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Water Productivity Indices of Onion (*Allium cepa*) under Drip Irrigation and Mulching in a Semi-Arid Tropical Region of Colombia

César Augusto Terán-Chaves [1,*], Luis Montejo-Nuñez [2], Carina Cordero-Cordero [2] and Sonia Mercedes Polo-Murcia [1]

[1] Corporación Colombiana de Investigación Agropecuaria—AGROSAVIA, Centro de Investigación Tibaitatá, km 14, Vía Mosquera-Bogotá, Mosquera 250047, Colombia; spolo@agrosavia.co

[2] Corporación Colombiana de Investigación Agropecuaria—AGROSAVIA, Centro de Investigación Motilonia, km 5 Vía a Becerril, Agustín Codazzi 202050, Colombia

* Correspondence: cteran@agrosavia.co

Abstract: Efficient water management is crucial for sustainable agriculture and water resource conservation, particularly in water-scarce regions. This study investigated the effect of different irrigation depths on onion (*Allium cepa* L.) yield and water use patterns in a semi-arid tropical region of Colombia, using a completely randomized design with five treatments. The treatments ranged from 0–100% of total available water (TAW), T1 (100% of TAW), T2 (80% of TAW), T3 (60% of TAW), T4 (40% of TAW), and T5 (20% of TAW). The experiment was conducted in a greenhouse during one growing season (2022–2023). The normalized water productivity (WP *), irrigation water productivity (IWP), consumptive water productivity, blue water footprint (WF_{blue}), marginal water use efficiency (MWUE), and elasticity of water productivity (EWP), as well as some parameters of quality onion, were determined. The soil in the experimental field was classified as sandy loam; the results show that the WP * of onion is 17.42 g m^{-2}, the water production function shows the maximum production will be achieved at a water application depth of approximately 943 mm, and beyond that, the biomass yield will decrease with additional water application, IWP values for onion ranged from 2.18 to 3.42 kg m^{-3}, the highest Wf_{blue} was in T5 (34.10 m^3 t^{-1}), and low Wf_{blue} was T1 (20.95 m^3 t^{-1}). In terms of quality, treatment T1 had the most favorable effects on bulb weight, polar diameter, and equatorial diameter, while treatment T5 had the least favorable effects. The study highlights the importance of efficient irrigation on sandy loam soils to maximize yield and water use efficiency. It provides valuable data for evaluating the potential yield benefits of precision irrigation in the study area. Optimizing irrigation depth can significantly improve onion yield and water use efficiency in semi-arid regions.

Keywords: drip system; onion quality; water management; water use efficiency

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1. Introduction

Bulb onion (*Allium cepa* L.) is a highly esteemed horticultural crop renowned for its economic significance and nutritional value [1,2]. This versatile vegetable is characterized by its diverse colors (yellow, red, or white) and taste profiles (sweet or non-sweet) [3]. It is widely consumed in both fresh and processed forms, including powdered, essential oil, and spice formats, owing to its distinctive aroma and flavor, which enhance food palatability [3]. The consumption of onions spans various culinary traditions and cultures, as they are valued for their nutritional properties and medicinal uses [4,5]. Onions are typically consumed either as dry bulbs at maturity or in their early green stage. However, onion cultivation and productivity levels exhibit considerable variations depending on geographical location and production systems [6,7].

The onion bulb and skin harbor a diverse array of bioactive compounds, including organosulfur compounds (OSCs), thiosulfinates, polyphenols (such as flavonoids), and fructooligosaccharides (FOS) [3,8]. Among these bioactive constituents, flavonoids have demonstrated remarkable efficacy. Onion (*Allium cepa*) possesses a wide spectrum of phytochemicals encompassing flavonoids, phenolic acids, and organosulfur compounds, which contribute to its diverse bioactivities. A. cepa exhibits a broad range of pharmacological properties, including antimicrobial, antioxidant, analgesic, anti-inflammatory, antidiabetic, hypolipidemic, antihypertensive, and immunoprotective effects.

Although various environmental factors influence onion growth, photoperiod emerges as the primary regulator of bulb initiation. Once the daylight duration reaches a specific threshold, onion plants undergo a metabolic shift from leaf development to bulb formation. Different onion cultivars exhibit distinct requirements regarding the minimum photoperiod needed to trigger bulb initiation, giving rise to the classification of long-day, intermediate-day, and short-day onions [9].

Short-day onions are primarily cultivated in low-latitude regions with distinct growing seasons. These onions are characterized by their mild flavor and are typically consumed shortly after harvest due to their limited storage capacity. The production of sweet onions can be achieved through specific environmental conditions, such as cultivating them in low-sulfur soils or employing low-pungency cultivars [10].

The demand for sweet onions, alternatively referred to as mild or low-pungency onions, has witnessed a surge in recent years, particularly in the United States, Europe, and Australia [11]. These onions are highly sought after as fresh ingredients in salads and fast-food preparations.

In Colombia, short-day onion varieties have demonstrated excellent adaptation in regions with warm to moderately cool thermal conditions, ranging from 800 to 2500 m.a.s.l. and temperatures between 16 °C and 27 °C. The formation of bulbs is significantly favored in cultivation areas characterized by high luminosity, high daytime temperatures (25–27 °C), cool nighttime temperatures (16–19 °C), and relatively low humidity during both day and night (60–70%) [12]. Commonly cultivated onion varieties in Colombia include Yellow Granex, Superex F1, Nirvana F1, Granex Carnaval, Yellow Granex Eden, Texas Early Yellow Gran 502, Red Creole, Colina F1, Híbrido Rojo F1, Rosada Milenio F1, Dulcinea F1, Sierra F1, Roja Eureka F1, and Francisca F1 [13].

In Colombia, onion production is characterized by heterogeneity in the planted area, planting times, and technology employed, including factors such as seed quality, variety selection, mechanization, and soil preparation. Additionally, onion production in Colombia faces challenges related to inefficient production costs due to the excessive use of pesticides and fertilizers and the low implementation of good agricultural practices. In 2022, the estimated apparent consumption of bulb onions in Colombia was 492,448 tons, with 54% attributed to domestic production and the remaining 46% accounted for by imports primarily from Peru, China, and Ecuador [14,15].

The cultivation area of onion in Colombia has experienced fluctuations over time, with varying planted areas ranging from 14,855 hectares in 2020 to 7906 hectares in 2006 [15]. Similarly, onion production has shown variability, characterized by periods of both high and low output. Depending on the availability of inputs and resources for farmers, the yield of onions in Colombian farmers' fields ranges from 5 to 45 t ha $^{-1}$ [15]; the average bulb onion yield in Colombia has consistently remained below 20 t ha $^{-1}$. In contrast, countries with intensive production practices have achieved impressive yields of 50 t ha^{-1} or higher.

The bulb onion production in Colombia benefits from favorable biophysical, socio-ecological, and socio-economic conditions that can help consolidate its supply. Therefore, strengthening production by establishing clusters that promote standardization and efficiency in production, processing, logistics, and marketing processes to ensure a consistent supply of quality and safe products that meet market demands can improve a country's competitiveness indicators [12].

In 2018, the Agricultural Rural Planning Unit (UPRA) conducted an all-encompassing study at a 1:100,000 scale to evaluate the suitability of onion cultivation in Colombia [16]. The methodology involved an assessment of various factors, including climatic conditions, oxygen and nutrient availability, ecological integrity, labor market and infrastructure, and logistics, as well as technical variables such as slope, adequate depth, texture, acidity, land cover, risk threats, and rural land price. The study findings revealed that 22,167,802 hectares (equivalent to 19.4% of Colombia's total area) were suitable for onion cultivation. Among them, 13.6% were categorized as highly suitable, 45.5% as moderately suitable, and 40.9% as having low suitability.

The bulb onion crop in Colombia has traditionally been concentrated in the Andean region in valleys with moderate to cool climates, contributing to a significant portion (60% to 70%) of the national bulb onion production [15]. However, in the medium term, there is potential for further consolidation and expansion of the onion supply by capitalizing on the productive advantages of the Caribbean region. The Caribbean region has a dry climate with slight variations influenced by small swamps, rivers, channels, mountains, savannas, and alluvial valleys. Within the Department of Cesar, located in the northeastern part of Colombia in the Caribbean region, the localities of Agustín Codazzi, Chimichagua, La Paz, Valledupar, and Aguachica have been identified as having the highest potential for onion cultivation [16]. However, irrigation is crucial for almost all commercial agricultural production because the availability of water resources is a limiting factor for crop production in this region.

Bulb onion is a shallow-rooted crop; its root penetration is around 0.18 m, so it cannot uptake moisture from deep soils [17]. The root systems of onion plants make them susceptible to fluctuations in soil moisture, leading to decreased yield. Therefore, it is crucial to maintain adequate soil moisture at the surface to promote optimal bulb development. In irrigated agriculture, onion cultivation is considered a significant consumer of water, with much evidence coming from research conducted in arid and semi-arid regions. Previous studies confirm that the seasonal water requirements of onions are highly variable depending on agro climate, location, and growth stage, as well as crop coefficients (Kc) ranging from 0.4 to 0.7 (initial stage), 0.85 to 1.05 (mid-development stage), and 0.6 to 0.75 (final stage), seasonal irrigation needs can vary from 225 to 1040 mm to produce yields ranging from 10 to 77 t ha^{-1} [18,19]. The growth stages most sensitive to water stress are emergence, transplanting, and bulb formation.

Furthermore, excessive water can also negatively affect the final crop quality [20]. Large amounts of irrigation water can result in low water productivity (WP) owing to relatively high deep percolation, mainly on sandy soils. Therefore, an efficient irrigation technology that can prevent plant water stress and minimize deep percolation will play a crucial role in water conservation and WP improvement.

Drip irrigation has emerged as a widely adopted irrigation method in arid agroecosystems worldwide, thanks to advancements in irrigation technology [21,22]. Unlike conventional irrigation methods such as flood or furrow irrigation, drip irrigation offers several advantages, including significant water savings and improved water productivity by directly supplying water to the root zone of plants [23,24]. These benefits are attributed to the ability of drip irrigation to provide water in a precise and controlled manner, reducing water losses due to runoff, evaporation, and deep percolation. Drip irrigation, which can provide small and frequent application depths, is often considered an effective method for water conservation and improving the WP of onions [25–28].

Mulching, whether with inorganic materials such as gravel or pebbles, organic materials such as straw or leaves, or even live lawns, can effectively retain soil moisture by manipulating the microclimate and creating a critical growth stage for vernalization and bulb development [29–31]. Mulching is recognized as a viable solution to combat water scarcity; likewise, the application of mulch has been shown to enhance soil physical conditions, thereby leading to increased yields [32].

In addition to moisture retention, mulching offers other benefits, such as reducing soil water evaporation, modifying soil temperature regimes, and controlling weed competition, all of which can improve overall crop performance [33]. In developing countries, organic and polythene film mulches, including onions, are often preferred for vegetable production because of their low cost and wide availability.

Despite the potential for bulb onion cultivation in the Caribbean region of Colombia, there need to be more scientific studies investigating the water productivity of bulb onions and the effects of different irrigation regimes on water use, growth, yield, and quality of onion. This knowledge gap necessitates further research to address this critical issue. Therefore, this study aimed to investigate the following:

(1) The effects of drip irrigation and polyethylene mulch on the yield and quality of bulb onion cultivation in the dry Caribbean region of Colombia.
(2) The water footprint of bulb onion cultivation and water productivity.

This study seeks to fill the existing knowledge gap and provide valuable insights for efficient water management in bulb onion cultivation in the dry Caribbean region of Colombia, with implications for sustainable agricultural practices, informed decision-making, and improved water resource management.

2. Materials and Methods

2.1. Experimental Site

The study was conducted at the Motilonia Research Center of the Colombian Agricultural Research Corporation AGROSAVIA, situated in the Central River Cesar Valley of Colombia (10°00′03.0″ N latitude and 73°14′53.3″ W longitude, 103 m.a.s.l.) (Figure 1). The study area experiences a long-term average annual precipitation of 1581 mm, with mean maximum and minimum temperatures of 38 and 24 °C, respectively [34].

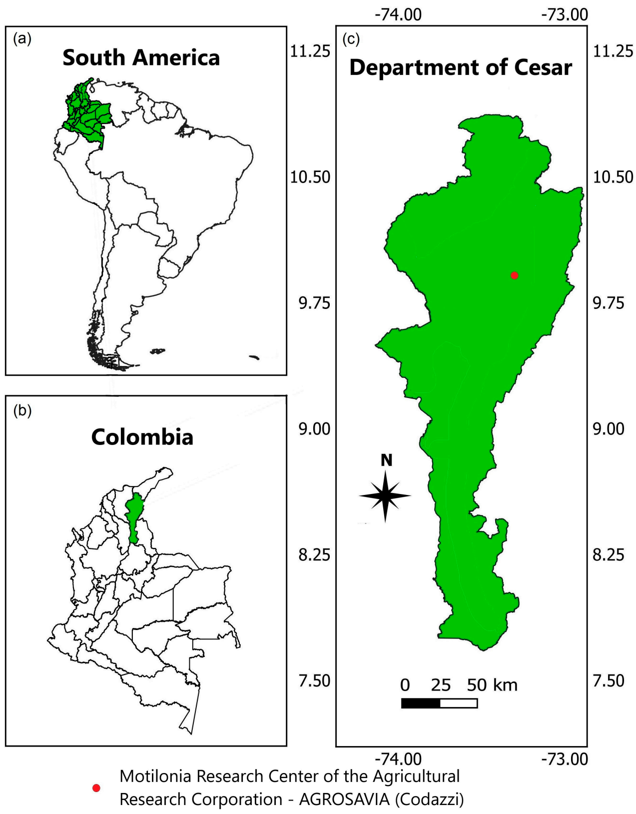

Figure 1. Study area location map. (**a**) Overview of South America, highlighting the position of Colombia. (**b**) Detailed map of Colombia indicating the location of the Cesar department. (**c**) Zoomed-in map of the Cesar department, illustrating the precise location of the research area.

The experiments were carried out in a greenhouse with a zenithal opening controlled to exclude the effects of rainfall and thus manage the effects of irrigation on plant response. The soil in the experimental field was classified in sandy loam textural class (58.38% sand, 21.86% silt, and 19.76% clay), acid pH (6.3), and low organic matter content (1.53%), EC 0.47 dS m^{-1}. The physical and chemical properties of the 0–20 cm soil layer before the experiment are shown in Table 1.

Table 1. Soil physical and chemical properties of the 0–20 cm soil layer before bulb onion transplantation in October 2022.

Soil Property	Value
Soil texture	Sandy loam
Bulk density	1.58 ± 0.05 g cm^{-3}
pH	6.30 ± 0.42
Field capacity soil moisture	$19.1 \pm 1.6\%$
Wilting point soil moisture (θ_w)	$10.3 \pm 0.3\%$
Soil organic matter	1.53 ± 0.13 g kg^{-1}
Available nitrogen	1280 ± 5.62 mg kg^{-1}
Available phosphorus	216 ± 0.82 mg kg^{-1}
Available potassium	176.30 ± 3.79 mg kg^{-1}
Available sulfur	3.66 ± 0.9 mg kg^{-1}

To monitor the environmental conditions inside the greenhouse, an iMetos 3.3 IMT280US (Metos, Weiz, Austria) weather station was installed. The weather station recorded air temperature, relative humidity, and solar radiation at 15-min intervals. The average maximum daily temperature in the greenhouse was 38.7 ± 2.56 °C, while the average minimum daily temperature was 22.3 ± 1.77 °C, resulting in a mean daily temperature of 28.2 ± 1.15 °C. Throughout the study period, the daily mean relative humidity consistently remained above 65%. The solar radiation levels inside the greenhouse remained below 100 W m^{-2} on most days. Moreover, the mean daily reference evapotranspiration, representing the combined water loss through evaporation and plant transpiration, was estimated to be 2 mm (Figure 2).

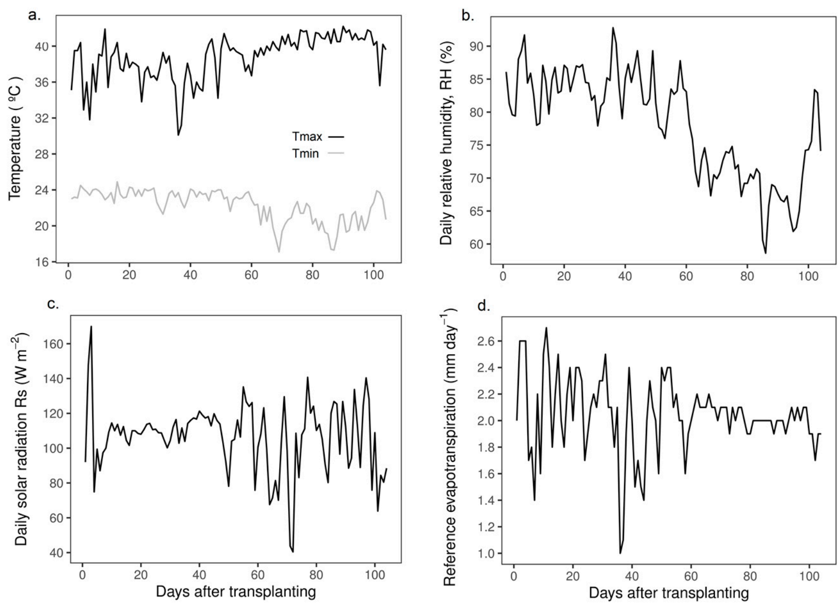

Figure 2. Climate characteristics and variation in reference evapotranspiration within the greenhouse during bulb onion growth in the Motilonia research center AGROSAVIA (4 October 2022–4 January 2023) (**a**) Temperature (Tmax and Tmin); (**b**) Relative humidity (RH); (**c**) Solar radiation (Rs); (**d**) Reference evapotranspiration (ET_0).

2.2. Experimental Design

The experimental design was completely randomized, with five treatments and eight replicates per treatment. We tested the impact of five irrigation levels: T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). TAW is estimated as the difference between water content at field capacity and water content at wilting point and changes during the growing season as a function of root depth (Equation (1))

$$TAW = \frac{FC - PWP}{100RD} \quad (1)$$

where TAW is total available water, FC is the field capacity soil moisture, PWP is the wilting point soil moisture, and Rd is the root depth (mm).

The irrigation system utilized was drip irrigation, which was automated through a FERMASTER II programmer by Talgil. This system allowed for precise control of the water volume applied by regulating a valve per bed. Each bed was equipped with two rows of drip irrigation. The emitters on each drip line were evenly spaced at 10 cm intervals, with a discharge rate of 1.43 L per hour for each emitter. These irrigation lines were positioned directly on the soil surface.

To retain soil moisture, both the beds and irrigation lines were covered with 0.02-mm-thick polyethylene mulch. Before applying the mulch, light irrigation was administered to create a uniformly moist soil surface. The polyethylene mulch was carefully placed one week before transplanting the bulb onions.

The plot beds had a width of 0.8 m, with a separation distance of 0.8 m between adjacent beds. Each plot consisted of four rows of plants measuring 16 m long and spaced 0.1 m apart. One hundred sixty onions were planted in each plot, with a planting interval of 0.1 m. A buffer zone measuring 0.8 m within each bed was left unplanted to separate the plots. Following the onion seedlings' transplantation, all experimental units were irrigated until they reached 100% field capacity. After seven days, the plants were irrigated based on their respective irrigation treatments.

2.3. Growing Conditions

Onion seedlings (*Allium cepa hyb.* "Yellow Granex") were transplanted on 4 October 2022 in the experimental field located within a greenhouse. The planting density of 200,000 plants per hectare was adopted for this study, following the recommended practice in the region. Onion bulbs were manually harvested on 4 January 2023 at the maturity stage.

Yellow Granex is a short-day bulbing onion variety that thrives under specific environmental conditions. It requires a minimum of 12 h of daylight for optimal development and bulb formation. Cultivating Yellow Granex in well-drained soil with a pH range of 6.0 to 7.0 is recommended to ensure favorable growth outcomes [35]. This soil characteristic promotes proper root development and nutrient uptake, enhancing overall plant performance. Maintaining average daily temperatures between 15 and 29 °C throughout the experiment optimizes physiological processes, minimizes stress, and supports healthy growth and bulb formation [36].

All the experimental units received the same fertilizer doses; the recommended doses of N, P, K, S, Ca, and minor fertilizers were applied. The basal dose, which was applied from the first day to 21 days after transplanting (DAT), consisted of 90 kg N, 14.5 kg P_2O_5, 18 kg K_2O, 60 kg S, 14 kg MgO, 2 kg Zn, 0.2 kg B, and 52 kg organic matter per hectare. From 22 to 60 DAT, 25.6 kg N, 29 kg P_2O_5, 51 kg K_2O, 13.5 kg S, 37 kg MgO, 2.7 kg Zn, and 0.16 kg B per hectare were applied. After 60 DAT, 13.8 kg N, 15.7 kg P_2O_5, 2.8 kg K_2O, 7.3 kg S, 1.9 kg MgO, 0.14 kg Zn, and 0.001 kg B per hectare were applied, distributed uniformly in each period through daily fertigation.

The dates of the main crop stages during the growing season are reported In Table 2.

Table 2. Phenological growth stages of onion in the study area.

Growth Parameter	Days
Sowing to emergence	11
Emergence to transplant	35
Transplant to leaf development stage	10
Transplant to vegetative phase	30
Transplant to start of bulbing stage	40
Transplant to maximum root depth	77
Transplant to maximum canopy cover	79
Transplant to maturity	85
Transplant to start of senescence	90
Transplant to harvesting	92

2.4. Irrigation Water Application

The irrigation schedule was based on the calculation of water depletion from soil moisture readings. Daily monitoring of soil water was performed by gravimetric method. Individual irrigation events were triggered according to the measured available water content within the rooting zone.

The daily water balances of each of the experimental units were calculated using Equation (2):

$$I_{i+1} = \theta_{i+1} - \theta_i + ETa_{i+1} \tag{2}$$

where I_{i+1} is the irrigation amount for the current day (mm), θ_{i+1} is the current day soil moisture (mm), θ_i is the previous day soil moisture (mm), and ETa_{i+1} is the crop evapotranspiration on the current day (mm).

The net irrigation requirement for each treatment was defined as a function of the soil moisture depletion level (Equation (3)).

$$\theta_{CLI_j} = \theta_{FC} - \left(\text{TAW} \times Z_j\right) \tag{3}$$

where θ_{CLI_j} is the critical threshold for decision irrigation management in each treatment ***j*** (volume base) (%), θ_{FC} is the moisture content of the soil at field capacity (volume base) (%), TAW is total available water (volume base) (%), and Zj is the depletion level of the treatment (decimal).

Therefore, when $\theta_{i+1} < \theta_{CLI_j}$, the irrigation time was calculated, considering the flow rate of the dripper and the irrigation volume required to reach the upper threshold of the determined treatment.

2.5. Canopy Traits and Yield

The plant height (7 days) and canopy coverage were measured starting after transplanting, with an interval of 4 days. The average plant height (cm) was measured from the soil surface to the tip of the longest leaf of three randomly selected onion plants in each experimental unit [37]. Every 7 days, three onion plants were extracted from each plot and divided into bulbs and leaves to measure their fresh weight. Subsequently, they were dried at 70 °C until a constant weight was achieved to determine the bulbs' aerial biomass and dry weight.

To estimate the onion bulb yield, an area of 0.8 × 1.2 m was marked in the center of each plot. The average bulb weight was determined from the measured weight of a single bulb and the number of bulbs harvested in this area [38]. Similarly, the yield of marketable bulbs was determined after discarding split, centered, and rotten bulbs from each subplot. The split, centered, and rotten bulbs obtained in each subplot were weighed separately and expressed as a percentage of losses relative to the typical weight of the bulbs.

2.6. Bulb Quality Attributes

The polar diameter is defined as the distance between the crown of the bulb to the bottom part of the bulb from where roots germinate. The equatorial diameter is the extreme breadth of an onion bulb measured perpendicular to the polar diameter [39]; both diameters were measured with the help of a digital Vernier Caliper of 0.01 mm least count and was measured as per methods suggested by Dabhi & Patel [40], for 5 randomly selected onion samples after harvesting in each subplot.

The onion bulbs were classified into four grades according to their mean size: A (size > 50 mm), B (size 40–50 mm), C (size 30–40 mm), and D (size < 30 mm) [38]. The percentage of bulbs in each grade was determined. Total soluble solids (TSS) were measured with a portable refractometer (PR-32α, Atago Co. Ltd., Tokyo, Japan). The harvested onions were separated into unmarketable (rotted or sprouted, physiological disorder) and marketable onions and weighed to calculate the percent of marketable onions.

2.7. Estimation of Water Productivity Indices

Irrigation water productivity (IWP) index, real crop water productivity (RCWP), normalized water productivity (WP*), and water footprint index (Wfblue) were estimated. Total irrigation water applied during the whole crop season was calculated by cumulating the irrigation-wise depth of water delivered and the number of irrigations applied.

The IWP was calculated based on Brar & Singh [41]; IWP is defined as the ratio of the yield of bulb onion to the volume of irrigation water applied (Equation (4)).

$$\mathrm{IWP} = \frac{\mathrm{TBY}}{\mathrm{IW}} \tag{4}$$

where IWP (kg m^{-3}) is the irrigation water productivity index, TBY is total bulb yields (kg), and IW is the volume of irrigation water (m^3) applied during the entire onion growing period.

RCWP is defined as the marketable crop yield over actual evapotranspiration (Equation (5)). A higher RCWP results in either the same production from fewer water resources or a higher production from the same water resources, so this is of direct benefit to other water users [42].

$$\mathrm{RCWP} = \frac{\mathrm{TBY}}{\mathrm{ET_{act}}} \tag{5}$$

where RCWP (kg m^{-3}) is the real crop water productivity index, TBY is total bulb yields (kg), and ET_{act} is the actual seasonal crop water consumption by evapotranspiration (m^3 ha^{-1}). When considering this relation from a physical point of view, one should consider transpiration only [42,43].

The normalized water productivity (WP*), which is defined as the ratio of biomass (dry matter) produced (enhanced by increases in [CO_2]) to water transpired (Equation (6)), involves two environmental factors: evaporative demand of the atmosphere and air carbon dioxide concentration ([CO_2]). The water productivity is normalized for climate by dividing the amount of water transpired (Tr) with the reference evapotranspiration (ET_0), and the normalization for CO_2 consists in considering the biomass water productivity for an atmospheric CO_2 concentration of 369.41 ppm (parts per million by volume). The reference value of 369.41 is the average atmospheric CO_2 concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii (USA). Normalization makes WP* applicable to diverse locations and seasons, accounting for ET0 variations, and over a time span of years, accounting for rising [CO_2] [44,45].

$$\mathrm{WP}* = \left[\frac{\mathrm{B}}{\sum \frac{\mathrm{Tr}}{\mathrm{ET_0}}}\right] \times \mathrm{f_{CO2}} \tag{6}$$

where WP* is the normalized crop water productivity (g m^{-2}), B is the cumulative biomass production (g m^{-2}), Tr is the daily crop transpiration (mm), ET_0 is the daily reference evapotranspiration (mm), and f_{CO2} is the correction coefficient for CO_2 (value to calculate with Equation (7)).

$$f_{CO_2} = \frac{[CO_2]_i/[CO_2]_0}{1+([CO_2]_i-[CO_2]_0)[(1-w)b_{sted}+w(1-f_{sink})b_{face}]} \tag{7}$$

where $[CO_2]_0$ is reference atmospheric CO_2 concentration (369.41 ppm); $[CO_2]_i$ is actual atmospheric CO_2 concentration for the year i (ppm); the value of bsted is 0.000138 [41]; bface is 0.001165; w is weighing factor, the threshold of 550 ppm is selected as the representing value for the elevated CO_2 maintained in the face experiments; fsink is crop sink strength coefficient. The value of fsink is taken as zero in this study (based on an analysis of crop responses in face environments by Vanuytrecht et al. [44] and Li et al. [46]).

The units of biomass water productivity after the adjustment for climate are mass of above-ground dry matter (g or kg) per unit land area (m^2 or ha). After normalization for atmospheric CO_2 concentrations and climate, recent findings indicate that crops can be grouped into classes having a similar WP*. A distinction can be made between C4 crops with a WP* of 30–35 g m^{-2} (or 0.30–0.35 ton per ha) and C3 crops with a WP* of 15–20 g m^{-2} (or 0.15–0.20 t ha^{-1}) [45].

The water footprint of a crop can be categorized Into three components: green, blue, and gray water footprints. The green water footprint represents the amount of rainwater consumed by the crop. The blue water footprint refers to the surface and groundwater consumed in the crop production process. Lastly, the gray water footprint quantifies the volume of freshwater needed to assimilate the pollutant load according to the prevailing ambient water quality standards [47]. These different measures of water footprints serve as indicators for assessing both direct and indirect uses of freshwater resources in crop cultivation.

The water footprint is widely used as an indicator to measure both direct and indirect water consumption [48]. In the context of crop production, the water footprint is calculated as the volume of water relative to the mass of the product, which is the inverse of water productivity (kg product m^{-3} water) [49]. The use of this ecological index would be highly beneficial as it helps determine the magnitude of the impact on water resources attributed to onion production in the study area. Blue freshwater, which refers to surface and groundwater sources, plays a crucial role in agricultural activities aimed at food production. However, the increasing demand for higher crop yields has led to the expansion of irrigated agriculture, resulting in concerns regarding blue water scarcity. The limited availability of blue water for agricultural purposes can have significant negative consequences [50].

Water footprint blue was calculated based on Hoekstra et al. [51] method (Equations (8) and (9)).

$$WF_{blue} = \frac{CWU_{blue}}{TBY} \tag{8}$$

where WF_{blue} is water footprint (m^3 t^{-1}), CWU is crop water use (m^3 ha^{-1}), TBY is total bulb yields (t ha^{-1}).

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{act,blue} \tag{9}$$

where $ET_{act,blue}$ is the daily evapotranspiration (mm day^{-1}). The summation is performed over the period from the day of planting (day 1) to the day of harvest (lgp stands for length of growing period in days).

2.8. Water-Yield Production Function

Water production functions (WPF) were created using data on crop water use and yield. The relationship between yield and the amount of irrigation water applied through drip irrigation treatments was determined through non-linear regression analysis. In this modeling approach, all components of the water balance, including the various drip irrigation treatments, were considered to predict bulb onion yield. By taking into account the comprehensive irrigation treatments and their impact on water balance, these WPFs provide valuable insights into optimizing water use and maximizing crop yield in drip irrigation systems.

As suggested by Sarkar et al. [52], we calculated two measures of water use efficiency. The first measure is the marginal efficiency of water use, which is obtained by taking the first derivative of the production function. The second measure is the elasticity of water production (EWP), which represents the percentage change in the dependent variable (crop yield) divided by the percentage change in the independent variable (water application). EWP provides information about the sensitivity of crop yield to changes in water application. A higher EWP value indicates that crop yield is more responsive to changes in water application (Equation (10)).

$$\mathrm{EWP} = \frac{\frac{\mathrm{dB}}{\mathrm{B}}}{\frac{\mathrm{dIW}}{\mathrm{IW}}} \tag{10}$$

2.9. Statistical Analysis

The statistical analysis was conducted using R version 4.0.2 (Posit, Boston, MA, USA). A comprehensive analysis of various parameters, encompassing agronomic and irrigation variables, was performed through analysis of variance (ANOVA). Mean separation was carried out at a significance level of $p < 0.05$, employing Tukey's test.

To investigate the relationship between bulb size and level of irrigation, we utilized the ggbar-stats () function in R. This function enabled the computation of the chi-square ($\chi 2$) test and Cramer's V effect size, which was then visualized in a stacked bar chart. The chi-square test assessed the presence of a significant association between the two variables, with the corresponding p-value indicating the significance level. A p-value below 0.05 was considered indicative of a statistically significant association. From 0 to 1, Cramer's V offered insights into the extent of association, where a value of 0 denoted no association, and a value of 1 represented a perfect association between the variables.

3. Results

3.1. Effects of Different Amounts of Irrigation and Mulch on Onion Growth Parameters

In this study, five treatments with irrigation depths ranging from 525 in T5 to 1500 mm in T1 were applied. The T1 treatment received the most significant irrigation depths, while the T5 treatment received the minor depths and was the most stressed. The onion plant height increased with time, following an S-shaped growth curve. Initially, the plant height was negligible during the establishment stage, but it overgrew and reached its highest value at DAT 45. However, the plant heights for treatments T3, T4, and T5 were significantly smaller than that of the T1. Treatment T5 had the lowest plant height among the treatments, as shown in Figure 3. The growth rate, expressed as the increase in plant height, was fastest until 50 DAT and then stabilized. At 45 DAT, the plant height ranged from 46.9 to 52.4 cm; days later, the height stabilized and then reduced to 34.5–38.4 cm until harvest.

Figure 4 shows that as the onion crop matures, the canopy cover (%) declines due to leaf senescence. The observation data confirms that treatments T4 and T5, subjected to significant water stress conditions, had lower canopy cover than treatments T1 and T2. The maximum and minimum observed canopy cover values were 45% and 20%, respectively, and these growth trends were well-suited for mulch conditions. Overall, the results indicate that the onion crop's canopy cover increases with the number of days after transplanting (DAT) while decreasing with less irrigation.

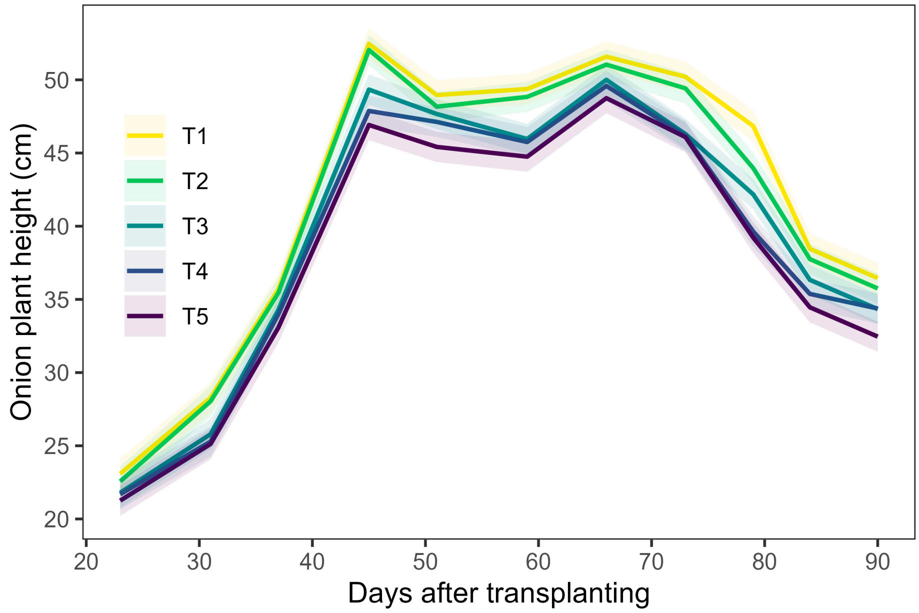

Figure 3. Temporal variation of onion plant height (PH) under different irrigation treatments. T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). The solid line connects the PH means, and the shaded area shows the standard deviation from the mean values.

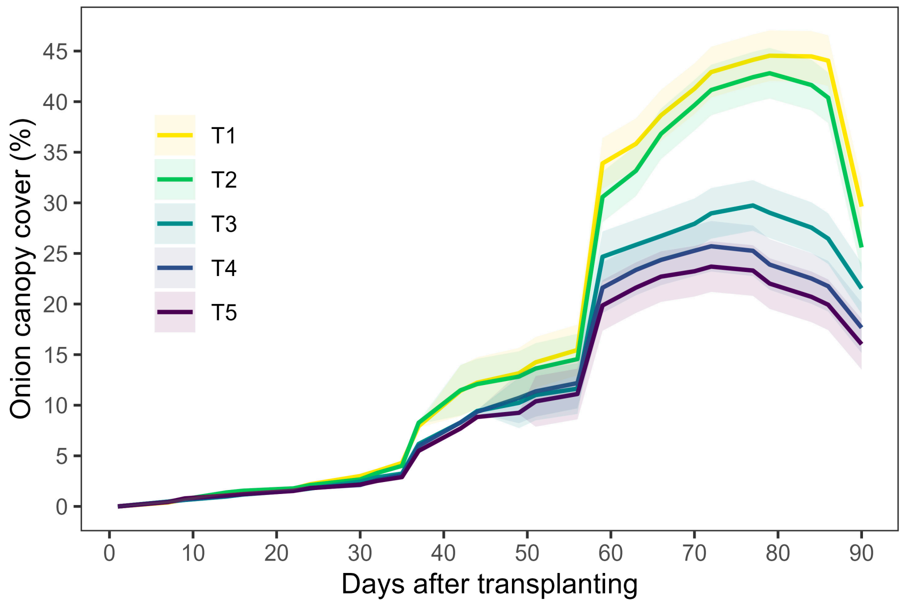

Figure 4. Temporal variation of onion canopy cover (CC) under different irrigation treatments. T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). The solid line connects the CC means, and the shaded area shows the standard deviation from the mean values.

The biomass increased throughout the growing season up to DAT 92 (Figure 5). The biomass was reduced for the T4 and T5 during the development and bulbification stages. The maximum differences of biomass between treatments were noticed at 70–80 DAT, indicating the highest sensitivity of onion to bulb development stage under water deficit until harvest.

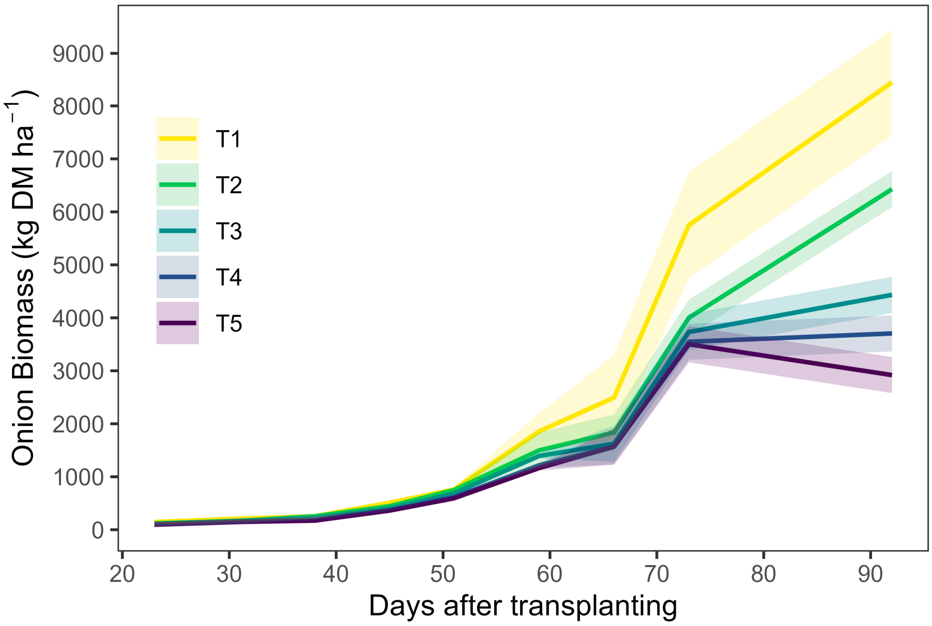

Figure 5. Temporal variation in dry matter biomass of onion under different irrigation treatments. T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). The solid line connects the onion biomass means, and the shaded area shows the standard deviation from the mean values.

3.2. Yield and Quality of Onion Bulbs

The yield of onion bulb in fresh matter (FM) was significantly higher in T1 compared to treatments T3, T4, and T5. The maximum bulb yields were observed in T1 (100% TAW). Further analysis indicates that the bulb yields obtained under T2, and the optimum T1 water regimes were almost equal (Figure 6). The mean yield in T1 was 45.8 t ha^{-1}, while T2, T3, T4, and T5 had yields of 37.79 t ha^{-1}, 28.25 t ha^{-1}, 24.11 t ha^{-1}, and 18.0 t ha^{-1}, respectively. Although the yields of T3 were higher than T4 and T5, the differences were not statistically significant.

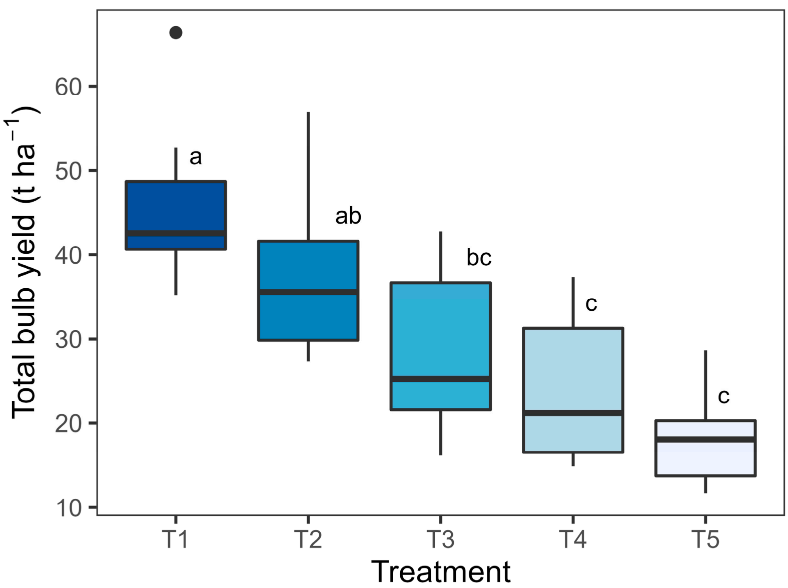

Figure 6. Box plot of the yield of onion bulb fresh matter (FM) for each treatment. T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). Different lowercase letters indicate significant differences between the different treatments ($p < 0.05$, Tukey's HSD test). Boxplots are colored according to the median.

In onion production, it is essential to consider the crop's quality to ensure it can withstand transportation, meet market standards, and facilitate storage. Our study evaluates this quality based on the mean bulb weight and the average bulb diameter, as well as by measuring the Total Soluble Solids (TSS). Our results indicate that non-marketable production accounted for approximately 20% of the total yield across all treatments.

The weight of onions varied from 48.9 to 78.1 g; T1 had the highest bulb weight, followed by T2, T3, T4, and T5. The differences between treatments T1 and T5 are statistically significant. The polar diameters of onions were between 45.2 and 53.7 mm, while it varied from 32.7 mm to 64.3 mm for equatorial diameter. T1 has the highest polar diameter, followed by T2, T3, T4, and T5. The differences between treatments are statistically significant, except for T2 and T3, which are not significantly different. T1 has the highest equatorial diameter, followed by T2, T3, T4, and T5. The differences between treatments are statistically significant, except for T4 and T5, which are not significantly different. The TSS of onions varied from 6.6 to 7.8 Brix; T1 has the lowest TSS, followed by T2, T3, T4, and T5. The differences between treatments are not statistically significant. Overall, the results suggest that treatment T1 has the most favorable effects on bulb weight, polar diameter, and equatorial diameter, while T5 has the least favorable effects. However, the treatments do not have a significant effect on TSS (Table 3).

Table 3. Onion quality parameters relative to all irrigation treatments.

Treatment	Bulb Weight (g)	Polar Diameter (mm)	Equatorial Diameter (mm)	TSS (Degrees Brix)
T1	78.1 a	53.7 a	64.3 a	6.65 a
T2	75.6 a	50.7 ab	59.5 a	6.74 a
T3	71.0 ab	47.4 bc	44.6 b	6.82 a
T4	57.9 ab	46.2 bc	39.0 bc	7.76 a
T5	48.9 b	45.2 c	32.7 c	7.83 a

Notes: T1 (100%) of the total available water serves as the control group. T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of the total available water (TAW) represent different treatment groups. Re-sults that share the same letter within each column are not significantly different ($p < 0.05$, Tukey's HSD test).

Figure 7 shows the distribution of different equatorial diameter sizes of bulbs across the irrigation treatments. The chi-square test was employed to determine the association between bulb size and irrigation treatments. The strength of association was measured using Cramer's V. The results reveal that when irrigation is non-limiting, the share of A-grade bulbs is more significant compared to B and C-grade bulbs. There are no significant differences in D-grade bulbs among the treatments. Specifically, the number of A-grade bulbs increases under irrigation treatment T1. The relatively strong relationship between irrigation treatments and the distribution of bulb sizes is supported by Cramer's V value of 0.49, which agrees with the p-value. However, water regimes for T4 and T3 significantly reduced the percentage of A-grade bulbs, with a total absence of this class in T5. Moreover, our findings indicate that bulb yields variations mainly result from weight and size differences.

In contrast, the polar diameter of the bulbs showed a moderate association with the irrigation treatments (Cramer's V = 0.27). Treatments T1 and T2 had the highest proportion of bulbs with polar diameters more significant than 50 mm, while T5 had a higher proportion of B-type bulbs: 40–50 mm (42%) and C-type bulbs: 30–40 mm (28%) (Figure 8). These results indicate that the onion plants can develop bulbs with reduced water but not as high-quality bulbs as analyzed before relative to bulb sizes.

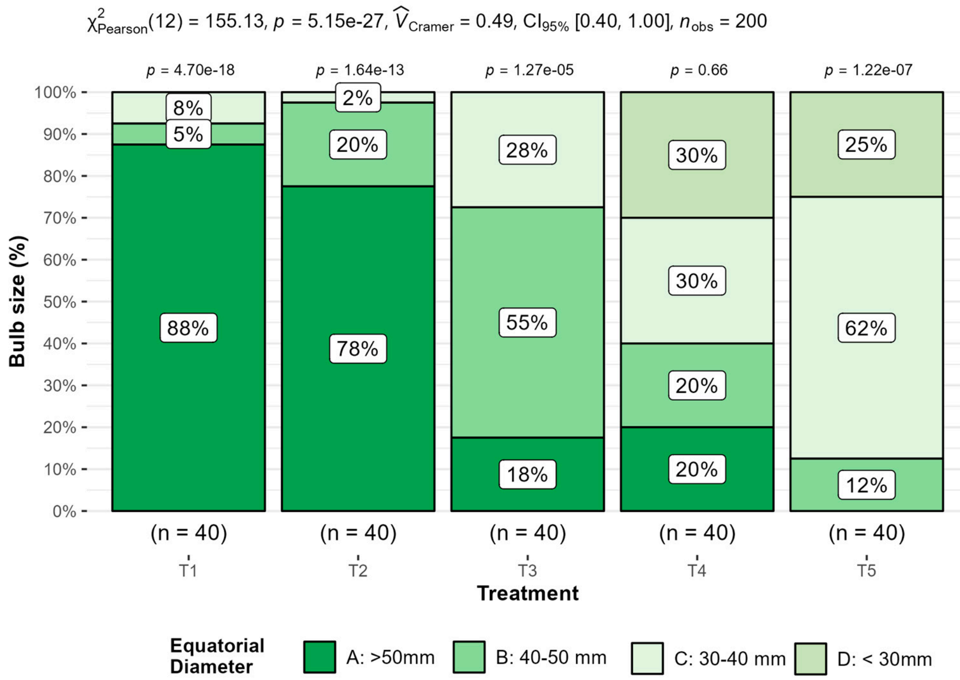

Figure 7. Percentage of different equatorial diameters of bulbs onion for each irrigation treatment. T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). Notes: significant differences between groups, which were calculated using Chi-Square Pearson Test, *p* values shown above plot, $p < 0.05$.

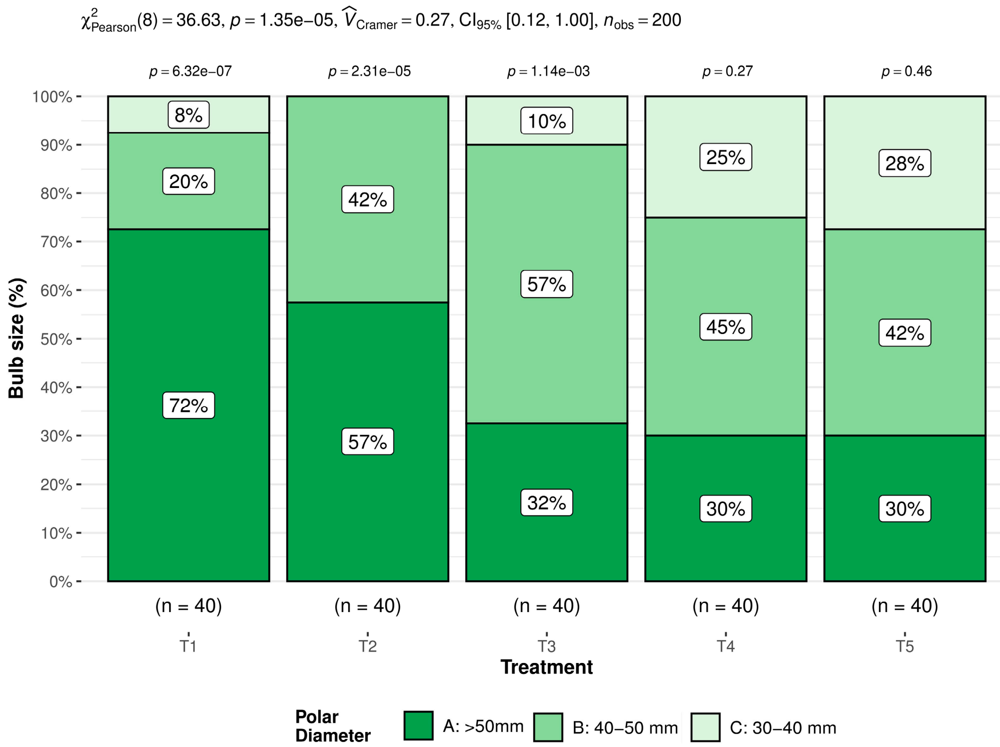

Figure 8. Percentage of different polar diameters of bulbs onion for each irrigation treatment. T1 (100 %) of total available water as a control, T2 (80 %), T3 (60 %), T4 (40 %), and T5 (20 %) of total available water (TAW). Notes: significant differences between groups, which were calculated using Chi-Square Pearson Test, *p* values shown above plot, $p < 0.05$.

3.3. Relationship between Water Productivity and Water Regimes

As defined here, water productivity is a function of yield and consumptive water use. From the perspective of maximizing production, one strategy to improve WP is to increase yield. The results demonstrate that the yield of bulb onion was significantly influenced by the irrigation water applied. Table 4 presents water productivity indices of onion (*Allium cepa*) in the experimental site. The treatments are labeled T1 to T5, and the variables measured include the applied irrigation water (IW), actual evapotranspiration (ET act), crop transpiration (Tr), bulb onion yield (kg ha^{-1}), irrigation water productivity (IWP), consumptive water productivity (RCWP), and blue water footprint (Wf_{blue}). The results show that treatment T1 had the highest applied irrigation water (1500 mm) and also had the highest bulb onion yield (45871 kg ha^{-1}) compared to other treatments. The ET act decreased as the amount of applied irrigation water decreased. Treatment T5 had the lowest applied irrigation water (525 mm), lowest bulb onion yield (18001 kg ha^{-1}), and the highest Wf_{blue} (34.10 m^3 t^{-1}), indicating that it required the bluest water (surface and groundwater) to produce a unit of bulb onion yield. The IWP, the crop yield produced per unit of applied irrigation water, was highest in treatment T1 (3.06 kg m^{-3}), indicating that this treatment was the most efficient water use for crop production. The RCWP, the crop yield produced per unit of consumptive water (water used by the plant), was also highest in treatment T1 (47.72 kg m^{-3}). These results suggest that treatment T1 was the most productive regarding crop yield and water use efficiency.

Table 4. Water Productivity Indices of Onion (*Allium cepa* L. hyb. Yellow Granex) at the Motilonia Research Center, AGROSAVIA.

Treatment	T1	T2	T3	T4	T5
IW (mm)	1499.52 a	1330.17 b	1293.23 c	821.77 d	525.17 e
sd (mm)	6.5	0.5	0.5	0.4	4.6
ET act (mm)	96.13 a	91.59 ab	71.3 c	65.32 cd	61.39 e
sd (mm)	1.5	1.3	1.5	1.8	1.7
Tr (mm)	76.23 a	74.15 b	54.24 c	48.63 d	44.79 d
sd (mm)	0.9	0.8	1.3	1.1	1.4
Bulb Onion (kg ha^{-1})	45,871 a	37,791 ab	28,255 bc	24,110 c	18,001 c
sd (kg ha^{-1})	9861	10,508	10,291	9009	5477
IWP (kg m^{-3})	3.06 a	2.84 a	2.18 a	2.93 a	3.43 a
sd (kg m^{-3})	0.3	0.4	0.6	0.6	0.4
RCWP (kg m^{-3})	47.72 a	41.26 a	39.63 a	36.90 a	29.32 a
Sd (kg m^{-3})	13.0	13.7	18.9	18.1	11.9
Wfblue (m^{-3} t^{-1})	20.95 b	24.23 ab	25.23 ab	27.09 ab	34.10 a
sdWfblue (m^{-3} t^{-1})	3.2	5.0	7.8	7.6	7.5

Notes: T1 (100%) of total available water as a control, T2 (80%), T3 (60%), T4 (40%), and T5 (20%) of total available water (TAW). Values with different lowercase letters within a column differ significantly ($p < 0.05$, ANOVA with post hoc Tukey test). IW = volume of irrigation water (mm) applied during the entire onion growing period. ET_{act} = actual seasonal crop water consumption by evapotranspiration (mm); Tr = crop transpiration (mm); IWP = Irrigation Water Productivity; RCWP = Real Crop Water Productivity; Wfblue = Blue Water Footprint.

WP* is a parameter used to measure water productivity by normalizing the amount of biomass produced per unit of land and per unit of water transpired over time. This normalization makes it more versatile and applicable in various locations, seasons, climates, and management practices. To obtain the WP* parameter, we used the method of Steduto et al. [43]. This method involved calculating the ratio of cumulative evapotranspiration data to reference evapotranspiration and drawing a line that best fits the coordinate points for the cumulative biomass and WP* values (Figure 9). The slope of this line represents the value of WP* for the crop. The value of WP* for onion production was found to be 17.42 g m^{-2}, which means that the onion crop yielded 17.42 g of onions per square meter of land per unit of water used, normalized by a reference evapotranspiration value (ET_0) that represents the water demand of the crop. This result is consistent with the values reported for C3 crops (WP* = 15–20 g m^{-2}) [45].

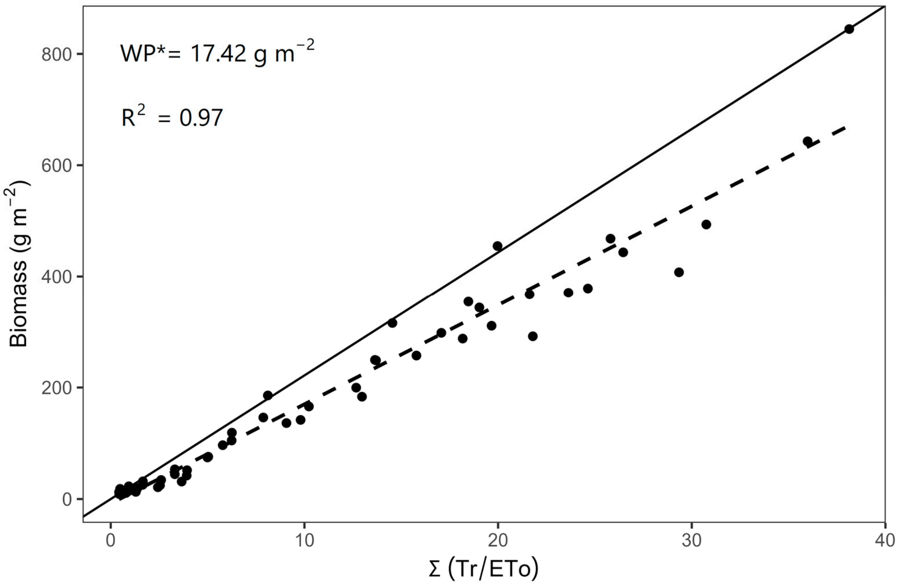

Figure 9. Relationship between onion biomass (normalized for CO_2) and cumulative transpiration (normalized for ET_0). Fitted linear regression curve (dashed line) and equality line (solid line).

3.4. *Water Productivity Function of Onion*

Water production functions are shown in Figure 10, and a strong second-degree polynomial relationship was best fitted. The predicted regression equations are given below (Equation (11)). The coefficient of determination (R^2) was found to be 0.80, statistically significant. The mean maximum onion biomass yield (3732 DM kg ha^{-1}) was estimated at the inflection point of the quadratic regression curve with 943 mm of irrigation water.

$$WPF_{onion} = -5.8 \times 10^{-3}\ IW^2 + 10.34\ IW - 890.75 \quad (11)$$

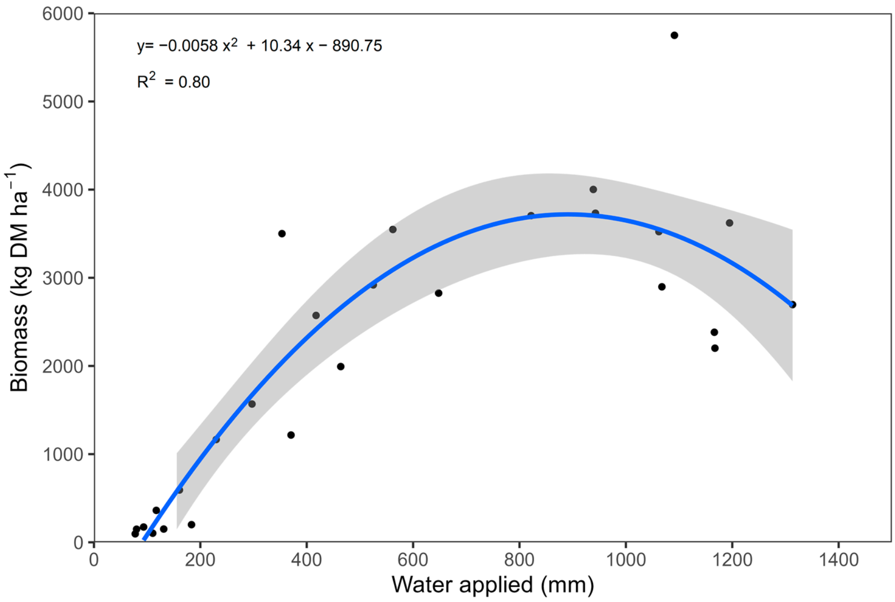

Figure 10. Water productivity function of onion. Relationships between onion biomass dry (measured at 91.4% water content) and water applied.

The marginal water use efficiency (MWUE) presented in Equation (12) was calculated by differentiating Equation (11):

$$\text{MWUE}_{\text{onion}} = 10.34 - 1.16 \times 10^{-2}\ \text{IW} \tag{12}$$

Similarly, by differentiating Equation (11) according to Equation (10), the expression for the elasticity of water productivity (EWP) shown in Equation (13) was computed as:

$$\text{EWP}_{\text{onion}} = \frac{10.34 - 1.16 \times 10^{-2}\ \text{IW}}{-5.8 \times 10^{-3}\ \text{IW}^2 + 10.34\ \text{IW} - 890.75} \tag{13}$$

According to the solution of Equation (11), onion biomass production is started after a threshold of 90.76 mm of water application depth. The maximum production will be achieved at a water application depth of approximately 943 mm, and beyond that, the biomass yield will decrease with additional water application. The yield will be zero if the water application depth exceeds 1782.7 mm. These findings can help plan how to maximize onion yield by water supply in the study area.

4. Discussion

The increase in plant height observed in the experiment may have been due to the maximum retention of soil moisture using polythene films during the growing period. Job et al. [53] and Sarkar et al. [30] reported that plastic mulch significantly affects plant height, and this altered favorable growing micro-climatic environment in the soil may affect bulb length and diameter. The amount of water applied affected the height of onion plants, canopy coverage, and biomass. Onion crop canopy cover was increased with an increase in the number of days after transplanting while decreasing with an increase in deficit irrigation [54].

It was reported that sandy loam soil requires frequent irrigation with less water per irrigation. Onions have shallow roots; unless the moisture supply is constant, the bulb will mature early, and the resulting sizes may be small. In our study, we applied daily irrigation throughout the growth period; the maximum root depth was, on average, 4.86 cm, with no significant differences between treatments, so the amount of water supplied varied between 525 mm (T5) and 1500 mm (T1). The differences in dry biomass weight directly resulted in differences in yields for all treatments, which are related to the effects of irrigation amounts on bulb size [55,56].

Our results regarding TSS are consistent with those reported by Enciso et al. [57] and Abdelkhalik et al. [58], who found that onion bulb TSS was not affected by the level of irrigation, which agrees with our observation of no significant differences between treatments. The reason for the lack of differences observed between the irrigation treatments in relation to the bulb soluble solids content may be attributed to the similarity in dry matter content among all bulbs. This implies that there was a consistent dilution of soluble solids across all bulbs, leading to similar TSS values despite variations in the applied irrigation water. On the other hand, Kumar et al. [55] and Leskovar et al. [59] reported that higher irrigation amounts increased onion bulb TSS. Our results showed an inverse relationship between applied water and TSS. The mean bulb weight and bulb size were similarly affected by irrigation level as bulb weight per plant, as these quality parameters are closely related to the dynamics of bulb formation. In contrast, TSS appears to be less sensitive to differences in irrigation management. In addition, the percentage of grade A bulbs decreased, and grade C bulbs increased with decreasing irrigation water. A similar effect of irrigation on onion bulb size was also observed by Martín de Santa Olalla et al. [60] under drip irrigation.

From a commercial perspective, it is worth noting that treatments T1 and T2, characterized by higher water application, yielded significantly larger and heavier bulbs. This implies that larger onions can be produced by increasing water application, which is consistent with findings from previous studies [57,58] that reported higher total marketable, jumbo, and colossal yields with more frequent irrigation. The commercial relevance of this observation lies in the fact that jumbo onions command a higher market value. Therefore, irrigation during the bulb stage is a promising commercial strategy.

In this study, the irrigation water productivity (IWP) values for onion crops ranged from 2.18 to 3.42 kg m^{-3}, which were found to be considerably lower than those reported by Ramalan et al. [61] in Ethiopia (9.16–15.94 kg m^{-3}) and Igbadun et al. [29] in Nigeria (3.8–5.2 kg m^{-3}). However, the findings of this study also indicated that the water productivity of onion crops is comparable to that reported by Nyath et al. [62] for traditional vegetables (1.29 kg m^{-3}) and alien vegetables (1.37 kg m^{-3}). These discrepancies in water productivity could be attributed to several factors, such as differences in location, irrigation methods, and crop varieties. Although IWP is a widely used index to quantify crop water use efficiency, a more appropriate index for comparative purposes is RCWP. Unlike IWP, RCWP is calculated based on a relative increase in crop yield and transpiration under a particular treatment over the situation where the crop faced maximum water stress in the soil. Therefore, it can better assess the actual water use efficiency. The overall results of our study indicated that both deficit and excess irrigation did not significantly affect either yield or water use efficiency.

Non-linear regression analysis determined the relationship between biomass production and applied irrigation water. Onion biomass was considered as the dependent variable and plotted against applied water to derive mathematical functions that can predict onion yield under similar agro-climatic conditions without conducting costly crop experiments. These equations can also guide potential water allocation decisions related to limited irrigation water. Similarly, curvilinear (second-degree quadratic) relationships were found in studies conducted on onion crops [6,63], indicating efficient utilization of applied water that improved water productivity (WP). However, other studies reported a linear decrease in WP with increasing seasonal water deficits for different onion cultivars [58,64].

The blue water footprint (WF blue) of the onion crop varied from 34.1 m^3 t^{-1} in T5 to 20.91 m^3 t^{-1} in T1, which was 89% lower than the values reported by Al-Gaadi et al. [65] and Esmaeilzadeh et al. [66], who reported a WF of 136.15 m^3 t^{-1}. The values obtained for crop water footprint in this study are slightly lower than the results reported in previously published studies.

The water requirement at which maximum production was achieved in this study was found to be higher than the water requirement for optimal bulb yield reported by other studies. The difference in the threshold water level at which bulb yield begins between actual crop evapotranspiration and applied irrigation water can be attributed to water retained at the depth of the root zone in the soil and loss through deep percolation typical of sandy soils [29].

Our study has yielded significant findings regarding water use by assessing multiple indicators. These findings hold practical implications for producers and development entities engaged in bulb onion production within the Colombian dry Caribbean region, enabling them to make informed decisions regarding water management strategies. One limitation of this study is the limited scope of onion cultivars used. Consequently, future research should prioritize the inclusion of multiple cultivars to broaden the available options for onion producers. Mulching is critical in conserving soil moisture, suppressing weeds, and regulating temperature, significantly impacting water use efficiency and overall onion growth. Future regional studies should encompass various mulching materials and techniques to expand our understanding of their effects on water use efficiency and crop performance. Our study lays a solid foundation for further research. It provides valuable insights for practitioners and decision-makers involved in onion cultivation in the Colombian dry Caribbean region.

5. Conclusions

The field experiments conducted under tropical semi-arid conditions in Colombia revealed significant positive effects of mulching and irrigation on onion growth, yield response, bulb quality, and water use efficiency. The application of these practices resulted in increased bulb diameter and total bulb yield, indicating their importance for maximizing onion production.

The study assessed irrigation water productivity (IWP) values for onion crops, which ranged from 2.18 to 3.42 kg m^{-3}. To further enhance IWP, it is recommended to adopt advanced water-saving technologies and implement optimum (need-based) strategies for fertilizers, agricultural films, and pesticides. The efficient utilization of these inputs can significantly improve water productivity in onion cultivation.

The findings emphasize the need for improved irrigation management, specifically regarding irrigation schedules and drip irrigation design, based on the components of the soil water balance. Optimization of these factors is crucial for enhancing crop transpiration relative to total water use, ultimately leading to improved irrigation system performance.

The study underscores the potential benefits of implementing efficient irrigation practices and utilizing advanced water-saving technologies to enhance onion yield, quality, and water use efficiency in tropical semi-arid regions. These findings provide valuable insights for farmers and policymakers, enabling them to optimize water usage and maximize crop productivity in similar geographical areas.

Considering the high economic cost of water, it becomes crucial to minimize water consumption in onion cultivation. In situations where water is expensive, it is advisable to apply reduced irrigation levels, such as those used in treatments T4 or T5. However, if larger-sized bulbs have greater economic value, it may be preferable to utilize full irrigation water. Striking a balance between water consumption and bulb size can optimize water usage while maximizing economic returns in onion production.

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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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