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# Irrigation Alternatives for Avocado (*Persea americana* Mill.) in the Mediterranean Subtropical Region in the Context of Climate Change: A Review

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**Abstract:** Due to congenital features, avocado (*Persea americana* Mill.) trees are substantial water users relative to other fruit trees. The current growing deficiency of water resources, especially in arid and semi-arid avocado-producing areas, has led to the demand for more sustainable water-saving measures. The objective of this review was to analyze the role of deficit irrigation as a strategy to face climate change and water scarcity through achieving efficiency, saving water, and maximizing the benefits that could be achieved at the level of the irrigated agricultural system. Particular attention is devoted to studies performed in the subtropical Mediterranean climate, in which irrigated avocado orchards are common. These studies analyzed irrigation demand, deficit irrigation, and determination of water status through physiological parameters, leading to possible sustainable irrigation programs for avocado in the context of water shortage scenarios. Through these insights, we conclude that under the current climatic circumstances with respect to available water resources, avocado farming requires sustainable resilience strategies to reduce irrigation water consumption without affecting the yield and quality of the fruits. Water stress inevitably affects the physiological processes that determine yield. Therefore, an admissible yield loss is required with smaller fruits and water savings made through deficit irrigation strategies. In addition, modern consumers tend to prefer foods based on sustainability, i.e., there is a high demand for socially responsible and environmentally friendly products.

**Keywords:** avocado; climate change; deficit irrigation; subtropical Mediterranean farming; water use efficiency



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## 1. Introduction

Avocado (*Persea americana* Mill.) is a member of the Lauraceae family, which includes 50 genera and about 2500–3000 species, with three main horticultural breeds (Mexican, Guatemalan, and West Indian) [1,2]. The avocado fruit reached relevance in world trade due to its benefits for human health, as described by numerous studies. Its nutritional value is due to its high protein content and exclusive fat-soluble vitamins [3,4]. It is used in the pharmaceutical and cosmetic industries for its high oil content [5], and is highly valued nutritionally for its omega fatty acids content [6,7].

The avocado tree is extensively cultivated in tropical and subtropical regions, and, according to FAOSTAT [8], the area devoted to avocado cultivation in the world reached 807,469 ha in 2020, with an average growth rate between 2016 and 2020 of 29%. Clearly, avocado production worldwide is growing rapidly due to international demand and the good price level for both farmers and marketing companies. In 2020, world avocado production exceeded 8 million tons, 41% higher than in 2016. The main avocado producing countries are Mexico (2,394,000 t), Colombia (877,000 t), Dominican Republic (676,000 t), Peru (660,000 t), and Indonesia (609,000 t), which represent 71.2% of total production [8].

Similarly, in relation to avocado exporters, Mexico is the main world supplier with 1,159,000 t, and the main importers are USA (1,117,000 t); the European Union (EU), including the Netherlands (414,000 t), Spain (174,000 t), and France (171,000 t); and the United Kingdom (UK) (122,000 t). In the EU, the flow of imports is continuous throughout the year and derives mainly from re-exports from the Netherlands (27% of the total value) and Spain (12%), as well as direct exports from Peru (18%). Spain is the only producing country in Europe, and this production is exported to EU and other countries. According to the Agricultural Outlook 2021–2030 report of the OECD and the FAO, avocado will become the most commercialized tropical fruit in 2030, with a world production of 12 million t expected for this year, of which over 3.9 million t will be exported. The USA and EU will continue to be the main importers in the next decade, representing 40 and 31% of world imports in 2030, respectively.

According to Crane et al. [9] "Hass" is the major avocado cultivar, accounting for 90% of export trade. The cv. "Fuerte" is slightly smaller than the cv. Hass and has a green skin with darker spots, with its pulp tasting sweeter and less buttery than that of the Hass cultivar. "Reed" avocados are a late-season cultivar with an upright growth habit and spherical fruit. In contrast, fruits cv. "Bacon" are oval-shaped and have smooth, slim skin that is dark green in color with weak mottle throughout. This cultivar has light yellow–green pulp and is less fatty than cv. Hass. There are many other avocado cultivars (Ettinger, Lula, Pinkerton, Gwen, Zutano, Lamb Hass, Mexicola, Queen, etc.), and their production can vary depending on the producing country and the opening times and pollination behaviors of flowers.

Avocado is a crop that adapts well to tropical and subtropical climates, and this versatility makes its cultivation possible in regions with a typical Mediterranean climate. In these areas, the availability of water is limited in summer, with a high potential salinity risk of irrigation water, which is typical in coastal areas, posing a challenge for cultivation in the context of the changing climate. For this reason, in the Mediterranean basin, water is the main limiting factor for crop production [10]. In this sense, water scarcity threatens the agricultural sustainability of arid and semi-arid regions; therefore, the efficiency in the use of irrigation water must be improved, particularly under global warming conditions [11]. Many studies reported that climate change will exacerbate these circumstances through increasing temperature and frequency of droughts and reducing rainfall depths [12–14]. Therefore, agricultural production systems must adapt to meet the growing demand for food in the face of increasingly adverse weather conditions and an increase in extreme weather events. In this context, it is well known that that agricultural systems are the largest consumer of water resources, with a significant amount of all global freshwater withdrawal [15,16]. In addition, a large amount of water related to avocado cultivation circulates from producing countries, causing chronic problems of water stress in regions richer in water (USA, Japan, Canada, and the EU) [17,18].

The growth of the European market, due to upward trends in consumption of this fruit, provoked many Mediterranean avocado-producing countries to increase their areas and levels of production [19]. From this perspective, according to the latest FAOSTAT report [8], Israel is the main avocado grower with 147,000 t, followed by Spain (99,070 t), Morocco (69,940 t), Lebanon (18,623 t), Turkey (5923 t), Greece (9570 t), France (2040 t), Cyprus (940 t), Palestine (794 t), and Tunisia (319 t). Under the current circumstances, it is urgent to adopt substantial changes for the cultivation of irrigated avocado, and it will be imperative to change the traditional irrigation systems with high amounts of water for systems that reduce water consumption. This method means developing efficient water management strategies and redesigning irrigation scheduling in a challenging environment [20,21].

The contribution of agricultural systems in protecting food security and the economy of the region are essential in the Mediterranean basin. Thus, given the particular climatic conditions in the area (e.g., absence of precipitation in the warmer months, high intra- and inter-annual variability, and frequent droughts), irrigation is essential to maintaining crop yields [22,23]. Moreover, irrigation-related issues become more pressing and complex when the groundwater resources are overexploited or saltwater intrusion occurs, as was reported by Mas-Pla et al. [24] and Alfarrah and Walraevens [25] for the coastal zones of arid and semi-arid areas in the Mediterranean basin, especially in those areas devoted to avocado farming [26]. Regarding adaptations in irrigated agriculture in the semi-arid Mediterranean region, Harmanny and Malek [27] identified 31 adaptation strategies in five categories: "water management, sustainable resource management, technological developments, farm production practices, and farm management". Of these strategies, the most frequently used by farmers in the region correspond to the categories water management and farm production practices.

The avocado tree is especially reactive to a lack or surplus of water, with the water supply being a key factor affecting yield. Two main irrigation systems are used for avocado cultivation: sprinkler irrigation, which suitable for sandy soils; and drip irrigation, which is a more appropriate technique for saving water. It is well known that, in Mediterranean conditions, water is progressively becoming a limited resource due to the competition between different demands, especially agriculture, tourism, industry, domestic, and environmental uses [19,28,29]. For agricultural activity, due to the growing shortage of irrigation water in semi-arid regions in a changing climate, farmers are being forced to consider sustainable water savings through adopting deficit irrigation options [30,31]. Saving water through deficit irrigation strategies is crop-dependent and normally involves minimal or no yield loss, thus increasing water productivity. Thus, the water management system in modern avocado farming demands adaptive and proper irrigation scheduling because unsuitable use of water, either in excess or deficit, can lead to irregular productivity and accordingly distorted fruit yield.

The main objective of this review is to offer a general description of the current knowledge on irrigation strategies for avocado, as well as the aspects that should be the focus of future research to improve productivity and water use efficiency (WUE) for avocado cultivation in the Mediterranean subtropical regions.

## 2. Avocado and Water Requirements

Since the avocado tree is native to humid subtropical and tropical regions with plenty of rainfall, its cultivation in other climatic regions and environmental conditions requires supplementary irrigation to cover water requirements [32,33]. According to Fonseca et al. [34], the avocado water requirements are dependent on cultivar and cultivation environment. The Antillean, Guatemalan, and Mexican types are the best adapted and most resistant to low temperatures.

Generally, the calculation of crop water requirements is based on the reference evapotranspiration ($ET_0$) and crop coefficient ($K_C$) [35]. The $K_C$ takes into consideration the specific edaphoclimatic conditions and phenological state, which allows the specific water requirements during the entire crop cycle to be estimated. The conventional estimation of $K_C$ values is based on lysimeter studies, either via weighing or drainage [36–39]. In general, a mature tree requires at least 1000–1300 mm of rainfall per year. In subtropical regions with annual rainfall equal to or less than 1000 mm and long periods without rainfall, it is necessary to provide water to the crop through irrigation [40–42]; in contrast, tropical environments with short dry annual periods disregard avocado irrigation, as stated by Erazo et al. [43]. Kalmar and Lahav [44] reported that avocados grown in areas of Israel with winter rains require around 6680 $m^3$ $ha^{-1}$ $year^{-1}$ are irrigated only 8 months a year, while in areas such as South Africa irrigation is necessary all year round. A study in California found that avocados required 7875 $m^3$ of water per ha year [45]. In Mediterranean environments, a single tree can require up to 51 mm of irrigation water per week during the warm and dry summer months. Thus, in hot climates, avocado water use is about 45 L $day^{-1}$ in spring, while ranging from 136 to 220 L $day^{-1}$ in summer and 121 L $day^{-1}$

in autumn [46]. Similarly, in Israel, Lahav et al. [47] recommended irrigation application rates for the mid-summer and young trees for the first, second, third, and fourth years of 4–8, 8–15, 20–50, and 80–150 L $day^{-1}$ $tree^{-1}$, respectively. In agreement with Olalla [48] and Farré [49], the irrigation requirements in the Spanish Mediterranean semi-arid conditions ranged between 7500 and 8000 $m^3$ $ha^{-1}$.

A study conducted by Mazhawu et al. [50] in South Africa using the eddy covariance technique determined that the mean daily water use for the season was 2.69 mm $day^{-1}$, with a mean daily use of 3.98 and 1.64 mm $day^{-1}$ in summer and winter, respectively. According to these authors, the estimation of $K_C$ showed a good correlation between ET and $ET_0$, suggesting that they could be used to provide rational ET values for avocado orchards. Recently, Moreno et al. [40] reported for the subtropical Mediterranean Spanish coast that the water irrigation in avocado plantations was usually about 5300 $m^3$ $ha^{-1}$ $yr^{-1}$, but can amount to 7000 $m^3$ $ha^{-1}$ $yr^{-1}$, which contrasted with other producing regions, which required 8000–9000 $m^3$ $ha^{-1}$ $yr^{-1}$, as Ferreyra and Sellés showed [51]. Holzapfel et al. [52] highlighted an irrigation dose of 10,071 and 8887 $m^3$ $ha^{-1}$ $yr^{-1}$ for fruit yields of 29.6 and 26.9 t $ha^{-1}$, respectively. In agreement with Carr [33], for Mediterranean regions, the use of water was maximum in summer, being between 3 and 5 mm $day^{-1}$, and the $K_C$ was usually between 0.4 and 0.6, with WUE between 1 and 2 kg $m^{-3}$. Similarly, in SE Spain, Olalla et al. [48] reported that the use of a $K_C$ of less than 0.55 decreased both yield and growth, and prolonged use could cause further reductions. With this value of $K_C$, an average water consumption of around 8500 $m^3$ $ha^{-1}$ $yr^{-1}$ would be obtained. Durán et al. [42] estimated that full water requirements for terraced avocado plantations were 7868 $\pm$ 286 $m^3$ $ha^{-1}$ per season.

Taking into consideration the fact that the climatic conditions are becoming warmer and dryer, and water availability and quality cannot be guaranteed, agricultural production systems that traditionally cultivated rainfed plantations are currently changing to systems with additional irrigation [53,54]. In this context, Cantuarias et al. [55] in Brazil evaluated the response to supplemental irrigation in cv. Hass avocado orchards. A rainfed crop was compared with two irrigation strategies, applied during the entire and half of the irrigation run time, which corresponded to 5091 and 2545 $m^3$ $ha^{-1}$, respectively. They found that complementary irrigation administered during half of the run time improved fruit yield by 18.2%. In addition, for rainfed systems, Silva et al. [56] concluded that taking into account the duration of each phenological stage in avocado, it is possible to program the applications of foliar fertilizers and soil amendments, at the appropriate time, during shoot or root growth flushes, respectively, in order to guarantee the ideal nutritional status of the crop.

The avocado tree has shallow roots that spread mainly in the top of soil and are not efficient in exploiting water from deeper soil layers. Maintaining soil moisture within an optimal interval led to improved fruit yield and decreased alternate bearing in avocado [47,57,58]. From this perspective, to maintain appropriate water requirements, frequent light irrigation supplies may foster shallow root system growth, making the tree less tolerant to drought and strong winds [59]. Flooding is also not desirable as it provokes root rot as well as water and nutrient runoff [60,61]. According to Roets et al. [62], the data obtained from continuous soil moisture readings showed that water withdrawal patterns differ significantly throughout the avocado's phenological cycle. Few studies have previously been carried out on the water requirements relative to phenological stages, in contrast with the effect of stress during different phenological stages. Thus, determining the seasons of shoot and root flushing, flowering and fruit set may help in optimizing the water requirements and, consequently, the scheduling irrigation in avocado orchards [63,64].

Thus, the calculation of irrigation requirements based on avocado phenology could be used as a tool to develop water use trends for annual water requirements and adapted for given climatic conditions throughout the production season. Table 1 shows a brief summary of studies related to the avocado water requirements.

**Table 1.** Studies in relation to avocado water requirements.

| Avocado Cultivars | Growing Regions | Treatments | Measurements | Main Findings | Reference |
|---|---|---|---|---|---|
| Hass | New Zealand | Edaphoclimatic conditions and fruit load | Water use ($ET_0$, plant transpiration, and $K_C$) | Water use in January was 2.7 mm day$^{-1}$, while in June it was 1.2–1.4 mm day$^{-1}$. The average monthly $K_C$ was 0.60–0.65. $K_C$ for fruit load (from 0.50 to 0.85). | [65] |
| Hass | New Zealand | Water deficit in flowering and fruit-development stages | Water use | $K_C$ ranged from 0.45 to 0.60 for mature and from 0.25 to 0.30 for youth trees. The control had a higher average yield (36.4 ± 1.1 kg tree$^{-1}$) than the water-stressed (27.8 ± 1.0 kg tree$^{-1}$). Trees with deficit irrigation during spring flowering not greatly affected by water stress. | [66] |
| Hass | Israel | Lysimeter experiment with three treatments and two soil volumes (100 and 200 L) | Effects on avocado water stress and plant performance | The abscission was more severe in 100 L than 200 L containers (Irg3 > Irg2 ≫ Irg1). Net $CO_2$ assimilation at fruit growth declined under moderate or severe water stress (Irg2 and Irg3, respectively); fruitlet abscission was the consequence of carbohydrate stress. | [57] |
| Hass | Chile | Irrigation doses based on $ET_C$ | Water use, elucidating the proper $ET_C$. | Irrigation based on 90 and 100% $ET_C$ severe water stress was contrasted with 110 and 130% $ET_C$. The $K_C$ of 0.72 was closer to the latter treatments, which corresponds to irrigation of 7000 and 9000 m$^3$ ha$^{-1}$ yr$^{-1}$, respectively. $K_C$ value for the entire season was 0.72. In fruit yield terms, 110% $ET_C$ was the most effective dose. | [67] |
| Hass and Fuerte | South Africa | Alternating wet and dry periods at different phenological stages (I, II, and III). | Water use | Yield was not affected. The impact of water stress induced through the dry period during fruit growth on fruit size was variable. For summer, water use amounted to 5 and 4 mm ha$^{-1}$ day$^{-1}$; for winter, it amounted to 1.5–2.0 mm and below 1.5 mm ha$^{-1}$ day$^{-1}$; and, for the whole season, it amounted to 1020 and 890 mm for cvs. Fuerte and Hass, respectively. | [68] |

$K_C$, crop coefficient; $ET_C$, crop evapotranspiration; $ET_0$, reference evapotranspiration.

### 2.1. Water Stress Effects on Avocado Tree

Water stress negatively affects numerous functions of the plant physiology, such as photosynthetic capacity, vegetative growth and productivity, which are sharply reduced. To combat this problem, plants have developed complex physiological and biochemical adaptations (e.g., secondary metabolism) to face a variety of surrounding environmental stresses.

In this context, high temperature and/or low relative humidity generate a high evaporative demand that is best characterized mechanistically as vapor-pressure deficit (VPD). Under water stress conditions, a high VPD eases diffusion of water vapor out of and away from the leaf surface into the air, and windy conditions can increase water vapor flux. Generally, at low VPD, there is less difference in water vapor concentration between leaf and air, leading to low transpiration rates. Avocado trees respond to increasing VPD by closing their stomata to reduce transpiration in an adverse environmental situation [69,70].

#### 2.1.1. Phenological Stages

Water stress adversely impacts avocado phenological growth stages, provoking different collateral responses in consonance with the stress level applied. According to Silber et al. [52], the avocado tree has a potential photosynthetic capacity to yield more than

30 t ha$^{-1}$ with 17% of oil content. However, the prevailing yield is regulated through high abscission rates of flowers and fruits; therefore, the average avocado world production is around 10.0 t ha$^{-1}$, as noted by Garner and Lovatt [71]. These authors reported that fruit and flower abscission is not linked to tree growth or other factors, such as soil moisture or leaf nutritional status. From this perspective, the large requirements for carbohydrates throughout the fruit development stage often concur with elevated temperatures and high evaporative demands, which may be the principal reason for fruit abscission, as was revealed by Wolstenholme et al. [72]. Moreover, there are periods where water availability is vital: flowering, fruit set, and seed development. High starch concentrations were found during the flowering set stages to be an adaptive strategy against water stress in order to maintain carbohydrate reserves during alternate bearing cycles [73,74].

In a Mediterranean environment, the period of avocado fruitlet development occurs in the season of less water availability and when high temperatures are also frequent, which can cause fruitlet abscission. Many authors showed that water stress provoked a decrease in annual flushes, leaf area, shoot length, and trunk growth; an inferior canopy volume; and a decrease in volume of fine roots [47,75,76]. Particularly, Chartzoulakis et al. [76] reported that cv. Hass was more susceptible to water stress than cv. Fuerte, highlighting cultivar-specific effects on water requirements.

The avocado stomas react to temperature variations faster than to changes in air humidity, with trees reacting to high evaporative demand as air temperature rises. In the avocado flowering stage, raised transpiration in response to larger potential transpiration levels is reduced to 10 mm day$^{-1}$ [77]. Under non-irrigated and high evaporative demand conditions, the water stress expands in the avocado tree canopy because of an excess of transpiration related to uptake and conduction of water from the soil. In this situation, the water required can be partly provided using the water stored in its tissues; hence, severe water stress at early fruit set and fruit growth periods can result in reduced water between fruits and leaves. Under such circumstances, according to Borys [78], the leaves take water from fruits, which wilt severely, and if they do not recover their turgor, abortion can occur. This result is more evident for the most demanding phenological stages: flowering and fruit set, where a great quantity of carbohydrates are conducted from the leaves to the fruits, and the fruit-growth period, where a high demand for carbohydrates is required for the formation of fatty acids, as was revealed by Liu et al. [79,80] and Burdon et al. [81]. In addition, water deficit throughout early-season growth was proved in leaf chlorosis, increasing in gravity as flower buds emerged and flowering occurred [41], provoking significant leaf defoliation and fruit abscission. In this context, the fruit abscission is ascribed to water stress impact as few carbohydrates are available to contribute to the growth of avocado fruits [41,82].

Water provision is critical at the flowering period due to the transpiration rate of flowers usually being larger than that of leaves, and fruit growth is mainly linked to water storage in its tissues. In this sense, Blanke and Lovatt [83] determined that the avocado floral stomata were highly functional and their share of the total water usage of a tree was significant, concluding that during flowering stage, there are more than 2 million transpiring flowers with an estimated surface area of 54 m$^2$ in the tree periphery. According to Chanderbali et al. [84], avocados usually flower plentifully, reaching up to 1 million flowers per tree; however, fewer than 0.1% of these will be able to pass the next stage of fruit set, where water stress should be avoided.

In addition, Whiley et al. [69] reported that in the flowering stage, the evaporative area increases by up to 90% due to the abundant small avocado flowers with an elevated evaporation ratio, leading to an augmentation of tree transpiration ratio from 13 to 15%. Under these circumstances, the water stress at this phase can provoke flower abortion, fruitlet abscission, and early leaf drop [85]. Thus, the water stress limits the photoassimilate availability to maintain fruit set and disturbs the productive potential [86]. In this context, Lahav et al. [47] concluded that a restricted water supply at flowering and fruit set phenological periods might also lead to reduced fruit size and avocado fruit quality.

Fruit growth can generally be considered to take place in different stages: fruit set, fast cell division, cell enlargement, maturation, and ripening. After fruit set, cell division, and cell enlargement stages are controlled by hormones, the cell division phase being more critical than posterior cell expansion in establishing final fruit size; the optimal water supply in avocado trees is crucial for encouraging these stages.

Chartzoulakis et al. [76] proposed that avocado trees use osmotic adjustment as their main dehydration strain tolerance in water stress states. In this context, Sharon et al. [87] determined that avocado trees adjusted osmotic potentials in response to transpiration losses. This means that avocado trees exposed to water stress respond by closing their stomata to control transpiration water losses, allowing them to survive temporarily and maintain levels of photosynthetic activity using plant water storage [87]. A heavy fruitlet abscission usually takes place from flowering to the stage of initial cellular development and is induced via competition between young fruit and vegetative growth, vulnerability to air temperature, and water stress [88,89].

In general, water stress during fruit set and early fruit development could lead to lower fruit yields or even important losses. From this perspective, the avocado fruit size could be negatively impacted by low water availability. In an experiment conducted by Durán et al. [42], it was demonstrated that water availability influenced avocado fruit growth and weight; as a result, the fruit size was adversely affected by water-stressed trees (avocado fruit length from non-stressed, moderate, medium, and severe water-stressed trees of 97.3, 87.0, 88.9, and 79.4 mm, and fruit widths of 66.2, 60.5, 60.5, and 54.9 mm, respectively). This finding is in consonance with findings of Holzapfel et al. [52], determining a positive relationship between irrigation volume and fruit size. However, there are some studies showing that fruit size is linked to number of fruits per tree, rather than the irrigation administered [75,90].

Figure 1 shows the effect of different water stress levels derived via sustained deficit irrigation on avocado tree development, which could be ascribed to the decline in growth either directly through its effect on turgor or indirectly through restricting carbon gain.

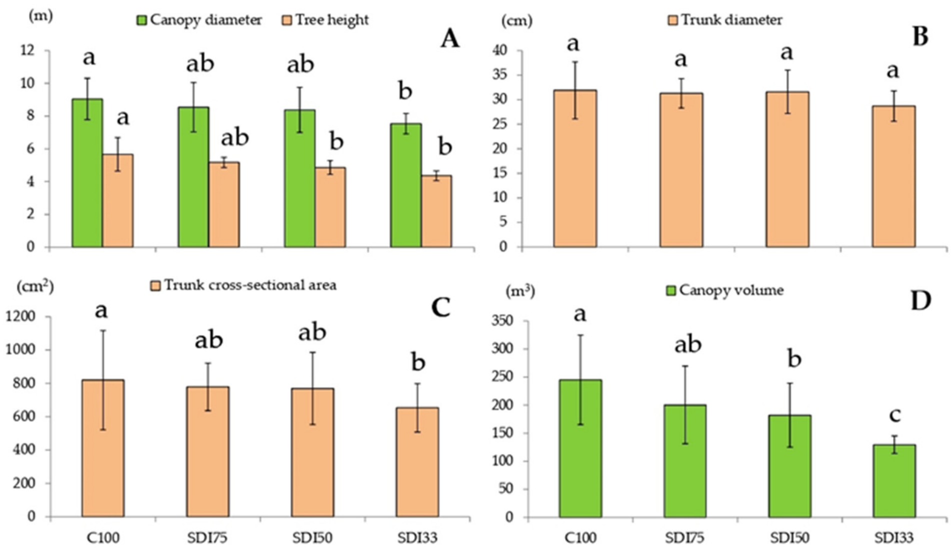



**Figure 1.** Response of avocado canopy diameter–tree height (**A**), trunk diameter (**B**), trunk cross-sectional area (**C**), and canopy volume (**D**) to deficit irrigation treatment. SDI, sustained deficit irrigation; SDI33, at 33% $ET_C$; SDI50, at 50% $ET_C$; SDI75, at 75% $ET_C$; C100, control at 100% $ET_C$. Values followed by same letter within same column are not significantly different using Tukey's least significant difference test ($p < 0.05$). Vertical bars are standard deviation.

### 2.1.2. Root System

The responses of most crop root systems to water stress involve complex biological processes [91]. Overall, well-watered roots provide a well-developed branching pattern that uptakes water and nutrients, providing storage and better root growth. Ding et al. [92] reported for peanut (*Arachis hypogaea* L.) that water stress augmented the root biomass, surface area, and volume at 20–40 cm soil depth but declined in the soil layers under 40 cm. In relation to the avocado root system, Lahav et al. [47] reported that its distribution is fairly shallow (more than 70% at 60 cm soil depth) and sensitive to water deficit, which may be proven in wilting or abscission of leaves and fruits and might irreversibly impact final fruit quality [93,94]. According to Doupis et al. [95], the avocado root system has a reduced hydraulic conductivity, elevated oxygen demand, and low water-uptake efficiency that has attracted special attention in research related to providing proper water management supplies adapted to these particular features. Schaffer et al. [32] reported that water stress also restricts root expansion; this issue may diminish stem water potential ($\Psi_{stem}$) and biomass production [96,97].

No evident effect of irrigation frequency on root zone volume, flowering intensity, or fruit set was found by Silber et al. [57]. However, the fruit drop was more severe the lower the root volume and the higher the irrigation frequency every two days. In addition, these authors pointed out that the daily irrigations mitigate water stress, and irrigations every other day provoke serious water stress. In this sense, Cantuarias et al. [98] and Salgado and Cautín [99] conducted studies to determine the soil texture effect and type of irrigation system on this particular distribution. Accordingly, the ability of soil exploration and water absorption is reduced and, as a result, highly sensitive to water stress periods. Thus, the avocado root system is probably an intrinsic feature, which is still a problem in the context of water scarcity for Mediterranean region, due to the low rainfall depths and irregular annual and intra-annual distribution. Many studies revealed that the development of roots is highly dependent on the amount of water provided and, consequently, its uptake by the tree [44,57,100].

According to Metcalfe et al. [101] and Lima et al. [102], lower water availability during root flush can delay root growth and, particularly during a longer dry period, decrease the avocado surface root length density by 25% [103]. This problem is of high importance because root flushes have an alternating growth pattern with shoot flushes and fruit growth, competing for carbohydrate resources and available water [104].

Conversely, the selection of an appropriate rootstock provides a suitable tool to manage the growth, water uptake, and fruiting of the scion [105,106]. From this perspective, Fassio et al. [107] determined rootstock Duke 7 to have a 29% larger sap flow rate and transpiration than Toro Canyon. These findings indicate that the variations in water consumption by cv. Hass on different rootstocks may be linked to the efficiency of the roots in taking up water via conductive tissue, which may be related to differences in the area of root xylem vessels. Recently, Beyer et al. [106] observed differences in aerial, root growth, and water use efficiency between cv. Hass trees on two different rootstocks: Dusa (clonally propagated) and Mexicola (sexually propagated). The study determined notable differences in root hydraulic properties in the latter case, showing fine roots and a greater capacity for water uptake. These findings highlight the importance of taking into account this physiological knowledge in avocado rootstock breeding programs to deal with water stress conditions resulting from water scarcity.

#### 2.1.3. Avocado Fruit Yield and Fruit Quality

Water stress can practically impact all plant morphological and physiological processes, particularly if the duration and severity of stress are intense, which ultimately affects crop yields. In this context, Wolstenholme and Whiley [74] reported that avocado has a certain degree of tolerance to water stress, although its adaptation is mostly mesic. In a Mediterranean environment, water stress generated via deficit irrigation based on 40–60% of the FAO-56 calculated $ET_C$ water requirements during the growing season lowered avocado yield by 30% [40].

In Israel, Lahav et al. [108] reported a significant relationship between irrigation water amount and relative avocado yield, determining that for a 1000 $m^3$ $ha^{-1}$ reduction in the water requirement, yield loss amounted to 2.2 and 1.6 t $ha^{-1}$ for cv. Hass and cv. Fuerte, respectively. This result pertained to roughly 20% yield loss. Recently, in Spain, the water stress imposed through sustained deficit irrigation based on reduction fractions of 33, 50, and 75% $ET_C$ in relation to control trees (100% $ET_C$) provoked yield losses of 33, 19, and 8%, respectively [42]. Holzapfel et al. [52] reported the effect of water stress on productivity in four irrigation treatments based on 25, 50, 75, and 100% $ET_0$, with yields of 14.5, 17.8, 22.1, and 23.0 t $ha^{-1}$, respectively. Comparably, Gil et al. [109] determined the avocado fruit yield irrigated with 0.65 and 0.77 $ET_0$ as 13.4 and 15.4 t $ha^{-1}$, respectively. In this context, the reduction in water irrigation relative to $ET_0$ over 4 years showed an amelioration of WUE by 87–93% without any loss impact on yield [110]. In addition, Silber et al. [41] found yields for non-water-stressed trees ranging from 25 to 31 t $ha^{-1}$; this figure differs significantly for water-stressed trees with lower yield, the yields of which ranged from 6–21 t $ha^{-1}$. From this perspective, Bayram et al. [111], in a study conducted in Turkey without irrigation limitations, reported a mean average fruit yield of 76.9 kg $tree^{-1}$ (~15.4 t $ha^{-1}$). In Spain, Moreno et al. [40] reported an average fruit yield of 10.34 $\pm$ 1.98 t $ha^{-1}$ for 6-year monitoring seasons in conventional irrigation (6503 $m^3$ $ha^{-1}$) and 16.5 and 8.7 t $ha^{-1}$ for on-crop and off-crop seasons, respectively.

Finally, Darwish and Elmetwally [112] reported that a combination of drip and sprinkler systems in avocado orchards resulted in larger fruit yields due to a more distributed and improved root system, yielding 21.0 and 14.6 t $ha^{-1}$ for cvs. Hass and Ettinger, respectively.

Conversely, according to many studies, water stress led to a delay and uneven yield in post-harvest avocado fruit ripening [85,113–115], as well as physiological disorders, such as gray pulp and pulp spot, as was highlighted by Bower et al. [85] and Arpaia [116]. According to Kalmar and Lahav [44] reduction in irrigation intervals tended to raise the avocado oil percentage of fruits, which may stall the harvest date. It was determined that the 21-day interval was the ideal irrigation frequency for avocado cv. Hass trees. In this sense, water-stressed trees under deficit irrigation conditions exhibited reduced avocado fruit size but augmented the omega-3 and omega-6 fatty acid contents, as well as the unsaturated fatty acids (oleic), in a Mediterranean subtropical environment [42]. There is scarce scientific evidence for the water stress effect on avocado fatty acid profile; however, studies on other fruit crops, such as almonds, highlighted an increase in fatty acids under water stress conditions. In this sense, Gutiérrez et al. [117] reported that with deficit irrigation, an increase in both monounsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFAs) were registered. Similarly, Lipan et al. [118] observed a rise in PUFAs but a decrease in MUFAs as a result of water stress.

### *2.2. Water-Saving Irrigation Strategies*

In a convoluted scenario exacerbated due to climate change and rising population demand, it is vital to adopt crop production systems that entail a lower use of irrigation water. Thus, with a rising shortage of water resources and the requirement for irrigation, optimization is urgent for water-saving strategies [10]. In this context, deficit irrigation (DI) is a strategy that aims to maximize the productivity of irrigation water, with a seasonal application concentrated in the growth stages of crops. DI is the application of water below full crop water requirements and is the main tool used to achieve targets for lessening irrigation water use.

There are two major types of DI: sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI). The SDI provides the same percentage of $ET_C$ throughout the entire phenological cycle, which implies an increase in water stress throughout the crop cycle. In contrast, the RDI concentrates water stress in specific phenological stages based on the response of the plant at each stage, allowing greater control over vegetative growth, yield, and fruit size. Another type of DI is partial root drying (PRD), which is applied in many fruit crops [119,120] and fundamentally based on wetting only half of the root system, while the other half remains dry, alternating between wet and dry cycles every 7 to 10 days. This alternation between dry and wet periods fosters biochemical reactions, driving a balance between vegetative and reproductive growth, as reported by Tamrat [119]. The induced water stress in the root system triggers abscisic acid (ABA) generation, which is responsible for the adjustment in the closure or opening of the stomatas. Thus, DI may be considered as a sustainable technique for saving water irrigation in water-scarcity situations with the aim of promoting WUE.

In this context, Kaneko [66] determined the influence of water stress via RDI on flowering and fruit development through establishing rainout shelters for young trees. The non-stressed control trees registered higher average yield than the water-stressed trees. Thus, deficit irrigation in spring during flowering seems not to be a very sensitive state for the tree, while the period of early fruit growth causes a strong reduction in fruit size. In an experiment by Silber et al. [41], water stress induced via RDI provoked significant fruit yield reduction compared to non-water-stressed trees. From this perspective, Chartzoulakis et al. [76] revealed a decrease in photosynthesis and stomatal conductance ($g_S$) rates and alterations in leaf anatomy of avocado grown with deficit irrigation. Schaffer and Whiley [121] and Silber et al. [57] reported that moderate or severe water stress lowered net $CO_2$ assimilation during the avocado fruit-growth stage, which would have presumably led to fruitlet abscission. Durán et al. [42] reported the impact of different water stress levels through SDI for cv. Hass avocado plantations (Figure 2), recommending moderate water stress (75% $ET_C$) as the most suitable strategy in stabilizing yield (assumable loss) and saving irrigation water.

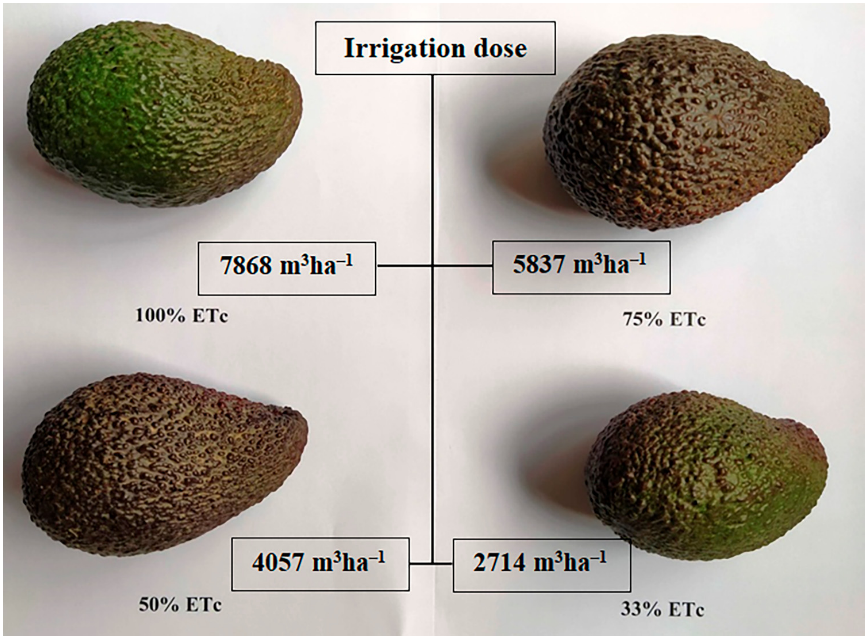



**Figure 2.** Irrigation doses and avocado fruits under different sustained deficit irrigation (SDI). $ET_C$, crop evapotranspiration; 100% $ET_C$, control; 75% $ET_C$, $SDI_{75}$; 50% $ET_C$, $SDI_{50}$; 33% $ET_C$, $SDI_{33}$.

In an experiment with cv. Hass trees, the effect of different irrigation treatments on accumulative yield was only shown in the fourth year [75]. These authors highlighted the best treatment of irrigation at 70% of reference evapotranspiration ($ET_0$), while the treatment that provided more water (111% $ET_0$) gave the largest trees but lower yield. Martinez-Ferri et al. [122] found that mild water stress can provoke a primed state in the white root rot (WRR)-susceptible avocado rootstock Dusa and showed that "cross-factor primin" with water stress is efficient for enhancing avocado tolerance to *Rosellinia necatrix*. Therefore, its potential application may encourage WRR tolerance in avocado trees and improve water use through short-frequency deficit irrigation strategies.

Neuhaus et al. [82] reported that applying PRD strategy could spare water without considerably decreasing avocado yield. They determined that drying half the root system could maintain the axial conductivity of trunks and incite a root signal to drive the reduction in water use and plant growth, as compared to drying the whole root system. In this context, the tyloses (suberized growths of radial or axial parenchymal cells) occluded 34% of the xylem vessels when drying the entire root system in contrast to the absence of tyloses in PRD. Thus, the study concluded that watering half of the root system used a similar water amount as a full-irrigation system. Moreover, avocado inflorescences appeared to be one of the vegetative structures of the tree most tolerant to soil drying. The main findings from experimental studies concerning deficit irrigation strategies are shown in Table 2.

**Table 2.** Deficit irrigation experiments in avocado production.

| Avocado Cultivars | Growing Regions | Treatments | Measurements | Main Findings | Reference |
|---|---|---|---|---|---|
| Hass | Spain | Sustained deficit irrigation (SDI) strategies supplying 33, 50, 75% $ET_C$, with a control (100% $ET_C$). | The tree growth, yield, and fruit quality parameters were evaluated. | The yield, tree growth, and fruit size were lowered using SDI. The SDI strategies increased the omega-3 and omega-6 fatty acids as well as the unsaturated fatty acids (oleic). $SDI_{33}$ significantly declined the yield, size, and fruit weight. The $SDI_{75}$ is the most suitable, since it does not affect the yield and saves 25% of irrigation water. | [42] |
| Hass | Chile | Deficit irrigation strategies, 25, 50, 75, and 100% $ET_0$. | Fruit production and size in a mature orchard. | Fruit yield reduced in the "off-crop" years due to alternate bearing. Yields from 25 to 50% $ET_0$ were only 22% of the yield obtained in the two years of high production, whereas the yields of 75 and 100% $ET_0$ were 42% of the yield obtained in the "on-crop" years. | [52] |
| Hass | Chile | Four deficit irrigation treatments, control $T_0$ (100% $ET_0$), $T_1$ (65% $ET_0$), $T_2$ (77% $ET_0$), and $T_3$ (132% $ET_0$) | Trunk growth, chlorophyll concentration, yield, and fruit quality. | Significant differences in trunk contraction and growth rate, though differences for chlorophyll content and trunk transversal diameter were negligible. The highest yield was for $T_2$, in contrast with $T_0$, which had a significantly lower production. Fruit size for $T_1$ was lower compared to $T_3$, and fruit weight from $T_1$ was lower than $T_3$. Fruits from $T_0$ exhibited significant lower fruit firmness. | [109] |
| Pinkerton | Israel | Deficit irrigation treatments [100% (control), 125%, 75%, and 50% according to pan evaporation]. | Fruit yield and quality of avocado fruits | No differences in the number of fruits per tree or total yield among treatments; However, the average fruit size and its distribution were reduced in the most stressed irrigation (50%). Under mild-irrigation stress (75%), similar results were exhibited in all the tested parameters compared to control and over-irrigated trees. Potentially, 25% of the water irrigation can be saved without affecting the fruit yield. | [123] |
| Hass | Australia | Extended partial root drying (PRD). | Avocado yield and fruit Ca content as an indirect measure for improving fruit quality. | The dry root zone beneath the whole or half of the canopy had no effect on Ca in fruits and is unlikely to affect their quality. PRD and abscission in fruits is mainly linked to the dry soil around the roots, rather than the water status of leaves or fruits. Prolonged drying of half the root zone in one season decreased irrigation efficiency over two seasons through promoting fruit abscission to the same extent as that when the entire root system was exposed to long drying. | [103] |

**Table 2.** *Cont.*

| Avocado Cultivars | Growing Regions | Treatments | Measurements | Main Findings | Reference |
|---|---|---|---|---|---|
| Hass | Australia | Extended partial root drying (PRD). | Avocado yield and fruit Ca content as an indirect measure for improving fruit quality. | The dry root zone beneath the whole or half of the canopy had no effect on Ca in fruits and is unlikely to affect their quality. PRD and abscission in fruits is mainly linked to the dry soil around the roots, rather than the water status of leaves or fruits. Prolonged drying of half the root zone in one season decreased irrigation efficiency over two seasons through promoting fruit abscission to the same extent as that when the entire root system was exposed to long drying. | [103] |
| Hass, Ettinger, and Fuerte | Israel | Irrigation regimes at 70%, 100% (control), and 130% of recommended (7000 $m^3$ $ha^{-1}$). | Fruit yield | Yields varied considerably, with only significant effects for the 130% that increased the total yield for cvs. Ettinger (40.7 t $ha^{-1}$) and Fuerte (39.5 t $ha^{-1}$) trees by 32 and 15%, respectively; in contrast, the yield of cv. Hass was not affected by rate of irrigation. | [124] |
| Hass and Fuerte | Israel | Deficit irrigation of 2890 (60%), 3930 (80%), 4750 (100% at tensiometer of 20 cbar), and 5720 (120%) $m^3$ $ha^{-1}$. | Fruit yield | The shortening in water dispensation by 1000 $m^3$ $ha^{-1}$ was followed by a significant decline in fruit yield of 2.2 and 1.6 t $ha^{-1}$ for cvs. Hass and Fuerte trees, respectively. This corresponds to approximately 20% of the total crop. Moreover, there was a reduction in fruit size in cv. Hass, even sometimes below export quality. | [108] |

$ET_C$, crop evapotranspiration; $ET_0$, reference evapotranspiration.

Thus, to ensure sustainable WUE, it is essential to base irrigation programming on the physiological responses of the crop. Water requirements must be determined in each phenological stage, taking into account the plant–water relationships and the edaphoclimatic conditions to define an adequate irrigation strategy.

## 3. Soil–Water–Plant–Atmosphere Relationships

The plant–water relationships explain how the plant reacts physiologically to changes in water availability and environmental restrictions or changes in growth cycle water demands at each phenology stage. These changes affect the volume and rate of transpiration, as well as the fruit yield and quality, when water supply does not meet water requirements. The development of tenable irrigation practices requires the biophysical processes of root water uptake in soil and transpiration mechanisms from plant canopies to be determined. For this action, the solar energy is the driving force of the majority of the biophysical processes in the plant system and water movement from soil to the atmosphere.

The phytomonitoring technique was developed on the basis of information from the soil–water–plant–atmosphere system, supplying an early, quantitative perception of plant responses to existing soil water availability, with the purpose of establishing, in real time, irrigation strategies to maximize plant growth. This technique is based on the use of various specific sensors related to the plant and the data interpretation for adjusting irrigation scheduling and other controllable crop aspects [125,126].

### *3.1. Plant Physiological Response to Water Stress*

The control of plant development and prevention of water stress requires knowledge of water status, as its determination based on the plant-based measurements in the field is generally impractical due to a lack of automation, the time-consuming process, and the skilled labor and proper data interpretation required.

Plants developed complex physiological and biochemical processes to regulate and mitigate different environmental stresses. Water stress negatively affects many plant physiological functions, particularly photosynthetic capacity, plant growth, and productivity, with the latter being especially severely reduced in extended conditions. Knowledge of the mechanisms used by plants to adapt to water stress through a regulatory network is essential. This information allows us to have the necessary data to improve the tolerance to water stress of the plants, thus stabilizing or maintaining crop yield and quality. Moreover, there is feedback from the end-product metabolite that is connected to the control of the net photosynthesis rate [127,128]. Importantly, however, these indicators are related to the phenological state of the tree.

The plant-based water stress indicators [leaf water potential ($\Psi_{leaf}$), stem water potential ($\Psi_{stem}$), stomatal conductance ($g_S$), trunk diameter, sap flow, canopy temperature ($T_C$), etc.] were commonly considered in many studies that focused on different irrigation regimes in field conditions. Thus, direct measurements related to plant water uptake are essential for any sound appraisals of these indicators. From this perspective, the water potential (leaf or stem) parameters are considered the most suitable tools for irrigation indicators; however, their measurement in the field is highly time-consuming and labor-intensive and requires specialized technicians, as stated. In contrast, the measurements made using devices installed in the field with continuous reading, such as dendrometers and sap flow, are able to save time and provide reliable data of crop water status [107,129–131]. According to Winner and Zachs [132], the determination of the daily maximum trunk contraction (difference between the maximum and minimum diameter in a determined day) in relation to a baseline reference could be used as a functional parameter to establish water stress and irrigation in avocado orchards. There are many dendrometer studies for avocado using helpful sensors, with the significant parameter derived from trunk diameter oscillation data for plant reaction monitoring being the maximum daily shrink [41,127,133,134]. In contrast, sap flow experiments for avocado are scarce [135,136].

It is well known that the increase in VPD leads to increased transpiration rates, thus triggering stomatal closure to save water. In this context, Pongsomboon et al. [137] determined the stomatal closure in avocados to be more conditional on VPD than other surrounding environmental elements, such as temperature. For the Mediterranean environment, according to Turner et al. [138], $g_S$ has been used in avocado as a proper water-deficit index. These authors highlighted that water stress in avocado trees induced the stomata to close before any other modifications in other parameters. Similarly, other authors, such as Schaffer and Whiley [121], revealed that $g_S$ is a reliable water-deficit indicator, being superior to $\Psi_{leaf}$, $\Psi_{stem}$, and growth parameters.

Neuhaus et al. [82] found that the development of avocado tree was appreciably reduced in non-irrigated compared to well-irrigated conditions, with reductions in sap flow rates registered over a 44-day soil drying period. At day 45, the dry non-irrigated trees required 7 days to restore to the $\Psi_{leaf}$ of the well-watered trees, although sap flow readings were maintained in a low range. According to Barrientos and Rodríguez [139], the photosynthesis, $g_S$, transpiration, and WUE were highly influenced through water deficit, and in re-watering recovery at permanent wilting point did not recover until after 24 h. The water osmotic and turgor potentials, as well as the relative water content, were similar for fully irrigated and water-stressed plants, which seems to indicate that an osmotic adjustment took place in the latter group. The proline content was also significantly higher at the permanent wilting point with respect to the control, being similar to ABA, which doubled its content with respect to irrigated plants.

In this context, Carr [33] highlighted that $g_S$ starts to decrease progressively as $\Psi_{leaf}$ levels reach $-0.4$ mPa and continues until the stomata totally close with values from –1.0 to –1.2 mPa, accordingly triggering a decrease in photosynthesis rates. According to Ferreyra et al. [140], non-water-stressed avocado trees register $\Psi_{stem}$ between –0.40 and –0.50 mPa for VPD values between 1.4 and 3.0 kPa, respectively. In an experiment conducted by Celedón et al. [133], the reactivity of $\Psi_{stem}$ and maximum daily trunk shrinkage (MDS) was compared for avocados with holding irrigation and a control (fully irrigated trees). These authors found that MDS was more effective in detecting water stress than $\Psi_{stem}$ but showed greater variability. Thus, this high sensitivity of MDS can be key factor for avocado irrigation scheduling where prompt detection of water stress is required. From this perspective, Sharon [141] and Sharon et al. [87] proved the sensitivity of trunk and leaf changes to diurnal shifts in $\Psi_{leaf}$ (from $-0.15$ to $-1.05$ mPa); both studies showed how stomata stayed open during the day, with this fact being ascribed to the trees' ability to maintain a quick transpiration rate for rapid root hydraulic conductivity. In this context, other studies linked to $\Psi_{stem}$ in avocado exhibited values of $-1.0$ to $-1.2$ mPa as water stress signals [70].

An experiment conducted by Durán et al. [42] determined that throughout the growing season, the different evaporative demand achieved $\Psi_{leaf}$ values varying from –0.60 to –1.06 mPa in non-stressed control trees (100% $ET_C$), in contrast with the harsh water stress-affected trees with $\Psi_{leaf}$ between $-0.98$ and $-1.78$ mPa (33% $ET_C$). Despite this high variability in $\Psi_{leaf}$, the behavior of the most severe deficit irrigation treatments (33 and 50% $ET_C$) contrasted notably to that of fully irrigated trees. These authors fixed the maximum $g_S$ rate at midday in control trees (100% $ET_C$) ranging from 129.4 to 155.2 mmol $m^{-2}$ $s^{-1}$, whereas the severe 33% $ET_C$ treatment varied from 115.9 to 135.0 mmol $m^{-2}$ $s^{-1}$ as water stress triggered the stomatal closure; consequently, this could have induced a rise in leaf temperature. Figure 3 displays the relationships between $\Psi_{leaf}$ and $g_S$ throughout the water stress period in Mediterranean subtropical environment. In this sense, with elevated atmospheric demands, the increases in air temperature promote leaf temperature over that of air. Similarly, water stress decreased the $g_S$ rate, with a reduction in $\Psi_{leaf}$ below $-0.4$ mPa, and ceased with stomata closure between $-1.0$ and $-1.2$ mPa [33]. According to Cantuarias et al. [98], under these conditions of higher leaf temperature, the saturated water vapor pressure in the leaf substomatal chambers is increased, thus promoting the evaporation rate and water loss from the canopy, explaining the augmentation of the transpiration rate/potential transpiration ratio. The enhanced water uptake and beneficial canopy water status reached through extending the wetted soil volume were expressed as higher $\Psi_{leaf}$ and lower $T_C$ during periods of high evaporative demands. Thus, the extension of the wetted soil volume from 25 to 75% augmented the root growth rate and enhanced tree water status and transpiration response to high evaporative demands [98].

Hermoso et al. [142] applied water to the tree using a micro-sprinkler irrigation system to reduce $T_C$ in the periods of high evaporative demand in Spain. This approach led to water intake growing exponentially with the decrease in avocado leaf temperature; it also reduced $g_S$ rates, enlarging the average fruit size. In this context, Lazare et al. [143] reported that in avocado orchards in a semi-arid region in Israel, the use of sprinklers to cool the canopy during spring heat waves after flowering was able to reduce leaf temperatures by 10 °C. This outcome significantly decreased water stress and increased avocado fruit yields by 8–12%.

Conversely, Oyarce and Gurovich [144] highlighted a clear and rapid mechanism of electrical signal generation and transmission in avocado, which was positively correlated with the intensity and duration of stimuli (light intensity and water availability). Thus, the reading of the electrical potential can be used to measure the physiological responses of plants in real time; this technology can be used as a tool for the early detection of water stress and management of high-frequency automatic irrigation systems. Table 3 displays a brief summary of studies related to the physiological response of avocado to water stress conditions.

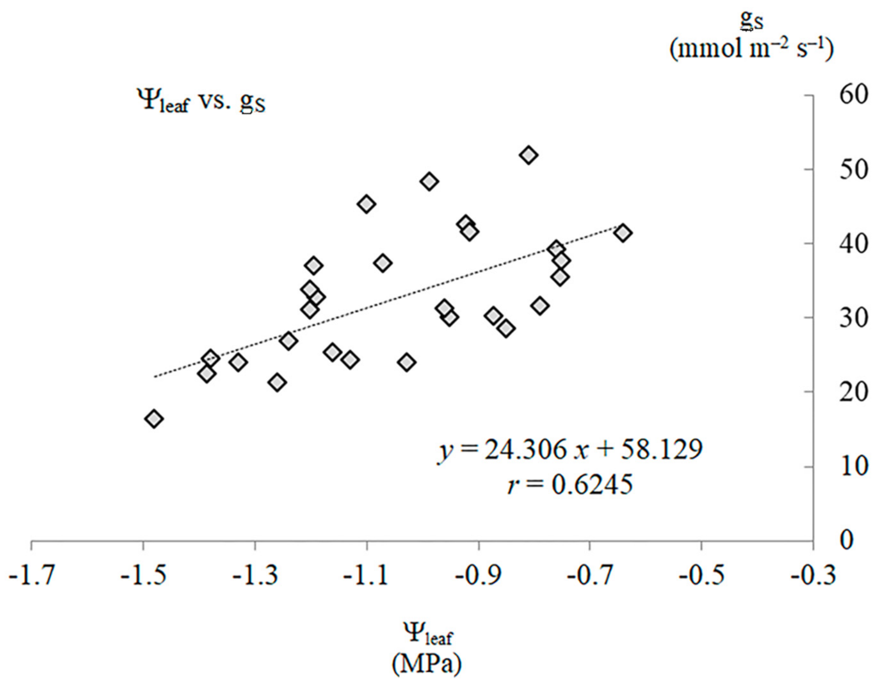



**Figure 3.** Leaf water potential ($\Psi_{leaf}$) vs. stomatal conductance ($g_S$) throughout monitoring period (deficit irrigation).

**Table 3.** Studies in relation to response of plant physiological parameters to water stress.

| Avocado Cultivars | Growing Regions | Treatments | Measurements | Main Findings | Reference |
|---|---|---|---|---|---|
| Hass | Chile | Irrigation regimes ($T_1$, Control; $T_2$ and $T_3$ with 29% less and 25% more than $T_1$; $T_4$ and $T_5$, the same as $T_1$ until the first and second fruit drop abscission, respectively, and then 29% less). | Fruit yield and physiological parameters. | The $\Psi_X$ (as a function of VPD in $\theta_W$ conditions without limit yield) declined in intensity and timing of water restriction; no treatment was affected for crop load. $T_2$ was not significantly detrimental to fruit size, production, or maturation, in spite of the achieved water content levels at the limit of the breaking point and the lower levels of $\Psi_{stem}$ than $T_1$ being recorded, with this being the highest water productivity. Comparing the baseline for non-stressed trees with a baseline from full irrigation based on the literature, a 30% water saving was achieved. | [145] |
| Hass | Israel | Two irrigation systems (total crop water requirements for using lysimeter data and other methods, applying 75% of this quantity). | Transpiration (T) and maximum trunk daily shrinkage (MDS) rates. | The increase in T with VPD was linear up to 1.3 kPa; above this value, the slope of the linear relationship decreased. The decrease in T led to changes in MDS with high VPD. The relationships indicate that MDS was linked to phenology: a VPD of 1.3 kPa was linked to an MDS of 50 µm at flowering and fruit set and to MDS of 150 µm at fruit growth and maturation. MDS highly correlated with $\Psi_{stem}$ and was a good stress indicator as long as VPD and phenological stages are considered. | [134] |

**Table 3.** *Cont.*

| Avocado Cultivars | Growing Regions | Treatments | Measurements | Main Findings | Reference |
|---|---|---|---|---|---|
| Hass | Israel | Irrigation with treated wastewater (TWW): freshwater (FW), blended TWW/FW (MIX), low-frequency TWW-irrigation (LFI), TWW irrigated tuff trenches (TUF), and TWW as the control. | Water use and physiological relationships in avocados cultivated in a clay soil. | The $g_S$ of FW, MIX, TUF, and LFI was larger than TWW, which raised net leaf $CO_2$ assimilation rate ($A_{leaf}$) and intercellular $CO_2$ concentration with limited intrinsic WUE. A strong negative relationship between WUEi ($A_{leaf}/g_S$) and $g_S$ was observed in all treatments, with highest in WUEi and lowest $g_S$ in TWW. Overall, the largest $g_S$, $A_{leaf}$, $A_{tree}$, and $K_{leaf}$ in FW, MIX, and TUF compared to TWW indicate the suitability of these strategies, with the FW being the most effective. | [146] |
| Hass | Israel | Lysimeter experiments with irrigation under different frequencies, evaluating the impact of fruit sink. | Stomatal conductance ($g_S$) and photosynthesis per unit leaf area (A). | Fruitless trees, despite their greater vegetative growth, had 40% lower water consumption than fruitful trees. The $g_S$ and A were not in agreement with irrigation treatments. Leaf-carbohydrate contents with and without fruits were smaller before sunrise and augmented during the day. These results suggest that leaf carbohydrates may be involved in the stomata aperture. | [89] |
| Hass and Fuerte | Greece | Two soil water regimes: 1) well irrigated at soil matric potential (SMP) of 0.03 MPa; and 2) water stress at SMP of 0.5 MPa. | Physiological parameters | Photosynthesis was inhibited through lowering the $CO_2$ diffusion (35–45%), both via stomatal closure and mesophyll structure. The $\Psi_{leaf}$ decreased by 0.9 and 1.2 mPa for cvs. Fuerte and Hass trees, respectively. Tissue elasticity seemed to be the physiological mechanism of drought adaptation. The cv. Hass trees appeared to be more influenced by moderate water stress. | [76] |

WUEi, intrinsic water use efficiency; $A_{leaf}$, leaf aassimilation rate; $A_{tree}$, tree assimilation rate; $K_{leaf}$, leaf hydraulic conductance; $\Psi$, water potential; $\theta_W$, soil water content; VPD, vapor pressure deficit; $g_S$, stomatal conductance; $\Psi_{leaf}$, leaf water potential; $\Psi_{stem}$, stem water potential.

### *3.2. Soil Water Content in Relation to Water Stress*

To extract water from soil, trees must exert some suction power, and as the soil dries, they require more effort that increases the stress on the tree. In general terms, plants have differing capacities to extract water, and different levels could be considered based on water stress: mild stress at −20 kPa, moderate stress at −40 kPa, and high stress at −60 kPa and above. It is well known that $\Psi_{soil}$ varies much less than $\Psi_{leaf}$ or $\Psi_{stem}$, which are influenced by highly variable weather elements, including VPD and the plant hydraulic conductance [147,148].

Soil moisture sensors have the disadvantage of the great variability in soil properties (texture, stoniness, organic matter, etc.) and their effects on soil water distribution; in some cases (with sprinkler irrigation systems), a large number of probes must be installed to obtain a representative measurement of soil moisture [145,149,150]. A drawback of soil measurements is that they do not provide a direct sign of plant water status, creating uncertainty over whether the irrigation is being applied according to the water requirements of the tree. Thus, the main disadvantage of soil-based irrigation systems is that programming is carried out based on the properties of the soil, without taking into account the water status of the plant [151].

The tensiometers were widely utilized to monitor soil water dynamics and optimize irrigation provision in avocado plantations [108,152]. From this perspective, according to du Plessis [46], the critical matric potentials for avocado at depths of 0.30 m were −30 and −50 kPa for sandy and clay soils, respectively. Although the avocado tree appears to be fairly tolerant to mild water stress, the critical period where irrigation is essential is at fruit set and the early fruit growth phenological stages.

In this context, Whiley et al. [69] recommended the irrigation based on tensiometer readings of −40 kPa at 30 cm soil depth during spring, whereas this value could be reduced to −30 kPa during the fruit drop period. The experiment conducted by Vuthapanich et al. [153] found that well irrigated cv. Hass trees under −20 kPa had twice the yield of trees subjected to drier treatments (−40 and −70 kPa at 30 cm soil depth) due to the existence of a greater number of fruits per tree. Bower [93] stated that a $\Psi_{soil}$ of −55 kPa at 25 cm soil depth should not be exceeded. From this perspective, Chartzoulaki et al.'s [76] study with Fuerte and Hass cultivars appraised anatomical and physiological changes by subjecting them to two moderate water deficits: irrigation was applied when the $\Psi_{soil}$ reached −0.03 and −0.5 mPa for the wet and dry treatments, respectively; this study determined that cv. Hass was most influenced by moderate water stress.

Similarly, Hermoso et al. [154] executed an irrigation experiment in Fuerte and Hass avocado plantations using a conventional irrigation system with two micro-sprinklers per tree. An alternating irrigation procedure was used as follows: each micro-sprinkler irrigated a larger area, and water was aggregated alternately to both sides of the tree via a duplicate irrigation system. The irrigation site was changed when $\Psi_{soil}$ reached −1.0 mPa at 50 cm depth of the soil, with no differences during the first season. However, for the second micro-sprinkler, the potential yield and the yield, as well as the size and number of fruits, were slightly higher, though not significantly, with alternate irrigation. According to Román et al. [155], maintaining soil tension up to between −40 and −45 kPa significantly increases fruit yield and growth, with water savings of up to 47% in comparison with maintaining soil at field capacity. These authors also reported that avocado is susceptible to decreased yield when available water is as low as 5% in the soil. Similarly, Roets et al. [156] found that the most favorable impact on yield and fruit size was with the $\Psi_{soil}$ of clay soil between −25 and −35 kPa. These values were considered to have low water stress with optimal transpiration and photosynthesis rates.

Recently, Erazo et al. [157] reported that the water content in the soil at a depth of 5–10 cm can be used as an indicator for irrigation scheduling in avocado. In addition, the available water in the upper 15 cm of the irrigation depth significantly influenced the total water requirements of the avocado tree. Many remote sensing studies that inter-relate the backscattering coefficient and incidence angle from synthetic aperture radar images with the surface soil water content 0–5 cm depth interval enable irrigation factors to be valued via the soil water dynamics.

In short, the increasing water scarcity for irrigation and water restrictions due to recurring droughts are driving farmers to enhance the WUE in their avocado plantations. Therefore, to ascertain how and when to irrigate, it is necessary to determine the soil properties and have systems that allow the water stress of the plant to be monitored, avoiding waterlogging and maximizing efficiency in the use of water.

## 4. Spanish Mediterranean Avocado Farming

The avocado market is one of the fastest growing worldwide, and the consumption of avocados, particularly in Europe, has increased in recent decades due to socioeconomic and marketing factors.

The Mediterranean climate is characterized by scarce and irregular rainfall. The average annual precipitation in some areas in SE Spain is less than 300 mm per year. Thus, irrigation is vital for crop productivity, though this activity must be optimized due to reduced water resources in this region. This approach is vital in arid and semi-arid areas, such as the Mediterranean region, where there is a scarcity of water due to the increase in population and high variability in rainfall distribution, while water resources are overexploited due to intensive use in agriculture, industry, and tourism. In Spain, according to the latest OPM statistics [158], avocado cultivation amounted to 12,832 ha, and most of this area is located in SE Spain (Andalucía) with 10594 ha (83%), followed by the Canary Islands (13%) and Valencia (9%) provinces.

The subtropical climatic conditions required for the development of the avocado tree, such as the cultivation area in Granada and Malaga provinces, are also suitable for cropping other irrigated subtropical fruits, such as mango (*Mangifera indica* L.), cherimoya (*Anonna cherimolia* L.), litchi (*Litchi chinensis* L.), dragon fruit (*Hylocereus undatus* L.), and loquat (*Eriobotrya japonica* L.). The climate of this region is characterized by temperate average temperatures (~20 °C throughout the year) with high environmental humidity. The region is a narrow strip about 12 km wide parallel to the Mediterranean coast that has a special microclimate due to the arrangement of the intertropical valleys, which have a north–south orientation and are protected against northerly winds by the Penibetic mountain range, which runs towards the edge of the coast from east to west.

The most abundant avocado cultivar in this subtropical region is Hass, grafted on Mexican rootstocks, with flowering and harvest taking place in March and between January and February, respectively; however, fruits can be preserved on the tree until July. The yields in the irrigated areas are very variable, varying from 6.26 to 10.06 t ha$^{-1}$. According to the latest data from the OPM [158], during 2020/2021, the avocado production amounted to 81,087 t, with an average price of 2.87 € kg$^{-1}$. The avocado trade campaign takes place from September to May, staggering among the different cultivars besides Hass, such as Bacon, Fuerte and Reed (Table 4).

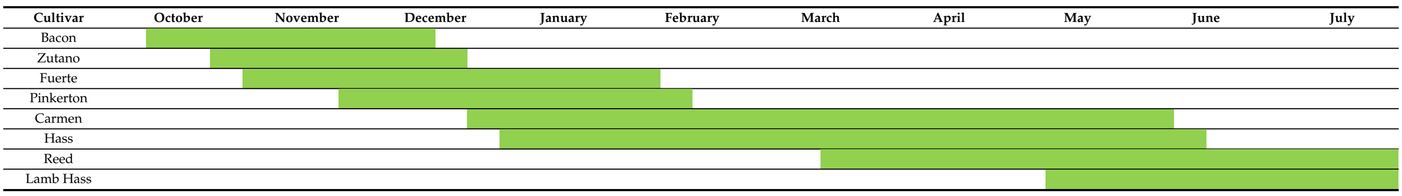
**Table 4.** Main characteristics of avocado fruits cultivated in southeastern Spain.

| Avocado Cultivar | Fruit Weight (g) | Fruit Color | Fruit Skin | Flower Type |
|---|---|---|---|---|
| Hass | 140–400 | Green–black | Coarse | A |
| Carmen | 140–400 | Green–black | Coarse | A |
| Fuerte | 170–500 | Green | Thin | B |
| Bacon | 170–510 | Green | Thin | B |
| Zutano | 200–400 | Green | Thin | B |
| Reed | 270–680 | Green | Thin-Ccoarse | A |
| Lamb Hass | 283–510 | Black | Coarse | A |
| Pinkerton | 230–425 | Green | Coarse | A |

Avocado trees with flower type "A" are cultivars open as female on morning of first day and close in late morning or early afternoon. Flower remains closed until afternoon of second day when it opens as male. By contrast, type "B" cultivars open as female on afternoon of first day, close in late afternoon and re-open in male phase following morning.

Table 5 shows the harvest dates for different avocado cultivars in the subtropical Mediterranean environment. Regarding international exports, more than 54% of avocado production is exported to other countries in the EU, with France being the main importer (43%), followed by Netherlands (15%) and Germany (14%); non-EU member the UK is also a major importer (5%).

**Table 5.** Avocado cultivars and harvest dates for subtropical conditions.




Green bars represent harvest period of each cultivar.

Due to the elevated prices of the avocado fruit, many farmers invest in planting avocados in hill slope areas on terrace orchards and establishing irrigation systems [42,159,160] (Figure 4). The proximity of the European market compared to traditional avocado-producing countries allows a better quality/price ratio and a reduction in carbon footprint. Andalusian avocado production represents 82% of the national total, while Valencia and the Canary Islands have a production share of 5 and 13%, respectively [158]. Given the economic value of avocado fruits and their competitive advantages in European markets, as well as the problems of water scarcity and associated environmental problems, an improvement in irrigation systems in avocado orchards implies a reduction in transpiration rates and lower production costs, particularly those associated with the environmental cost of water [19]. Thus, determining the maximum reduction required to improve the sustainability of irrigated avocado and supply adaptation strategies for water scarcity scenarios will be a crucial challenge.

**Figure 4.** Terraced avocado plantations in SE Spain.

Additionally, Spain has a strategic geographical location that gives it competitive advantages over other overseas producing countries, being able to export high-quality fresh avocados to nearby countries using water-saving strategies [42]. Furthermore, there is a preference among European consumers for healthy, fresh produce cultivated with ecofriendly and environmentally friendly practices [161,162]. Taking into account the requirements and preferences of consumers is necessary and can lead to innovation that differentiates the Spanish avocado market from the rest of the world through the use of logos or labels that highlight, among other aspects, the sustainability of water. Thus, water-saving strategies could be included in a new logo for consumers as a key element for the added value of avocados produced with environmentally friendly systems [163,164]. Thus, to guarantee the quality and origin of the fruits to consumers, a certification system should be developed to allow their identification in the market. These aspects can help to clarify the challenges in reaching sustainability in irrigated avocados, as well as possible solutions and future research requirements.

Consequently, the advances in research and innovation delivered using these hydro-sustainable strategies are of high importance, since Spanish avocado, as stated above, has strategic advantages in the markets, such as a higher fruit quality for longer maturation periods in trees and lower transportation costs to European markets. Moreover, modern avocado consumption grew rapidly in recent years due to the growing interest of consumers in healthy foods, increasing consumption of fruits and vegetables.

## 5. Conclusions and Future Perspectives

The Mediterranean is a region that suffers from water scarcity, facing the challenge of sustainable use and distribution of water among all economic sectors to guarantee that all sectors receive an adequate amount of water. Avocado producers, in the current climatic conditions and in view of the forecasts of increasingly frequent water scarcity scenarios, must implement strategies to save water and improve efficiency of its use based on the premise that suitable yields can be achieved with lower water use. Therefore, understanding the patterns and mechanisms of responses of avocado to water stress is crucial to predicting future functionality and resilience in recurrent drought scenarios. From the present review, we conclude that sustainability in Mediterranean irrigated avocado farming can be reached via the following means:

1. Under recurrent water shortage conditions in arid and semi-arid regions, irrigation based on conventional full irrigation calculated based on water balance is not sustainable. This problem necessitates resilience practices through redesigning irrigation management in order to face water scarcity in coming scenarios.
2. Deficit irrigation as a water-saving practice could be considered as a sustainable alternative to achieve environmental benefits in irrigated avocado farming with assumable yield losses. However, it is crucial that more detailed irrigation studies are carried out in the medium and long term, taking into account compressive factors of the management of water stress and the effects on its ecophysiology, as well as alternate bearing, yield, and fruit quality.
3. Improving our knowledge on the role of tree water relationships, especially physiological and phenological features that are pivotal to taking the next step in sustainable irrigation development.
4. Future studies on water stress-tolerant avocado rootstocks are necessary to foster yield when water resources are limited, such as rootstocks with adaptive features for deficit irrigation regimes that distinguish the rootstock effects on water relationships from those on vegetative vigor.
5. Studies focused on the response mechanisms of avocado rhizosphere to water stress are necessary to improve knowledge of the physiology of plant stress and improve agronomic breeding strategies, thus developing avocado trees tolerant to water stress and high yield.
6. Given avocado's high water demand, promoting high-density plantations in conjunction with deficit irrigation could be an option for irrigated semi-arid areas. For this, the control of vegetative growth is essential; however, these techniques were scarcely studied for this purpose over a long-term period.
7. The molecular and physiological mechanisms related to water stress tolerance and water use efficiency must be fully studied. Determining how these systems are regulated and contribute to reducing the impact of water stress on plant productivity will allow the development of plants more tolerant to water stress through biotechnology, while maintaining the yield and fruit quality.

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