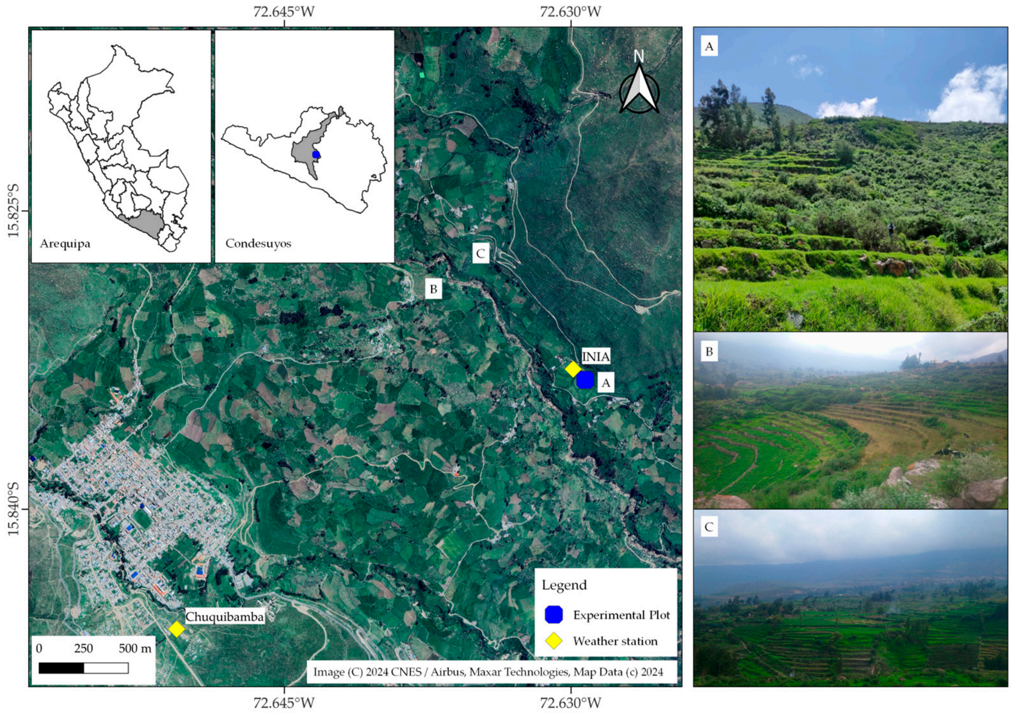


Figure 1. Study area in Condesuyos Province, Arequipa region, Peru. Some photographs from around the experimental plot are on the right side (A, B, C).

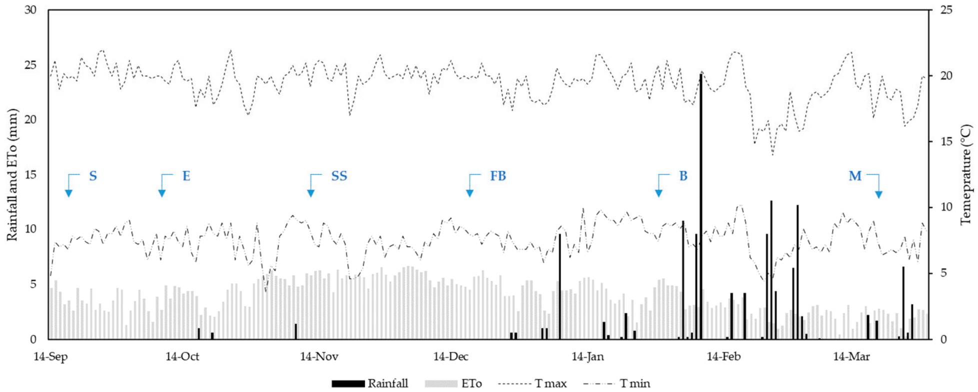


Figure 2. Daily meteorological parameters obtained during the potato season. Phenological stages are represented: sowing (S), emergency (E), side shoots (SS), floral button (FB), bloom (B), and maturity (M). ETo: potential evapotranspiration. Tmax: maximum temperature. Tmin: minimum temperature.

2.2. Experimental Design

A split-plot design with a 3 × 4 factorial arrangement was used. The main plot was defined by the location of terraces (A1: upper platform; A2: middle platform; A3: lower platform) and the subplot by different irrigation treatments based on crop evapotranspiration (ETc) (L0: surface irrigation with irrigation depth equivalent to 100% ETc; L1: drip irrigation with irrigation depth equivalent to 100% ETc; L2: drip irrigation with irrigation depth equivalent to 75% ETc; L3: drip irrigation with irrigation depth equivalent to 50% ETc). The design included 3 blocks comprising 36 experimental units (Figure 3). Each experimental unit had an area of 7.68 m^2 (2.4 m × 3.2 m). The planting spacing was 0.95 m between furrows and 0.25 m between plants [29] (plant density 42,105 plants·ha^{-1}).

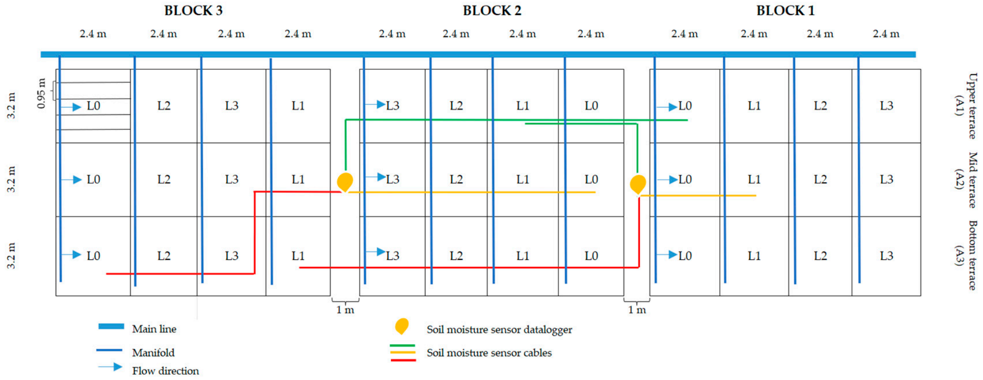


Figure 3. Layout of experimental units. L0, L1, L2, and L3: levels of the irrigation treatment applied.

2.3. Physical, Hydraulic, and Chemical Characteristics of Soils

Before installation, composite samples of the topsoil layer from each platform were collected at a depth of 0.30 m, where approximately 85% of the root length is concentrated [30,31]. The samples were entered into the Soil, Water, and Foliar Laboratory (LABSAF)—INIA Arequipa for physical and chemical characterization: texture [32], pH [33], electrical conductivity [34], organic matter (OM) [32], total N [35], available P [32], available K^+ [36], exchangeable cations (Ca^{+2}, Mg^{+2}, Na^+) [32], carbonates [32]. Additionally, undisturbed samples were extracted in metal core samplers (0.034 m length, 0.061 m diameter, 100 cm^3 sample volume) to calculate the soil bulk density by the cylinder method [37] at LABSAF-INIA and the water constants (i.e., field capacity (FC) and permanent wilting point (PWP)) at the Water and Soil Laboratory of the Faculty of Agricultural Engineering of the Universidad Nacional Agraria La Molina using the Richards pressure plate equipment [38]. The results of the soil characterization are shown in Table S1.

2.4. Conducting the Experimental Plot

The experimental plot was installed between September 2023 and March 2024 following the cropping calendar of local producers. Before its implementation, a drip irrigation system was installed, and an existing 300 m^3 geomembrane reservoir was given maintenance. The height difference between the reservoir and the entrance to the experimental field was 20 m. The main line was sized at 50 mm HDPE-SDR 21-PE 100, and the manifold (within each experimental unit) at 32 mm HDPE-SDR 21-PE 100. At the entrance to the field, a fertigation system via a Venturi-type injector ½″ (Hydro Environment, Tlalnepantla, Mexico) was implemented for pressurized irrigation treatments. Plots with the treatment of surface irrigation received basal fertilization. The valve manifolds were independent for each experimental unit, considering a manual control valve, air valves, and manometric control points. Two driplines were installed per crop row using Eolos 16 mm nominal diameter class 5000 with drippers of nominal flow rate 2.2 L·h^{-1} (nominal pressure 100 kPa) spaced every 0.20 m (Rivulis Irrigation, Ltd., Inofyta, Greece). The surface irrigation treatment units had a manual control valve that discharged directly into the upper platform inlet.

The land was left fallow for 4 years, plowed, turned over, and furrowed using tractor-powered implements. All subsequent agricultural work was carried out manually. After plowing, seeds of *Solanum tuberosum* L. cv. Imilla negra were sown. Based on the physical and chemical characterization of the soil (Table S1), the fertilizer application rate was calculated: 120–80–10 kg·ha^{-1} of N–P–K using ammonium nitrate, monoammonium phosphate, and potassium nitrate applied weekly via fertirrigation from the beginning of the branching stage for the treatments with pressurized irrigation. In the units with surface irrigation, soil application was carried out by distributing 60% of the fertilizer at sowing and the remaining 40% in the hilling (75 days after sowing (DAS). Pest and disease management included two applications (64 DAS and 75 DAS) of cymoxanil + mancozeb to control *Phytophthora infestans*, *Alternaria solani*, and *Rhizoctonia solani*; and three applications (73 DAS, 85 DAS, and 99 DAS) of methomyl and alpha-cypermethrin to control *Russelliana solanicola* and *Premnotrypes* spp. Manual harvest was performed at 187 DAS.

2.5. Irrigation Management

The first irrigation was applied immediately after sowing. Subsequently, irrigation was applied every 7 days at 100% ETc until 60 DAS. From this point on, the irrigation rates (LR) were applied according to the distribution of proposed treatments, maintaining the weekly irrigation frequency (L0: surface irrigation with irrigation depth equivalent to 100% ETc; L1: drip irrigation with irrigation depth equivalent to 100% ETc; L2: drip irrigation with irrigation depth equivalent to 75% ETc; L3: drip irrigation with irrigation depth equivalent to 50% ETc). The Irrigation Depth (ID) was calculated according to the soil water balance formula proposed by Allen et al. [39].

$$\mathrm{ID} = \mathrm{ETc} - \mathrm{Pe} \tag{1}$$

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc} \tag{2}$$

where ETc is the crop evapotranspiration (mm), Pe is the effective precipitation (mm), ETo is the reference crop evapotranspiration (mm), and Kc is the crop coefficient. Pe was calculated according to the USDA methodology [40]. The ETo value was calculated with the Penman-Monteith equation modified by FAO [39] from the climatic data recorded by the meteorological station installed in the surroundings of the experimental plot. The Kc varied according to the development of the potato crop, as stated by Doorenbos and Kassam [41]. After the beginning of the rainy season, approximately at 168 DAS until the harvest at 187 DAS, the crop water requirement was covered by rainfall, so the restricted layer treatments could not be applied. Six soil moisture sensors (ZL6 Basic data logger with soil moisture sensors Teros-10; METER Group, Munich, Germany) were installed at 0.30 and 0.60 m depth in the surface irrigation plots (L0) and 100% ET drip irrigation plots (L1) to monitor moisture content, as shown in Figure 2.

2.6. Determination of Biometric Variables and Performance Components

Plant height (cm) was measured every 7 days from the beginning of flowering (75 DAS), for which four representative plants were selected per experimental unit. Using a 3.5 m measuring tape, the height from the neck to the apex of the plant's stem was measured. Additionally, during the harvest, four representative plants were selected per experimental unit from which the root depth (cm), fresh weight (g), and dry weight (g) of the aerial and root parts were measured using an oven (75 °C until a stable weight was observed). The four previously selected plants were used to determine the yield components. The number of tubers per plant was counted, and tuber yield was categorized according to traditional local criteria based on tuber weight. First category (C1, tuber weight > 81 g), second category (C2, tuber weight between 41–80 g), and third category (C3, tuber weight < 40 g). The yield of each category was quantified and expressed in tons per hectare ($\mathrm{t{\cdot}ha^{-1}}$). Commercial yield (CY) ($\mathrm{t{\cdot}ha^{-1}}$) was calculated from the sum of the accumulated weights of C1 and C2. According to local practices, third-category tubers were used for personal consumption and/or feed for small animals. Tuber dry weight (g) was used to calculate the percentage of dry matter. The Harvest Index (HI) was also calculated (defined as the ratio between the fresh weight of tubers and the total fresh weight at harvest). An electronic balance was used to weigh the samples (Type: Electronic precision balance 5000 g, 0.01 g XingYun JA 5000C).

2.7. Water Productivity

The water productivity is an indicator that relates the actual yield achieved and the water use to produce it [17]. The water use can be based on the total used water (which includes rainfall and irrigation) or the water applied only by irrigation. Based on Pereira et al. [42], we calculated the Water Productivity ($\mathrm{WP_{irri}}$, kg $\mathrm{m^{-3}}$) and the Irrigation Water Productivity (WP, kg $\mathrm{m^{-3}}$) for each treatment:

$$\mathrm{WP} = \frac{\mathrm{Y_a}}{\mathrm{TWU}} \tag{3}$$

$$\mathrm{WP_{irri}} = \frac{\mathrm{Y_a}}{\mathrm{IWU}} \tag{4}$$

$\mathrm{Y_a}$ is the actual crop's commercial yield (kg·$\mathrm{ha^{-1}}$), IWU ($\mathrm{m^3\ ha^{-1}}$) is the irrigation water used throughout the entire campaign, and TWU ($\mathrm{m^3\ ha^{-1}}$) refers to the total water use, including the rainfall throughout the phenological development of the crop.

2.8. Profitability of Cultivation

The cost of production and the profitability rate for the different proposed treatments were examined, considering the data from the local agricultural market in the province of Chuquibamba, Arequipa. The profitability rate, defined as the amount of money received after covering the production costs [43], was calculated based on the net income and the total cost:

$$\mathrm{Profitability} = (\mathrm{NI}/\mathrm{TC}) \tag{5}$$

$$\mathrm{NI} = \mathrm{TI} - \mathrm{TC} \tag{6}$$

where NI represents Net Income, TI is Total Income, and TC is Total Cost. Total cost (TC) was determined by summing all production costs incurred throughout the crop cycle [44]:

$$\mathrm{TC} = \mathrm{DC} + \mathrm{IC} \tag{7}$$

where DC represents direct costs (i.e., machine hours or labor for land preparation, seed tuber, planting tasks, cultural tasks, reservoir and irrigation system maintenance, laying of irrigation lines, irrigation management, fertilization, phytosanitary control, harvest, land rental, mobility, and unforeseen events); and IC, indirect costs included financial expenses only (13.3% DC). Our analysis did not include the costs of installing irrigation infrastructure or equipment depreciation. However, costs associated with maintaining a pre-existing irrigation system were included (i.e., reservoir maintenance, network cleaning, and drip line laying). Regarding units with surface irrigation, the cost of aqueduct cleaning was assumed.

Total income (TI) for each experimental unit was calculated by multiplying the yield of each category of marketable potato tubers by their respective local market price at the time of harvest:

$$\mathrm{TI} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{R_i} \times \mathrm{P_i}) \tag{8}$$

where $\mathrm{R_i}$ is the yield of marketable potato tubers of category i, $\mathrm{P_i}$ is the local market price for category i at harvest, and n is the number of marketable potato tubers of category i. The local market price for C1 was 1.6 PEN·$\mathrm{kg^{-1}}$ (0.421 USD), and for C2, 1.00 PEN·$\mathrm{kg^{-1}}$ (0.263 USD). All monetary values were collected in the Peruvian national currency, the Sol

(PEN); however, they were reported in USD (1 USD = 3.8 PEN). The local cost of daily wages for heavy work (i.e., reservoir cleaning and planting), generally performed by men, was 90 PEN·day^{-1}. For other tasks, which both men and women can perform, the daily wage was 80 PEN·day^{-1}. The hourly rental price for a 96 HP tractor was 150 PEN·h^{-1}. The calculated values were extrapolated to the value of PEN per ha^{-1}.

2.9. Economic Water Productivity

Observing the WP under an economic perspective, the Economic Water Productivity (EWP) relates the monetary value of the achieved yield and the water used [42]. Based on [17], we calculate the economic water productivity (EWP, USD m^{-3}):

$$\mathrm{EWP} = \frac{\mathrm{NI}}{\mathrm{IWU}} \tag{9}$$

where NI represents Net Income (reported in USD·ha^{-1}), and IWU (m^3 ha^{-1}) is the irrigation water used throughout the entire campaign.

2.10. Statistical Analysis

The Analysis of variance (ANOVA) was performed using InfoStat (version 2020) [45] to evaluate the main effects and significance of the interaction. The Tukey test ($\alpha = 0.05$) was applied to compare means between the factor levels. The Shapiro–Wilk test (normality) and Bartlett's test (homoscedasticity) corroborated the model's assumptions.

3. Results

3.1. Effect on Biometric Characteristics of Potato

Except for plant height, the biometric parameters evaluated showed significant differences for the main effect of the irrigation factor but not for the platform factor or the interaction. Thus, the fresh weight of the aerial part of the L0, L1, and L2 treatments presented values statistically higher than the L3 treatment, without presenting significant differences between them, but with a higher average for L1 (Figure 4). However, it was observed that L2 stood out with a higher average dry aerial biomass, followed by the treatments with irrigation equivalent to 100% ETc (L0 and L1) and widely differentiated from L3. No significant differences were observed regarding root depth.

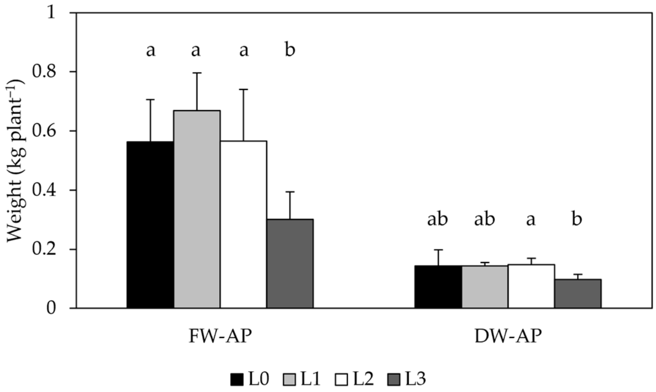
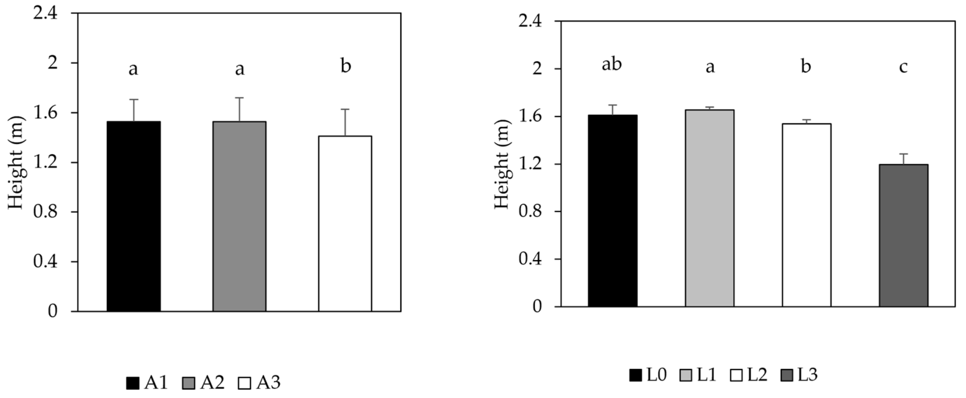


Figure 4. Potato aerial part weights at harvest. FW-AP: fresh weight of the aerial part. DW-AP: dry weight of the aerial part. L0, L1, L2, and L3: levels of the irrigation treatment applied. Different letters in each testing parameter represent statistical significance among groups at $p < 0.05$ for the Tukey test.

On the other hand, taller plants were observed for the upper and middle platforms compared to the lower platforms. In addition, the L1 treatment, with the highest theoretical water application efficiency, presented taller plants with values similar to L0. Consecutively, the decrease in irrigation depths was reflected in a decrease in the average height of the crop (Figure 5).



(**a**) (**b**)

Figure 5. Plant height at harvest. (**a**) Analysis by platform. (**b**) Analysis by irrigation treatment applied. L0, L1, L2, and L3: levels of the irrigation treatment applied. A1, A2, and A3 are upper, middle, and lower platforms, respectively. Different letters in each testing parameter represent statistical significance among groups at $p < 0.05$ for the Tukey test.

3.2. Effect on Potato Yield

Statistical significance was observed only for the irrigation factor. The highest fresh yields were achieved with drip irrigation at 100% ETc and 75% ETc (Figure 6). Although 100% ETc was applied in L0, the fresh yield was lower than with reduced irrigation depth applied by drip (L2). However, these differences were not maintained when analyzing dry weights of the harvested tubers, and no statistical differences were observed in the number of tubers per plant according to treatment. After categorizing the tubers by weight (Table 1), it was observed that the effect of irrigation was statistically different only in the first category (C1), where L1 stood out with the highest values. The 75% ETc irrigation treatment achieved yields similar to those of the control (L0) despite requiring a lower volume of water. For the second category (C2), a tendency to obtain higher yields was observed with reduced depth irrigation but applied in a localized manner (L2). The third category (C3) presents higher values related to irrigation with a higher total volume of water applied to the field. Thus, the commercial yield of L1 is significantly higher than the other treatments. Furthermore, a non-significant trend of L2 values lower than L1 and higher than L0 was observed. The L3 treatment achieved commercial yields around 50% of the best treatment.

Table 1. Potato yields according to commercial categorization.

Treatments	C1 (t ha $^{-1}$)	C2 (t ha $^{-1}$)	C3 (t ha $^{-1}$)	Y (t ha $^{-1}$)	CY (t ha $^{-1}$)
L0	11.12 ± 2.05 ^{bc}	10.51 ± 0.74 ^{a}	10.99 ± 1.76 ^{a}	32.61 ± 1.82 ^{ab}	21.62 ± 1.99 ^{bc}
L1	18.04 ± 1.84 ^{a}	12.1 ± 1.31 ^{a}	9.88 ± 0.90 ^{a}	40.02 ± 2.01 ^{a}	30.14 ± 1.83 ^{a}
L2	14.64 ± 0.69 ^{ab}	12.51 ± 1.34 ^{a}	11.05 ± 1.38 ^{a}	38.2 ± 2.40 ^{a}	27.15 ± 1.47 ^{ab}
L3	5.66 ± 0.79 ^{c}	11.33 ± 1.17 ^{a}	8.66 ± 0.64 ^{a}	25.66 ± 1.58 ^{b}	16.99 ± 1.48 ^{c}

C1: first category (tuber weight > 81 g); C2: second category (tuber weight 41–80 g); C3: third category (tuber weight < 40 g); Y: total yield; CY: commercial yield (C1 + C2). L0, L1, L2, and L3: levels of the irrigation treatment applied. Different letters in each testing parameter represent statistical significance among groups at $p < 0.05$ for the Tukey Test.

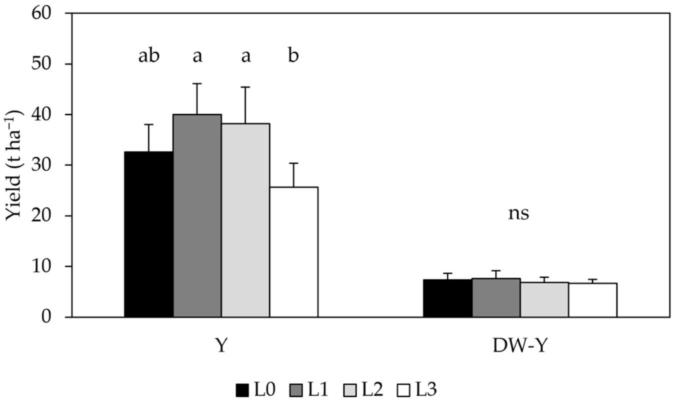


Figure 6. Fresh and dry potato yields according to irrigation treatment. Y: fresh yield. DW-Y: dry yield. L0, L1, L2, and L3: levels of the irrigation treatment applied. ns: indicates not significant ($p > 0.05$); different letters in each testing parameter represent statistical significance among groups at $p < 0.05$ for the Tukey test.

3.3. Crop Water Productivity

Drip irrigation treatments generated savings in water consumption compared to surface irrigation treatment (L0, 8296.5 $m^3 \cdot ha^{-1}$) of 33%, 47%, and 61% for L1 (5531.0 $m^3 \cdot ha^{-1}$), L2 (4366.7 $m^3 \cdot ha^{-1}$), and L3 (3202.5 $m^3 \cdot ha^{-1}$), respectively. Additionally, deficit irrigation treatments achieved additional savings compared to full irrigation (L1), reaching 22% and 44% water reductions for treatments L2 and L3, respectively. In this sense, the treatments where irrigation was applied through drip systems presented the highest Irrigation Water Productivity (WP_{irri}), highlighting the tendency to obtain a better result with a reduced depth of 75% ETc (L2, 6.15 ± 0.35 $kg \cdot m^{-3}$) over a more (L3: 50% ETc, 5.41 ± 0.41 $kg \cdot m^{-3}$) or less (L1: 100% ETc, 5.45 ± 0.34 $kg \cdot m^{-3}$) restrictive management (Figure 7). The Water Productivity (WP) displayed a similar pattern, with treatments using drip irrigation (L1, L2, L3) outperforming the gravity irrigation treatment (L0, 2.36 ± 0.21 0.34 $kg \cdot m^{-3}$). No significant differences were found between the WP of L1 (4.66 ± 0.29 $kg \cdot m^{-3}$), L2 (5.06 ± 0.22 $kg \cdot m^{-3}$), and L3 (4.18 ± 0.32 $kg \cdot m^{-3}$), with L2 maintaining the highest water productivity. The accumulated rainfall (939 $m^3 \cdot ha^{-1}$) represented a larger proportion of the total water used by the deficit irrigation treatments (L2: 17.7%; L3: 22.7%). In this regard, the difference between WP and WP_{irri} was greatest for L3 and L2. The numerical data are also presented in Table S2.

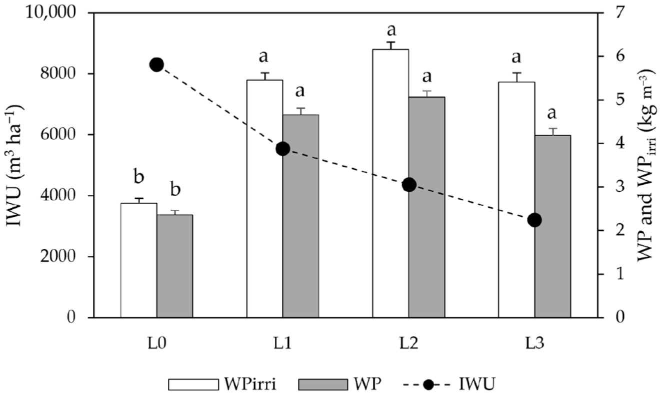


Figure 7. Applied irrigation water and water productivity per treatment. L0, L1, L2, and L3: levels of the applied irrigation treatment. WP: water productivity. WP_{irri}: irrigation water productivity. IWU: irrigation water use. L0, L1, L2, and L3: levels of the irrigation treatment applied. Different letters above each water productivity represent statistical significance among groups for the same parameter at $p < 0.05$ for the Tukey test.

3.4. Crop Economic Profitability

The profitability results (Table 2) during tuber harvest varied between the irrigation systems implemented, where L1 was statistically different from L0. Regarding deficit irrigation, it was found that 75% drip irrigation (L2) showed no significant difference with full drip irrigation (L1); however, these treatments are superior to 50% deficit drip irrigation (L3). The latter generated a loss of invested capital.

Table 2. Profitability indices, production cost components, revenues, and economic water productivity.

Parameters		L0	L1	L2	L3
Costs for agronomic management *	USD·ha^{-1}	3784.21	3763.16	3763.16	3763.16
Irrigation system conditioning	USD·ha^{-1}	0.00	507.89	507.89	507.89
Sprinkler and others related.	USD·ha^{-1}	500.79	500.79	500.79	500.79
Others **	USD·ha^{-1}	816.62	840.96	840.96	840.96
Financial expenses ***	USD·ha^{-1}	678.52	746.50	746.50	746.50
Total Cost	USD·ha^{-1}	5780.13	6359.31	6359.31	6359.31
C1 Income	USD·ha^{-1}	4680.11 ± 863.74 ^{bc}	7595.92 ± 776.25 ^{a}	6164.54 ± 292.29 ^{ab}	2384.59 ± 334.00 ^{c}
C2 Admission	USD·ha^{-1}	2764.53 ± 194.68 ^{a}	3184.51 ± 345.46 ^{a}	3291.80 ± 368.13 ^{a}	2981.79 ± 308.53 ^{a}
Total income	USD·ha^{-1}	7444.64 ± 834.24 ^{bc}	10,780.43 ± 724.24 ^{a}	9456.34 ± 435.52 ^{ab}	5366.38 ± 475.25 ^{c}
Net Income	USD·ha^{-1}	1664.50 ± 834.24 ^{b}	4421.12 ± 724.24 ^{a}	3097.04 ± 435.52 ^{ab}	−992.93 ± 475.25 ^{c}
Net Profitability	dimensionless	0.29 ± 0.14 ^{b}	0.70 ± 011 ^{a}	0.49 ± 0.07 ^{ab}	−0.16 ± 0.07 ^{c}
Economic Water Productivity	USD m^{-3}	0.20 ± 0.10 ^{b}	0.8 ± 0.13 ^{a}	0.71 ± 0.10 ^{a}	−0.31 ± 0.15 ^{c}

Note(s): * Includes land preparation, seed tuber, sowing, cultural work, fertilization, phytosanitary control, and harvest. ** Includes land rental, contingencies, and transportation. *** Capital interest (13.3% of incurred costs). C1 and C2: first and second commercial categories of tubers respectively. L0, L1, L2, and L3: levels of the irrigation treatment applied. Different letters in each testing parameter represent statistical significance among groups at $p < 0.05$ for the Tukey Test.

4. Discussion

Potato cultivation is susceptible to water stress, so its biometric development can be easily affected and expressed in yield losses depending on the cultivar [46,47]. Therefore, the use of deficit irrigation management allows for the evaluation of restriction thresholds to improve the efficiency of resource use. Thus, the results show that reducing the irrigation depth to 75% of the ETc (L2) from the beginning of the formation of stolons did not significantly affect the commercial yield or the WP of the *Solanum tuberosum* cv. Imilla negra crop. This result suggests that the level of induced water stress did not cause critical alterations in crop development [48] since only the height of the plant decreased directly to the reduction of the applied volume of water. In this sense, plant height is reaffirmed as a good indicator of water stress in sensitive stages of development where stomatal closure and inhibition of biochemical processes determine the growth of potato plants [49]. Thus, possible variations in the uniformity of discharge from uncompensated emitters and/or the inherent unevenness of application in surface irrigation systems could have affected the average height of the lower platform (A3). Results similar to those described for the main effect of the irrigation factor were reported when applying reduced irrigation depths up to 75% throughout the crop cycle [50]. However, it has been reported that the application of deficit irrigation plans focused on specific phenological stages can obtain higher WP depending on the agroecological conditions of the environment and the variety evaluated [49,51]. For our case study, the results show that the application of deficit irrigation at 75% ETc from the start of stolon formation is expressed in a slight tendency to reduce commercial yield that is not significant. In this line, it has been reported that certain potato varieties can maintain tuber formation under certain water stress conditions [52]. This is a good indicator of the capacity of the cultivar to maintain its aerial biomass under water stress conditions [53]. Regarding the above, the aerial biomass did not show significant differences between the treatments at 100% ETc and 75% ETc and suggests a moderate degree of resistance to water stress by the cv. Imilla negra. However, the reduction of irrigation by 50% of the ETc (L3) from the start of stolon formation had a negative effect on biometric parameters such as the fresh weight of the aerial part of the plant, plant height, commercial yield, and total yield. This suggests an irrigation management threshold of around 75% ETc, below which water stress limited key processes in potato development, such as stolon formation, tuberization, and tuber filling, which could have significantly impacted final production [48]. Previous studies corroborate similar results regarding yield losses under 50% deficit irrigation throughout the crop cycle [50,51,54]. In this sense, it is confirmed that irrigation water is one of the most important factors in producing fresh potato tubers [55]. On the other hand, it is worth mentioning that the L3 treatment did not present a significant difference in dry yield compared to the other treatments (Figure 5). This implies a high percentage of dry matter for L3 (dry matter: 26%), which depended on the total irrigation depth [56] and, therefore, a potential alternative for irrigation management if the objective of the crop is the industrialization of potato flour [57–60].

In recent years, various studies have been developed concerning the effect of water stress on the yield and development of tubers [46]. However, as far as we have been able to review, there is limited literature regarding research developed on terraces [61,62]. Furthermore, there is much less information on terraces in the Andes or the application of deficit irrigation management on terraces for potato cultivation. In this sense, similar experiences have been identified in Himalayan terraces [63], where deficit irrigation improved tomato crop yields and the consequent WP compared to traditional management. For the present study, it was observed that the location of the terraces did not determine significant variations in yield, which could be linked to the fact that the topographic variation between the terraces is not sufficient to determine variable microclimates that end up influencing crop growth [64]. This suggests the need to conduct field trials considering the variation in typical microclimates of larger terrace systems.

WP and WP_{irri} exhibited similar values for L0, where rainfall contributed only 10.2% of the total water incorporated into the system throughout the season. This highlights irrigation as a key factor in achieving yield. Such behavior is typical of regions with arid or semi-arid climates [17]. The observed pattern is likely associated with the low efficiency of gravity irrigation and the relatively low rainfall volume (939 $m^3\ ha^{-1}$) compared to the historical average for the rainy season (1799 $m^3\ ha^{-1}$). This further underscores the intrinsic relationship between WP and the spatial-temporal characteristics of the studied environment, such as environmental conditions and water availability during the agricultural season [17].

In accordance with Pereira et al. [42] and Niu et al. [65], WP and WP_{irri} generally increased as the applied irrigation depth decreased. However, this trend was reversed for the most restrictive irrigation treatment (L3). This observation supports the idea that irrigating at 75% of crop evapotranspiration (ETc) may represent a potential threshold for water use efficiency. Furthermore, the observed increase in agricultural productivity, despite a reduction in irrigation water use (IWU), can be attributed to physiological response mechanisms such as partial stomatal closure, which reduces water consumption without affecting photosynthesis, and the redistribution of moisture across the soil profile, which reduces the exposure of evaporative surfaces [51].

WP and WP_{irri} among treatments with drip irrigation did not show significant differences, although there was a tendency for higher WP_{irri} in the drip irrigation (DI) treatment at 75% ETc. This could suggest that the crop is potentially able to adapt to local conditions, making efficient use of rainfall and thereby mitigating water stress situations. On the other hand, the lack of significant improvements in water savings with DI could limit the utility of WP as a relevant indicator for decision-making [42]. This may negatively affect the adoption of DI techniques by smallholders, as their implementation requires additional investment [42], and the benefits may not be readily apparent in regions with surplus irrigation water supply and/or low water tariffs [17]. This premise underscores the importance of conducting economic analyses that demonstrate the benefits of technical proposals.

Adopting pressurized irrigation systems depends on the specific characteristics of each region (i.e., cultural, economic, geographic, and water availability characteristics) [66]. For the present research, drip irrigation systems positively affected the commercial yield and WP_{irri} of native potatoes grown on terraces, achieving a water saving of 33% compared to surface irrigation. These results coincide with previous studies that report higher yields and water productivity with drip irrigation, attributed to a homogeneous distribution of water, greater precision in the applied volume, and reduced evapotranspiration [67–69]. In addition, the use of fertigation would have reduced the leaching of nutrients compared to furrow irrigation, facilitating their absorption by the roots [70]. Soil moisture sensors confirmed that drip irrigation (L1) concentrated more moisture in the first 30 cm of soil, while surface irrigation distributed water at both depth strata (0–0.30 m and 0.30–0.60 m). However, potato roots developed mainly in the first 0.30 m, which limits the use of moisture concentrated at greater depth. Given the benefits mentioned above, drip irrigation exceeded the net profitability of surface irrigation, with an additional 0.41 USD being earned for each USD invested. However, if the implementation costs of drip irrigation are included, the profitability may not exceed that of surface irrigation. This is due to the high implementation cost of the rural location, the rugged geography, and the expenses associated with reservoir construction, equipment, accessories, and specialized labor [23]. Only the recurrent costs of conditioning the irrigation system have been considered in the research; those expenses after installation are based on the useful life of the accessories (e.g., drip tapes). The cost of preventive maintenance recommended for reservoirs and water conduction routes has also been incorporated. The latter involves local cultural practices linked to water resource management, such as channel cleaning and communal water rate payments [71]. In the case of terraces in the Peruvian Andes, irrigation water is limited but cheap (e.g., in the study area, the water rate depends on the cultivated area and is barely 10 USD ha^{-1} $year^{-1}$). Faced with this, Taylor and Zilberman [72] indicate that the adoption of drip irrigation will be more viable when the cost of water or the harvested product is high, so low water rates could contribute to limitations on the adoption of this type of technology in rural environments. To this can be added the limited evidence of using drip irrigation systems in terraces [63,73] despite various studies evaluating their adaptability for managing various crops in different soil and climate conditions [74–76]. On the other hand, the cost of land rental has been considered to reflect the local reality, where the fragmentation of rural properties motivates the need to rent land for agricultural production. From the economic point of view, no statistically significant differences were identified when comparing the irrigation plan at 75% Etc. (L2) with the irrigation plan at 100% Etc. (L1). This is based on the fact that the yields were similar, and the water savings (21%) were not reflected in monetary savings since the local water rate depends on the cultivated area instead of the volume used. In this sense, Shock et al. [77] conclude that in areas where water is not a limiting factor, the profitability of deficit irrigation does not show significant improvements. However, in regions with water scarcity, this practice can generate considerable economic increases [24,60]. Therefore, it is essential to promote public investment in technologies that improve the productivity of small farmers' crops and contribute to environmental and social sustainability [78]. To do so, it is essential to generate investment in basic infrastructure (e.g., reservoirs, filters, and main pipelines) that allows reducing implementation costs and improving the accessibility and adoption of new technologies adapted to local socioeconomic and cultural conditions. [79].

Another important approach is to make digital technologies for irrigation management more accessible to farmers. Enhancing the availability and accessibility of information can play a crucial role in promoting and organizing awareness programs on the efficient use of water resources. This, in turn, could facilitate the adoption of more efficient irrigation systems, such as micro-irrigation. In this context, the use of Irrigation Advisory Services (IAS) and Decision Support Systems (DSS) in agriculture helps to present management recommendations in a more comprehensible manner by 'translating' soil and climatic data into actionable guidelines that farmers can use to make informed decisions [80]. Additionally, the integration of remote sensing data and predictive climate models further enhances the potential for reducing data collection costs while providing results that are more aligned with real-world conditions [80,81]. Successful initiatives, such as CIMIS, BlueLeaf, and CoAgMet, leverage data from weather stations, while Manna Irrigation and IrriSAT rely solely on remote sensing data [81,82]. These initiatives help bridge the gap between scientific technical knowledge and its practical application by farmers, enabling optimized irrigation planning regardless of the irrigation system in use. However, several factors must be considered, including internet accessibility in rural areas, digital illiteracy, the costs of disseminating these technologies, and the investment required for their development. In this context, institutional support from the state plays a critical role in validating results in complex environments, such as the Andes, and in implementing participatory strategies that facilitate the adoption of these technologies.

Based on the above, the 75% ETc deficit irrigation treatment applied through drip irrigation (L2) achieved higher water yields compared to the other treatments (Figure 8). Although the WP_{irri} values of L2 were not statistically different from those of drip irrigation at 100% ETc (L1), L2 maintained a similar Economic Water Productivity (EWP) while reducing irrigation water use by 22%. This indicates the technical and economic feasibility of the proposed approach. In contrast, traditional gravity irrigation exhibited WP_{irri} and EWP values significantly lower than those of L1 and L2, associated with higher water consumption and lower yields. Finally, L3 was found to be economically unviable.

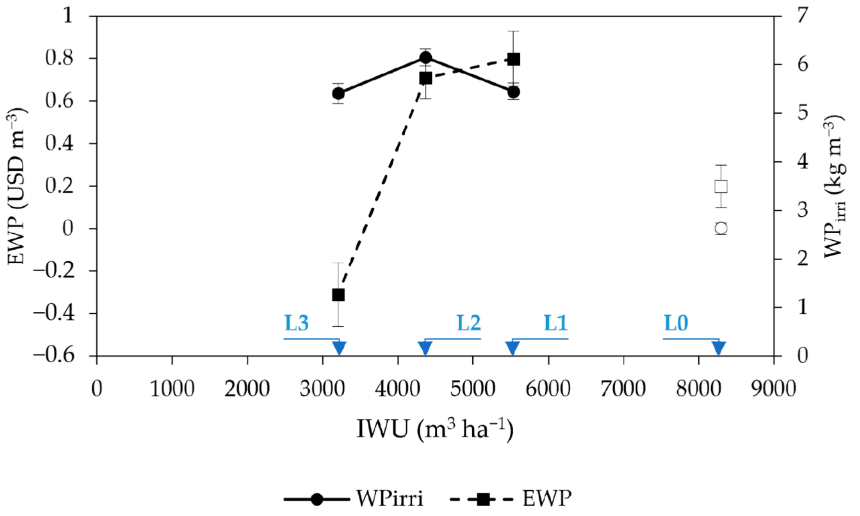


Figure 8. Economic Water Productivity (EWP) and Irrigation Water Productivity (WP_{irri}) as a function of Irrigation Water Use (IWU) for the evaluated treatments. Treatments L0, L1, L2, and L3 are represented in relation to their respective IWUs. The values filled with black represent the drip irrigation treatments, while the values filled with white correspond to the gravity irrigation treatment.

This study has potential limitations that constrained our understanding of the processes associated with deficit irrigation on terraces. Due to budgetary constraints, certain aspects were not implemented. For instance, the installation of soil moisture sensors in all treatments would have allowed for better monitoring of water behavior in the soil, both within and outside the Readily Available Water (RAW) thresholds. Additionally, to obtain a more comprehensive understanding of water stress, it would have been beneficial to include physiological indicators of water stress response, such as stomatal conductance and photosynthetic rate [83]. Furthermore, as discussed earlier, WP is influenced by the spatial and temporal characteristics of the environment and the season, suggesting that extending the research to include additional campaigns and new study areas would be valuable. Despite these limitations, this study provides an initial approximation of the combined use of drip irrigation (DI) technologies on platforms and presents an economic analysis of their application.

5. Conclusions

This research contributes to developing innovative strategies for sustainable water use in terraced systems, combining traditional practices, such as agricultural terrace use, with modern technologies, such as deficit irrigation practices and pressurized irrigation use. This represents a comprehensive approach that fosters the conservation of ancestral agricultural heritage while responding to the demands of water productivity and economic sustainability in rural contexts. The study introduces the evaluation of deficit irrigation at 75% ETc applied through pressurized irrigation systems on terraces, which is not only an underexplored interaction but also integrates water sustainability principles with the recovery of ancestral agricultural systems, especially in regions where water availability is limited but not necessarily expensive. This combination demonstrates that it is possible to modernize local traditional practices without losing their cultural and ecological essence.

The implementation of deficit irrigation at 75% ETc on terraces (L2) allows for the saving of 3930 $m^3 \cdot ha^{-1}$ of irrigation water compared to traditional surface irrigation (L0) and 1164 $m^3 \cdot ha^{-1}$ compared to drip irrigation at 100% ETc (L1). This results in a WP_{irri} of 6.15 ± 0.35 $kg \cdot m^{-3}$, with a commercial yield (CY) of 27.15 ± 1.47 $t \cdot ha^{-1}$, statistically similar to L1 (WP_{irri}: 5.45 ± 0.34 $kg \cdot m^{-3}$; CY: 30.14 ± 1.83 $t \cdot ha^{-1}$), and higher than traditional surface irrigation (WP_{irri}: 2.63 ± 0.23 $kg \cdot m^{-3}$; CY: 21.62 ± 1.99 $t \cdot ha^{-1}$). Economically, this water saving corresponds to a net income of 3097.04 ± 435.52 $USD \cdot ha^{-1}$ for L2, which is comparable to L1 (4421.12 ± 724.24 $USD \cdot ha^{-1}$) and much higher than traditional surface irrigation (1664.50 ± 834.24 $USD \cdot ha^{-1}$). Moreover, this strategy contributes to the preservation and revitalization of agricultural terraces, promotes efficient resource management in rural areas, and strengthens food security in the southern highlands of Peru. However, it also underscores the need to promote public investment in basic infrastructure that reduces implementation costs, improves access to technologies suitable for local conditions, supports validation efforts, and fosters the adoption of digital technologies that reduce management costs and bridge the gap between technical-scientific knowledge and its field application. In all cases, it is crucial to continue developing research focused on smallholder and family farming as a means of building resilience to climate change and achieving Sustainable Development Goal (SDG) 2 (Zero Hunger) and SDG 1 (No Poverty) [84].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17050668/s1, Table S1: Physical and chemical soil parameters; Table S2: Irrigation water use and water productivities per treatment.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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