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Review

Assessing the Seasonal Water Requirement of Fully Mature Japanese Plum Orchards: A Systematic Review

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Abstract: Japanese plums have relatively high water requirements, which depend on supplementing rainfall volumes with accurately quantified irrigation water. There is a lack of knowledge on the seasonal water requirements of plum orchards. This gap in the literature poses an imminent threat to the long-term sustainability of the South African plum industry, which is particularly plagued by climate change and diminishing water resources. The systematic literature review conducted in this study aimed to provide a foundation for supporting water management in irrigated Japanese plum [*Prunus salicina* Lindl.] orchards. Seventeen peer-reviewed articles obtained from the literature were analyzed. Approximately 66% of the cultivars were cultivated under different regulated deficit irrigation regimes for water-saving purposes and to increase fruit quality. This review of our knowledge provided benchmark figures on the annual water requirements of Japanese plums. The full-year plum crop water requirements obtained from the literature ranged between 921 and 1211 mm a^{-1}. Canopy growth, pruning and growing season length were the most common causes of differences in the water requirement estimates. Further research is required to measure the water requirement of plums from planting to full-bearing age and the response of plum trees to water stress, especially in the South African context.

Keywords: crop water requirements; evapotranspiration; *Prunus salicina*; regulated deficit irrigation; water stress

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1. Introduction

The production of deciduous fruits is practiced widely across the world. The South African deciduous fruit industry was valued at R 15.67 billion (~$795 million) during the 2020/21 crop year, with plums accounting for roughly 10.7% of its total gross production value [3rd behind apples and pears] [1]. Globally, South Africa is the sixth largest exporter of fresh plums and second in the Southern Hemisphere behind Chile. Plum production in the country has steadily grown since 2006, reaching a peak of 101,969 metric tons in 2021 [1]. Dzikiti et al. [2] attributed the increased production volumes of deciduous fruits in recent years to the use of improved plant material [e.g., scion–rootstock combinations] and orchard management practices [e.g., increased orchard densities and better cultivar selection]. Intensive, high-yielding plum orchards (>30 tons ha^{-1}) are becoming a common occurrence in the South African agricultural landscape. Naschitz and Naor [3] noted that increased crop yields were associated with higher crop water requirements. Plums, along with other high-value fruit crops, are grown under irrigation. As such, water availability is crucial for the sustainability and growth of the South African fruit industry.

Despite this, there is a relative paucity of knowledge on the seasonal water requirements of plums. In a time of changing climatic conditions [characterized by increased drought frequency and rainfall variability] and dwindling water resources, the aforementioned gap in the literature poses an imminent threat to the long-term sustainability and global competitiveness of the South African plum industry. The agricultural sector is the country's largest water consumer, with irrigated agriculture accounting for 62% of its total consumption [4]. Pavel et al. [5] emphasized that the goal of modern-day agriculture is to utilize less water for irrigation (improve efficiency) without decreasing fruit yield and quality. These sentiments have become more prevalent in recent years, where increased competition from municipal and commercial sectors has intensified the stress put on the agricultural industry to improve its water use efficiency. Therefore, it is imperative to equip water managers, policy makers and farmers with tools for accurately quantifying the unstressed crop water requirements of full-bearing (3–6 years), high-yielding plum orchards. This would assist in the allocation and licensing of water resources, as well as promoting improved water use efficiency (WUE) within the agricultural space through the development of water-saving strategies. Improved WUE and water-saving strategies are necessary given that South Africa is one of the driest countries globally [6] and that almost 98% of its available water resources have already been allocated [7]. Therefore, from a farmer's perspective, accurate information on crop water requirements would provide a framework for developing accurate irrigation scheduling programs and determining orchard water budgets. Stevens [8] revealed that less than 20% of South African farmers use science-based approaches to irrigation scheduling, with the majority implementing a knowledge-based approach, often leading to over-irrigation and increased non-beneficial orchard water use.

Although there is a multitude of methods for estimating the evapotranspiration (ET) and crop water requirements (CWR) of various field crops, limited experiments have been conducted on plums. Thus, there is little information on the seasonal water requirements of plums and the associated methodologies utilized that could inform water allocation to farms. The South African Department of Agriculture, Forestry and Fisheries [9] proposed a set of monthly water use estimates for full-bearing plum orchards (ranging from 32.2 mm month^{-1} in April and August to 193.8 mm month^{-1} in January). However, these only serve as a reference guideline, as site-specific conditions such as the soil texture and depth, climatic conditions, the chosen irrigation system, etc., must be considered when developing an irrigation schedule. There is therefore a need to collate the plum evapotranspiration data estimated/measured in the literature to assist with observing a precise benchmark water use figure for efficient on-farm management practices and water allocation. Evaluating the methods and technologies utilized in these various studies is also essential for future adaptation to fields with similar conditions. Therefore, the objectives of this study were (i) to perform a systematic review of the water requirements of full-bearing Japanese plum orchards, (ii) to present and discuss the principles and methods used to determine evapotranspiration in orchards and (iii) to summarize the findings on the water requirements of plum orchards.

2. Methodology

2.1. Scope, Literature Search and Inclusion and Exclusion Strategies

This review focused on past studies conducted on various Japanese plum cultivars (*Prunus salicina* Lindl.), with clearly and adequately described strategies, methods and technologies for estimating their crop water requirements. The scope includes all global studies conducted in different climates and agroecological zones. There were no restrictions on the articles' publication year to capture the development and advancement of the technology and methods.

A systematic literature search was undertaken within the Science Direct, Scopus and Web of Science databases to identify relevant studies on estimating the water requirements of various plum cultivars. The key search words included evapotranspiration, water use, water requirements, water consumption, crop coefficients, plum and *Prunus salicina*. The study utilized Boolean operators (OR, AND) to combine the keywords to refine the search using the following query code:

TITLE-ABS-KEY ((“evapotranspiration” OR “water use” OR “water requirement” OR “water consumption” OR “crop coefficient*”) AND (“plum” OR “prunus salicina”)).*

A total of 67 articles were collected from Scopus using the query code. These collected articles were thereafter exported into Excel for screening. The number of articles identified, excluded and included were recorded according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [10], as shown in Figure 1. The inclusion criteria considered for meta-analysis were based on studies (i) published in peer-reviewed journals as full articles, (ii) focusing on the estimation of water requirements of plums using detailed and clearly described strategies, methods and technologies and (iii) providing sufficient data for quantitative analysis. Further, this review excluded (i) studies on Prunus domestica plums, (ii) articles written in languages other than English due to constraints on the resources necessary for translation and therefore analysis, (iii) literature review papers since the paper focused on primary research studies, (iv) conference papers and proceedings and (v) press papers. A total of 18 articles were removed from the records using the listed exclusion criteria.

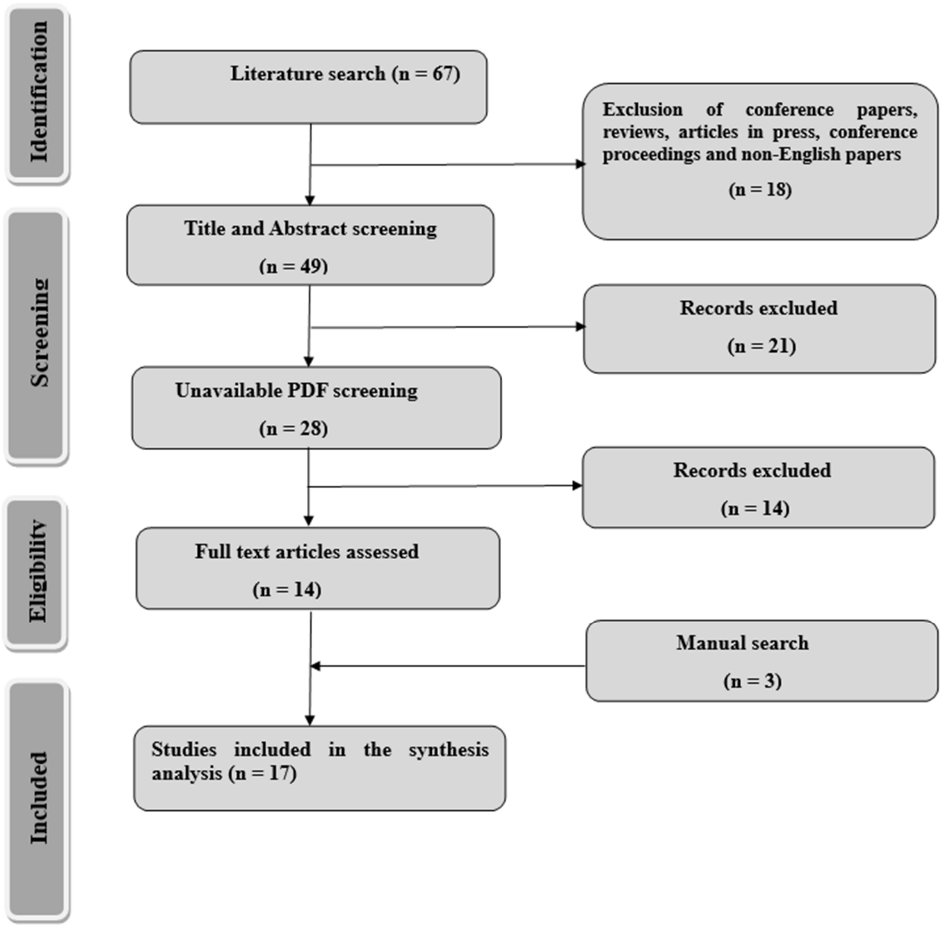

Figure 1. The PRISMA flow diagram shows the selection of considered articles.

The following stage involved examining the titles and abstracts of the remaining articles (n = 48) to check whether the studies had sufficient data and clearly described methods. A total of 21 irrelevant articles were excluded during the title and abstract screening. Of the 28 remaining articles, 14 were unavailable in full-text portable document (pdf) format and were excluded. Full-text-length articles contain detailed information on the study design, data, methodology, results and conclusions. This allows quality assessment to be performed and reduces bias, influenced by limited information. Additional articles (n = 3) were identified with the Google Scholar search engine using a reference list of the remaining articles (n = 14) using the backward reference searching strategy suggested by

Horsley et al. [11]. In total, 17 articles were assessed for eligibility, with all of them meeting the selection criteria.

2.2. Data Extraction and Analysis

Data were extracted from the comprehensive literature database and exported into an Excel spreadsheet. The exported data contained critical bibliographic information such as the author's names and the article title, abstract, keywords, publication year, uniform resource locator (URL) and digital object identifier (DOI). Additionally, information on the method/technology used, the plum cultivar being investigated and the study area location was extracted manually upon reading the articles.

All the retrieved articles and the respective extracted data were qualitatively synthesized and analyzed. The VOSviewer (version 1.6.20) software [12] was used to perform a bibliographic analysis of the retrieved articles and visualize key terms' occurrence and co-occurrence networks. Bibliographic analysis is a standard meta-analytical tool used to identify the interconnections of key terms from published articles in the form of linked clusters [13]. According to Van Eck et al. [12], a bibliometric map is created following four steps, which include (i) selecting the counting (binary or full) method, (ii) selecting the minimum number of term occurrences, (iii) calculating the relevance score for co-occurrence terms and (iv) using the selected terms to display the map. Following these steps, the retrieved articles' titles, abstracts and key terms were used as input data in VOSviewer to provide a graphical visualization based on the co-occurrence of the respective key terms.

3. Results

3.1. Systematic Review

The network map shown in Figure 2 categorized the identified literature into 4 clusters of concepts, highlighted in blue, yellow, red and green colors. The blue cluster circulated the networking of plum physiology with respect to ET and the water use efficiency (WUE) in plum orchards. The specific emphasis of this network is how these stated factors influence the quality of the harvested plums. The blue network aims to uncover insights that have the potential to be applied to improve fruit quality. This can be achieved by understanding plums' physiological processes and improved water management. The yellow cluster revolves around the WUE in plum orchards. This network explores various irrigation practices, the physiological aspects of water use in plum orchards and the collective influence of these factors on the overall WUE in plum orchards. The red cluster is based on the relationship between water stress and the factors influencing fruit production in *Prunus salicina* orchards. The network investigates how various irrigation systems, soil moisture and stem water potential (SWP) impact overall fruit production as well as the crop load in plum orchards.

Lastly, the green cluster centers on the application of RDI as a water management technique. The studies focused on the impact of RDI on plum tree growth and growth rates, performance and yield. Additionally, the network investigates the relationships between plant growth in plum orchards, water stress and yields concerning efficient water management practices. Overall, this network explains the retrieved studies' focus on efficiently managing water resources in plum orchards to obtain the maximum crop yields and fruit quality.

The results from this review illustrate that 14 plum cultivars were studied in the retrieved articles, as shown in Figure 3. The cv. Black Gold had the most (n = 5) studies [14–18]. The water requirements for the cv. Angeleno were estimated by three studies [19–21], while three studies estimated the water requirements for the cv. Red Beaut [17,22,23].

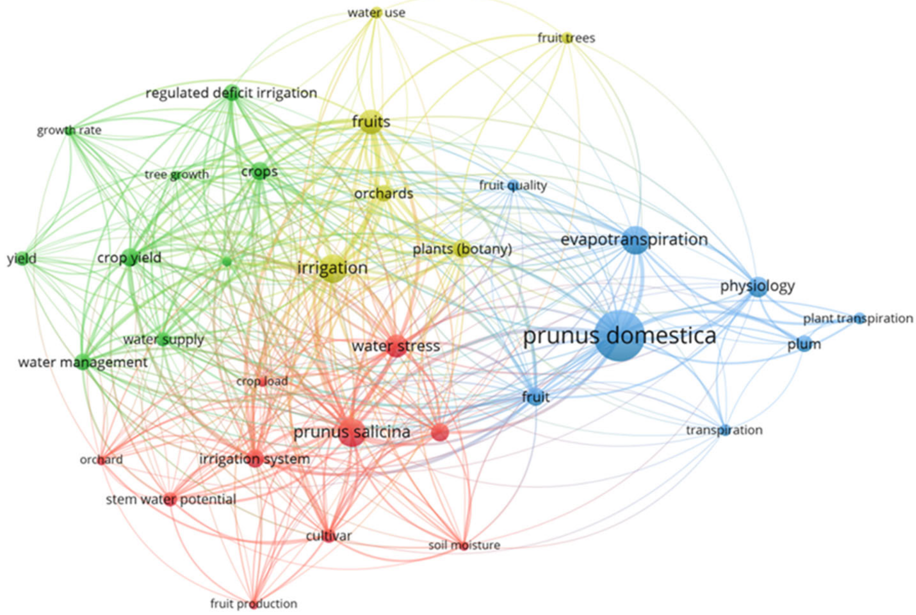

Figure 2. Network visualization of the topical concepts in plum water requirement estimation studies derived using the title, abstract and key terms.

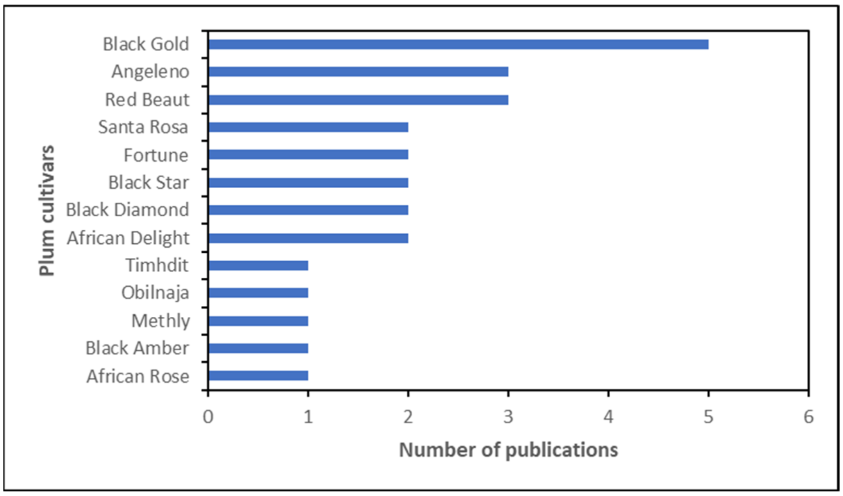

Figure 3. The number of studies that carried out experiments on the estimation of CWR for various plum cultivars.

According to the retrieved articles, two studies were carried out each for the cv. Fortune [17,24], cv. Black Star [17,18], and cv. Black Diamond [17,18]. The water requirements of mature and seedling crops of the cv. Santa Rosa were estimated by Hamdani et al. [17]. Thus, two studies were recorded as having been undertaken on this cultivar based on this frequency. The results show that only one study each was carried out for the cv. Timhdit [17], cv. Obilnaja [17], cv. Methly [25], cv. Black Amber [17], cv. African Rose [26] and cv. African Delight [24].

Three studies by Intrigliolo and Castel [14], Intrigliolo et al. [15] and Intrigliolo et al. [16] were carried out on the same orchard, planted with a young cv. Black Gold grafted onto the Mariana GF81 rootstock. The Black Amber and Black Diamond cultivars in this orchard were planted in guard rows as pollinators. The large size of the fruit of the cv. Black Gold is a critical component for achieving high economic returns. From the results obtained by Intrigliolo and Castel [14], crop level (aggregate yield of the fruit tree) and water stress do not have a considerable interactive effect on the performance of the cv. Black Gold. This speaks to the need to implement various RDI regimes on this fresh market cultivar with dark red skin to investigate its response to varying induced water stress. Understanding the stress recovery rate of plum cultivars under RDI is imperative, as this affects their CWR. Intrigliolo et al. [15] reported that the cv. Black Gold has a high recovery rate under RDI, as there is lower competition between vegetative and fruit growth due to crop load regulation. However, Intrigliolo et al. [16] recommended that RDI be applied with caution to avoid the carry-over effects of deficit irrigation. Even though the cv. Black Gold possesses these attributes, Hajlaoui et al. [18] identified the cv. Black Star as the most tolerant cultivar for deficit irrigation because it maintains a good water status.

The late maturing cv. Angeleno was the second most studied, as well as the cv. Red Beaut. The Angeleno cultivar was grafted onto the Mariana 2624 rootstock with 6 × 4 m spacing in all three studies included in this review [18–20]. Additionally, all orchards had cv. Larry-Ann and cv. Fortune trees planted, used as pollinators along with beehives. Studies have been conducted frequently to establish new water stress strategies more adapted to Angeleno. Samperio et al. [19] concluded that water stress intensity extensively impacts the final fruit size. This conclusion was confirmed in a study by Blanco-Cipollone et al. [20]. The relevance of fruit size has been used to justify the adoption of expensive thinning practices [21]. Similar to the cv. Angeleno, the cv. Red Beaut was grafted onto the Marianna 2624 rootstock in a study by Samperio et al. [22]. The Marianna 2624 rootstock is known for tolerating wet soils and moderately resisting diseases and oak root fungus [27]. The Black Diamond and Ambra cultivars were used as pollinators, while beehives ensured optimal pollination.

Regarding the geographical distribution, the studies included in this review were conducted in nine countries, as displayed on the map in Figure 4. These include four African countries (Morocco, Tunisia, South Africa and Egypt), two European (Spain and Poland) countries, two countries in the Americas (the United States of America and Chile) and an Asian country (Iran). All the articles were small-scale studies which involved experiments being undertaken at the farm or orchard level. In assessing the frequency of publication per country, the study observed that most of the studies were conducted in Spain (8), followed by South Africa (2). Egypt, Tunisia, Morocco, Iran, the United States of America (USA), Chile and Poland conducted a study each.

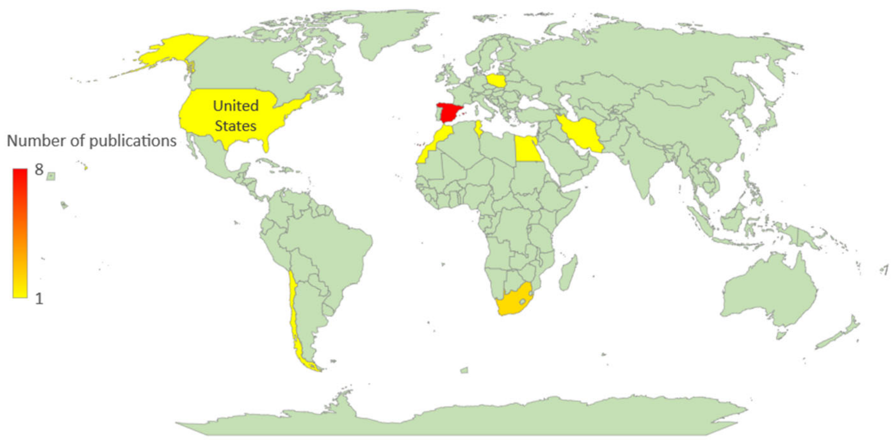

Figure 4. Geographical distribution of the studies conducted on the estimation of plum crop water requirements per country.

Spain, which recorded the most studies, is the seventh plum producer in the world and third in the European Union [28]. Plum production is of economic importance to Spain [29], as the cultivation of this fruit tree covers broad and climatically diverse regions within the country [30]. Spain is not exempted from the global effects of climate change and climate variability. An increase in high temperatures, especially in the regions characterized by the Mediterranean, causes a reduction in the accumulated chill, therefore affecting plum phenology. This is due to several influencing factors, including the importance of plums (*Prunus salicina* Lindl.) among the stone fruit species grown in Spain [29]. For the country to meet international standards and demands, the water demands of this fruit tree must be understood. A few studies have been conducted on the water requirements of *Prunus salicina*; thus, more studies need to be conducted to fill in this gap while sustaining the fruit industry. This same applies in South Africa and Morocco. Both countries have Mediterranean climates characterized by hot and dry summers, which require accurate information on crop water requirements for efficient irrigation scheduling. These climatic conditions have caused South Africa to be considered one of the driest countries globally [31]. Although South Africa is a water-scarce country, it is one of the major global exporters of plums [24], which is why more studies are being conducted to sustain the vibrant plum industry [32]. Collaboration between the country's research institutions and the relevant stakeholders makes it possible to prompt research into crop water requirements to optimize water use and management in plum orchards.

It is an interesting observation that no studies were retrieved for Australia considering that Europe and Australia have experienced severe climate change effects, which have caused drought conditions in recent years [33]. Ideally, more studies should be commenced in these circumstances to address the water scarcity issues that directly impact plum farming and thus the economy. However, there is hope that these spatial distribution gaps will be filled in time, as depicted by the temporal cumulative curve in the number of publications on the water requirements of plums globally (Figure 5).

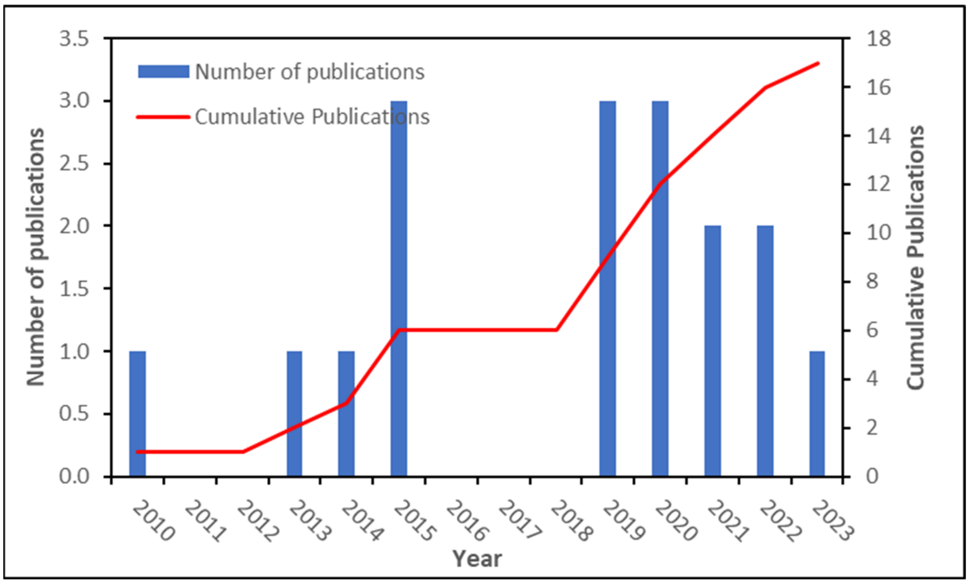

Figure 5. Frequency of studies published on the estimation of plum water requirements and the cumulative analysis of these publications.

According to Figure 5, the earliest publication that met the inclusion criteria was in 2010 [14]. Meanwhile, only a few (n = 5) articles were published between 2013 and 2015. No articles were published in 2011, 2012, 2016, 2017 or 2018. Most of the articles (n = 3) emerged in 2015, 2019 and 2020. There was a decline in the number of publications beyond these years i.e., in 2021, 2022 (n = 2) and 2023 (n = 1). Although a considerable fluctuation in publications was noted throughout the period, the cumulative graph shows that the number of studies on the estimation of plum water requirements has increased with time.

3.2. Evapotranspiration in Plum Orchards

The amount of water applied to a field is referred to as water use, and it either is consumed by crops through evapotranspiration (ET) or is not consumed [34]. Water consumption in a field is beneficial if it is consumed by crops through transpiration (T);

otherwise, it is non-beneficial if it is consumed as soil evaporation (Es) or by weeds. Therefore, there is a need to develop methods and technologies to estimate precise ET volumes due to the increasing incidence of water scarcity globally. Accurate estimation of ETc is essential to establish the maximum crop water requirements and therefore understand how water use is related to yield quality and quantity [34]. ETc is a primary component of the agricultural water balance. It represents the combination of the T (plants' water absorption from the root zone) and Es (vaporization from the soil surface) processes [35]. These processes are illustrated in Figure 6. While also contributing to the water cycle and surface energy balance, ETc can be used to compute the water requirements in a particular field. Since ETc rates are the same as crop water requirements, they can be used to measure crop water stress. The rate of ET is determined by the collective influence of meteorological factors, crop characteristics and orchard management practices.

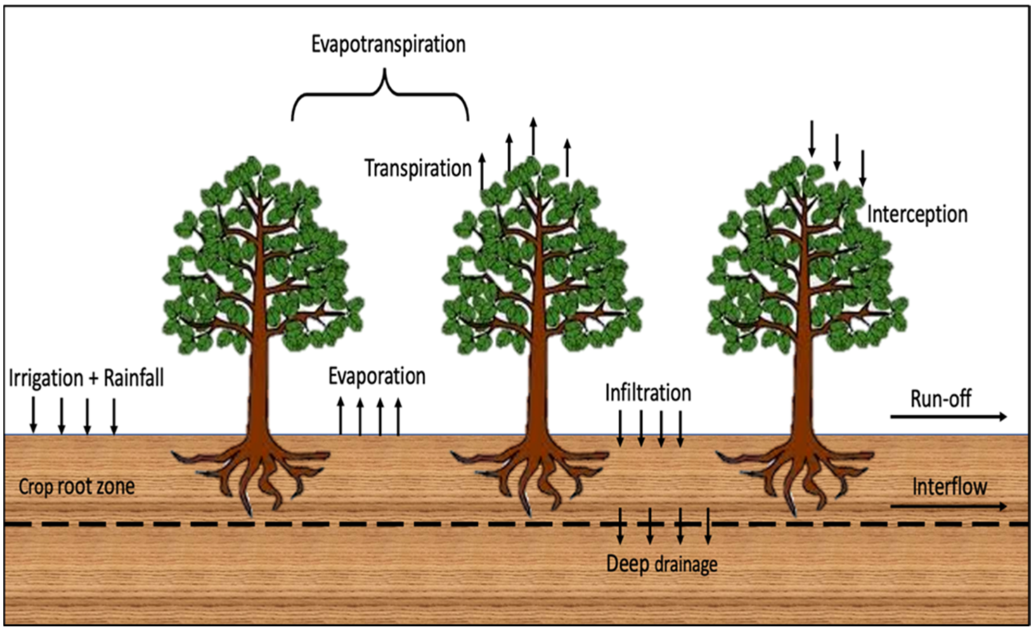

Figure 6. Illustration of water balance in an orchard setting.

The primary meteorological factors influencing ET are solar irradiance, relative humidity, air temperature and wind speed. The energy required to convert liquid water into vapor is provided by the incident solar radiation (and to a lesser degree, the ambient temperature of the surrounding air), whilst the atmospheric demand for vapor determines the rate, also referred to as the reference evapotranspiration (ETo) [36]. The influence of solar radiation on the ET rate is a function of the available radiation [which varies depending on the region, time of day, season, cloud conditions, etc.] and the fraction of incident radiation intercepted by the crop canopy. Stomata [mouth-like pores found in the epidermis of leaves and stems] regulate the gas exchange between a plant and the atmosphere [37]. The stomata open and close in response to a light stimulus (in this case, solar radiation), and as such, they are typically open during the day and closed at night. They facilitate the diffusion of carbon dioxide (CO_2) from the atmosphere into a leaf and the movement of water from the leaf into the atmosphere (transpiration) [38]. Jones et al. [39] highlighted the strong correlation between solar radiation and the observed transpiration rates given that water availability is not a limiting factor. The water holding capacity of the air changes with temperature, where warmer air has a higher holding capacity than colder, denser air. Therefore, the atmospheric demand for water vapor would be higher on warm, dry, sunny days than on cold, humid and cloudy days. The influence of wind speed on the ET rate can vary depending on the prevailing conditions. Generally, wind and air turbulence function to transfer water vapor from the evaporative surface to the overlying air. If the air at the evaporative surface is not replaced by drier air, the driving force for evaporation decreases due to the overlying air becoming saturated. The rate of ET increases with wind speed to the point where solar radiation or water availability becomes a limiting factor. At that point, a further increase in the wind speed will not increase the evaporation rate. Relative humidity (RH) and vapor pressure deficit (VPD) indicate the amount of water vapor in the atmosphere. RH has a negative relationship with ET, where increasing RH values decrease the ET over land surfaces. VPD, defined as the difference between the amount of moisture in the air and how much moisture the air can hold, is positively correlated with transpiration [40].

A combination of factors, which vary from crop to crop, influence the water usage within an orchard. These include the type and variety of crop, crop height, canopy structure and density and leaf area [36]. As such, different types of crops and potentially different cultivars will consume varying amounts of water under the same climatic conditions. Each crop type follows a set of phenological growth stages throughout the season, with each growth stage differing in terms of its water consumption. In the case of deciduous fruit trees, characterized by the seasonal growing and shedding of their leaves, orchard water use is typically lowest during the early and latter stages, with peak water use achieved midway through the season. Canopy size (aggregate area of vegetative growth) and canopy structure (spatial arrangement of a plant canopy) are regarded as the most critical factors influencing orchard water use throughout a season and the life span of an orchard [39]. The leaf area index (LAI) is commonly used to understand and compare the canopies of different trees better. Dzikiti et al. [2] investigated the influence of canopy cover and crop load on the seasonal water use of mature, full-bearing and young non-bearing orchards in two major apple production regions in the Western Cape (South Africa). The study concluded that canopy cover, as opposed to crop load, was the main driver of orchard water use in mature full-bearing orchards. Similarly, Intrigliolo and Castel [14] reported no statistical significance between different crop loads (medium and low) and the irrigation requirements in a 7-year-old Japanese plum orchard planted with the cv. Black Gold.

The movement of water from the soil through plants and into the atmosphere (the Soil–Plant–Atmosphere Continuum) is regulated by the resistive forces within the plant. These include the resistance at the soil–root interface, the roots' endodermic resistance, xylem resistance and the leaf's hydraulic resistance at the leaf–atmosphere interface [41]. The collective influence of these resistive forces and the stomatal conductance regulates the photosynthetic rate of a plant and consequently its transpiration [42].

The management practices employed in an orchard greatly influence water use. These include but are not limited to the use of netting or windbreakers, the chosen irrigation system (i.e., drip or microjet irrigation), the presence or absence of crop cover, its variety and the chosen planting system. The contribution of cover crops to total ET, particularly in apple orchards, has been well documented in the Western Cape. Ntshidi et al. [43] found that orchard floor evaporation (crop cover + soil evaporation) accounted for as much as 80% of the measured ET in young apple orchards with dense crop cover. This value was significantly lower in mature orchards (fractional canopy cover >55%), where the orchard floor evaporation contributed to less than 30% of the measured ET. Dzikiti et al. [2] obtained similar results, where floor evaporation accounted for 18 to 36% of the total ET in mature full-bearing orchards and over 60% in young non-bearing orchards. Both studies concluded that orchard water use could be reduced by decreasing floor evaporation rates. The planting system, which includes the tree planting arrangement, row orientation and the selected training system, and pruning and thinning practices influence orchards' ET by controlling the amount of solar radiation that can intercepted by the canopy [44]. Since photosynthesis is partly limited by light availability, modern-day training systems and pruning techniques aim to enhance light penetration through the canopy, maximizing photosynthesis and fruit production. Chootummatat et al. [45] investigated the effect of different training systems (Lincoln, Vase, Palmette and Tatura trellis systems) on the water use of a plum orchard planted with the cvs. Laroba and Santa Rosa. The differences in water use ranged between 9 and 18% depending on the chosen irrigation regime (a 40% or 110% class A pan evaporation rate), with the trees trained on the Vase and Tautra trellises using more water, at 40% and 110% irrigation, respectively. It is recommended that tree rows be orientated in the north–south direction (perpendicular to the sun's orbit path) to maximize light interception and minimize the amount of shade created by each tree [46]. However, additional factors, namely the local climate, slope of the land, prevailing wind direction and specific tree and fruit requirements, largely influence the exact orientation of orchards within a given region.

3.3. Principles and Methods to Determine Evapotranspiration in Plum Orchards

Over the years, various ET estimation methods have been developed and validated over a diverse range of land cover types (i.e., grasslands, agricultural land and forests). ET can be measured directly using instrumentation or empirically derived based on its relationship with other atmospheric and ground-based parameters [38]. The methods include meteorological methods (e.g., Penman–Monteith, Blaney–Criddle, Priestley–Taylor, Thronthwaite), micro-meteorological methods (e.g., the Bowen ratio, eddy covariance, scintillometery), eco-physiological techniques (e.g., sap flow, the isotope method, lysimeters) and more recently remote-sensing-based methods [47]. In many studies, the method selection is often motivated by data availability, the aim and proposed spatial and temporal scale of the study, the required accuracy and the associated costs of the study (available funds).

The main difference between these methods is their spatial footprint (the spatial scale at which they can accurately estimate ET). Eco-physiological methods, specifically the sap flow method, were developed to provide plant scale estimates of ET. In contrast, meteorological and micro-meteorological methods can measure the ET for a homogeneous surface (i.e., an orchard) at the local scale. These methods provide point estimations of ET, which, assuming a site's homogenous nature, represent the whole study area. A significant drawback of these methodologies, apart from scintillometry, is their inability to measure the spatial variability of ET fluxes over an area of interest. A network of stations is required for the application of meteorological and micro-meteorological methodologies to heterogeneous landscapes. However, several challenges are associated with this network, including the cost associated with the establishment, operation and maintenance of the stations and the costs of employing a team of experienced technicians needed to operate said stations. Another challenge relates to the interpolation of point ET estimates. Lott and Hunt [48] noted that interpolation introduces errors into the estimation of ET, particularly in mountainous areas (where meteorological conditions vary over short distances), as well as areas where stations are unevenly distributed, which is often the case. Remote-sensing-based models have been proposed as alternatives to traditional methods, as they can measure the spatial variation in ET across an area with relatively high accuracy [49]. Shoko [47] echoed the importance of accurately estimating ET levels and their spatio-temporal variability for improved water resource management and monitoring, particularly in water-scarce environments.

According to the results obtained in this study, the FAO-56 crop coefficient approach [36] is the most widely used approach for estimation of the water requirements of plum cultivars [50] (n = 10). Thirteen (13) methods and technologies were noted in the reviewed literature. A significant number of studies (49%) adopted the FAO-56 approach in their estimation of the water requirements of plums. The Soil Water Balance (SWB) model was only used in a study conducted on the cv. Angeleno by Moñino et al. [21]. The Treder, Grabarczyk and Rzekanowski and Press methods were all tested in one (4%) study conducted in Poland by Stachowski et al. [51]. Soil moisture sensors were used in conjunction with the IRRIX software to establish the water requirements of the Red Beaut cultivar [23]. The HYDRUS-2D and CROPWAT models were used in only one (4%) study each, by Jovanovic et al. [24] and Hajian et al. [25], respectively. Although the eddy covariance (EC) system has been used over the years to estimate the ET of various crops, it was only used in one (4%) study on the African-Delight cultivar by Dzikiti and Schachtschneider [52].

Remote sensing (RS) techniques (SEBALI and NDVI time series) were among the adopted methods (4%).

The FAO-56 coefficient approach by Allen et al. [36] was the most used method across the retrieved studies. In this method, ETo is determined using the Penman–Monteith method [34]. In a study by Hamdani et al. [17], crop water requirements were scheduled daily according to the ETo and Kc reported by [53]. The authors adjusted the Kc values to the tree canopy cover using a reduction coefficient (Kr) suggested by Fereres et al. [54]. This method performed well for all the trees studied since they had comparable vigor. The use of Kr yielded satisfactory results for the *Prunus domestica* cv. Stanely [55]. Millan et al. [23] used data from soil moisture sensors to calculate the water requirements of the Red Beaut cultivar using a cloud-hosted web platform called IRRIX. This platform also performs various tasks, including irrigation scheduling decision-making without any human intervention. Just like the study by Hamdani et al. [17], which calculated the water requirements using adjustment factors incorporated into the FAO-56 approach, the IRRIX algorithm described by [56] calculates ETc using the FAO-56 approach fused with an adjustment factor which personalizes the basal crop coefficient (Kcb) to the vigor of the plot. In some instances, some studies calculate Kc from the crop coefficient approach using the SWB method. This was the case in Blanco-Cipollone et al. [20], where weekly water requirements were adjusted using the SWB method with the neutron probe measurements described in Samperio et al. [19]. The total water requirements of the cv. African Rose were calculated using a theoretical irrigation rate and the ETc obtained using the FAO-56 approach [26].

The eddy covariance (EC) system, which uses the simplified energy balance method, is the most reliable micro-meteorological technique for estimating ET [38]. Due to the system's associated costs, Dzikiti and Schachtschneider [52] collected the data for a few days in summer during the optimum irrigation period. This is the probable reason the study did not report the seasonal ET for the cultivar. Studies often use EC-measured ETc data to validate model- or remote-sensing-derived ET data. This was the case in the study by Mhawej and Faour [57], where the ETc estimates obtained using SEBALI were validated using a network of EC systems. This validation yielded a Root Mean Square Error (RMSE) and a coefficient of determination (R^2) of 11.53 mm/month and 0.82, respectively.

A few studies adopted remote sensing techniques due to their large spatio-temporal coverage under specific resolutions. Gavilán et al. [58] integrated and harmonized the Normalized Difference Vegetation Index (NDVI) obtained from the Sentinel-2 and Landsat 8 sensors and obtained NDVI time series, used to estimate the ET through fit equations. The results from the study showed a significant correlation between the ETc and the NDVI from Landsat 8 in the plum orchard, reflected by a Pearson's correlation coefficient of 0.8, which is similar to that reported in the literature by Nagler et al. [59] and Glenn et al. [60]. Additionally, the remotely sensed ET correlated well with the actual measured ET data, producing bias and an RSME of −0.4 mm/day and 0.6 mm/day, respectively. These results allowed them to update the seasonal water balance of the study site, which improved the irrigation water management at the plot and the water distribution system scale. In a separate study, Mhawej and Faour [57] compared the ET obtained from a SEBALIGEE ET retrieval system with the eddy covariance (EC) values, and the accuracy had an acceptable bias of 0.48 mm/day. An improved bias of 0.32 mm/day and an R^2 value of approximately 80% were obtained after further calibration. Other studies have integrated the FAO-56 approach with remote sensing techniques to achieve more accurate results [18].

The HYDRUS-2D model was used by Jovanovic et al. [24] to calculate ET as the sum of the root water uptake and soil evaporation. The results from the HYDRUS model gave the best fit with the observed data after the model's soil water content data were calibrated through comparison with those measured using AquaCheck probes. Jovanovic et al. [24] concluded that the water requirements of plums calculated using the HYDRUS-2D model differed mainly depending on the duration of the growing season and the canopy cover.

Stachowski et al. [51] tested the usefulness of the Press, Rzekanowski and Grabarczyk and Treder methods for estimating the CWR of plum trees, among other fruit tree species, in plots where water deficits were observed. The seasonal ETc of the plums ranged from 455 to 718 mm using the Press and the Grabarczyk and Rzekanowski methods, respectively. The precipitation in the respective study periods did not meet the water needs of the plum trees. In addition, the study reported that the plants' water needs increased in the second and third decades compared to the first. The highest water needs were calculated using the Treder method and the lowest using the Press method. However, Stachowski et al. [51] recommended using the Treder method, which is the simplest and most accessible method.

This review observed that 67% (n = 12) of the retrieved articles adopted deficit and regulated deficit irrigation as practical irrigation strategies for saving water, especially in water-scarce environments. There have been conclusive observations that RDI techniques aid in improving crop quality, although they can reduce vegetative growth and therefore the yield of the respective cultivar. Hence, RDI treatments must be cautiously applied to avoid carry-over effects on tree performance. RDI treatments have been combined with several methods to accurately estimate the water requirements in plum orchards. These methods, however, have varying underlying principles of operation [61].

3.4. Water Requirements of Japanese Plum Orchards

The water requirements of an orchard vary throughout the course of a season, depending on the phenological growth stage and throughout an orchard's life span depending on its age and canopy cover [40]. Stone fruits are characterized by four phenological growth stages, namely (i) stage I: the first rapid fruit growth; (ii) stage II: pit hardening; (iii) stage III: the second rapid growth and (iv) stage IV: post-harvest [62]. Vegetative growth (the growth of leaves, stems and roots) mainly occurs during stages I and II, when plant vigor can be manipulated to control fruit size and quality. Fruit growth occurs exponentially during the first stage (stage I), typically lasting 30 days or less. This exponential growth is succeeded by a lag growth phase, during which the pit (stone) hardens and embryo development occurs (stage II). Stage III is characterized by a second period of rapid fruit growth where the fruit can double in size (up to 40–60%) [9,62]. By the end of stage III, the fruit is mature and ready to be harvested.

Each phase's duration and susceptibility to water stress differ for different stone fruit varieties (i.e., plums, peaches, apricots and nectarines) and cultivars, with early-season plum cultivars typically experiencing a shorter stage II growth phase [63]. In early-season cultivars, fruit growth will continue into the pit hardening phase (stage II), albeit at a slower rate, making it difficult to distinguish between the two stages [63]. In late-season cultivars, the pit hardening phase is longer, and the degree of fruit growth during this stage is minimal. Generally, peak water consumption is experienced during stage III when the second rapid fruit growth occurs, and the fruit cells begin to fill with water and sugar. After harvest, tree transpiration rates gradually begin to decline, resulting from reduced photosynthesis rates, associated with the onset of leaf senescence and a reduction in leaf area as the tree enters a winter dormancy period. Trees are more susceptible to water stress during stages I and III, so accurate irrigation scheduling is crucial to achieve an economically viable yield.

The water requirements and evapotranspiration data collated from the literature ranged between 331 and 1211 mm and are summarized in Table 1. A distinction was made between the water requirements during the growing season and throughout the year. The growing season is the period from bud-break (typically in early spring) to harvest. Full-year crop water requirements encompass the water requirements during the growing season along with the supplementary requirements before the beginning of the growing season and post-harvest. Irrigation during these periods, although at reduced rates, is essential for maintaining tree health and minimizing alternate bearing. As such, it should be considered when determining the total water requirement of an orchard, as well as water allocation. The full-year water requirements ranged between 835 and 1211 mm a^{-1} when considering figures from orchards under regulated deficit irrigation (RDI) regimes. When these were omitted, i.e., only the control orchards (irrigated at 100% crop water requirements) were considered, the water use ranged between 921 and 1211 mm a^{-1}. The water requirements during the growing season ranged between 331 and 864 mm.

Table 1. Summary of annual and seasonal plum water use estimates from literature.

Reference	Location	Method	Cultivar	Water Use (mm a^{-1})	Water Use (mm $season^{-1}$)	Key Findings
[24]	South Africa	HYDRUS-2D	Fortune, African Delight		858–864 (Septemebr–March) 534–641 (September–January)	Initial basal crop coefficients varied from 0.98 to 1.01, whilst basal crop coefficients for the mid-stage averaged between 1.11 (cv. African Delight) and 1.18 (cv. Fortune).
[17]	Morocco	FAO-56 Kc	Santa Rosa, Timhdit, Red Beaut, Black Amber, Black Diamond, Black Gold, Obilnaja, Fortune, Black Star			The cultivars' yield and fruit weight significantly decreased from the first year of deficit irrigation application. The cv. Fortune was the most insensitive to drought, whereas the cv. Black Diamond and the cv. Timhdit showed the lowest drought tolerability.
[18]	Tunisia	FAO-56 Kc	Black Diamond, Black Gold and Black Star			The three cultivars had tolerance to moderate stress with varying response times to drought stress.
[51]	Poland	Press, Grabarczyk and Rzekanowski and Treder			455–718	Regardless of the method used, the rainfall volumes received in the studied period did not cover the water requirements of the fruit trees. The Treder method seemed to be the simplest and most accessible method.
[26]	Egypt	FAO-56 Kc	African Rose			Deficit irrigation could be a sustainable novel solution to improve the fruit quality of the cv. African Rose grown under semi-arid conditions.
[21]	Spain	SWB	Angeleno	1011–1187		Deficit irrigation treatments were found to be effective at controlling tree vigor, with a lower trunk cross-sectional area growth and pruned wood weight.
[25]	Iran	CROPWAT	Methly			Moderate water stress (75% RDI) improved fruit yield and saved water without an undesirable effect on plum fruit quality.
[23]	Spain	Soil Moisture Sensors, IRRIX	Red Beaut			After two years of testing, the automated system could "simulate" the irrigation scheduling programmed by a human expert without human intervention.
[20]	Spain	FAO-56 Kc	Angeleno			After eight years of applying the RDI strategies, no carry-over effects on the orchard yield were observed. Based on these results, RDI appears to be a sustainable practice for the cv. Angeleno and the growing conditions.
[22]	Spain	FAO-56 Kc	Red Beaut	835–1159		The RDI treatments were suitable for reducing the total pruning weight. In the long term (five seasons), the effect of post-harvest RDI had no negative cumulative impact on tree productivity.
[19]	Spain	FAO-56 Kc	Angeleno	962–1211		This study suggests that allowing some degree of water stress during stage II and post-harvest appears to offer an effective management strategy for saving water and controlling vegetative growth without negatively affecting crop yield or farmers' economic return.
[16]	Spain	FAO-56 Kc	Black Gold			Crop load regulation is a valuable tool allowing plum trees to quickly recover from the detrimental effects of long-term deficit irrigation.
[15]	Spain	FAO-56 Kc	Black Gold			Deficit irrigation strategies should be used with caution in developing orchards. Only slight restrictions can be imposed to avoid the long-term carry-over effects of deficit irrigation on tree performance.

Table 1. *Cont.*

Reference	Location	Method	Cultivar	Water Use (mm a^{-1})	Water Use (mm $season^{-1}$)	Key Findings
[14]	Spain	FAO-56 Kc	Black Gold		432–525 (April–October)	The RDI strategy allowed for 30% water savings, increasing the tree water use efficiency with minimal effect on crop yield and fruit growth, providing that the plant water stress during the fruit growth period was low (stem water potential > −1.5 MPa).
[57]	USA	SEBALI		994		The proposed open-source system aims to improve the assessment of ET and water productivity and the management of water resources.
[58]	Chile	NDVI time series			331 (December–March)	It is possible to estimate evapotranspiration using a Normalized Difference Vegetation Index (NDVI) time series by integrating data from Landsat 8 and Sentinel-2 sensors, improving irrigation water management at the plot and water distribution system scales.
[52]	South Africa	EC	African Delight	921		Accurate estimation of crop water requirements attracts potential water savings of up to 20% in certain situations. These results apply at a very localized level. Western Cape farmers, compared to those internationally, show that they are two to nine times more efficient in their water use during fruit production than the international water footprint averages suggest.

In South Africa, Dzikiti and Schachtschneider [52] reported water use of 921 mm a^{-1} (1006 mm total irrigation) for a well-water drip-irrigated African Delight orchard (3 ha) in Robertson. This is ±30% lower than the figures reported for well-watered late-maturing orchards in Spain despite having a higher plant density (2667 trees ha^{-1}) and a markedly drier climate. Jovanovic et al. [24] observed similar water use figures for the same cultivar. Jovanovic et al. [24] estimated the water requirements of four full-bearing Japanese plum orchards (cvs. African Delight and Fortune) in Robertson and Wellington (South Africa). The late-maturing African Delight orchards in both regions displayed higher water usage figures of 858 and 864 mm in Wellington and Robertson, respectively, compared to 534 and 641 mm for the mid-maturing Fortune orchards. The differences in water use were attributed to the more extended growing season of African Delight (September–March) than that of Fortune (September–January). The observations from both studies suggest the need for better orchard management and water-saving practices in South Africa compared to Spain. However, further research on the plum water requirements in South Africa, particularly those of high-density orchards (>1000 trees ha^{-1}), is required for a more comprehensive assessment.

Recently, Mhawej and Faour [57] estimated the ET rates over a 307,000 km^2 agricultural plain in California. The average ET for plums was estimated to be 994 mm a^{-1} with a standard deviation of 188 mm a^{-1}, whilst the cumulative water consumption between 2017 and 2019 was estimated to be 4.1 km^3 (accounting for 0.65% of total water use across the study area). The remotely sensed estimates were validated using a network of eddy covariance flux towers, yielding coefficient of determination (R^2), Root Mean Square Error (RMSE) and average marginal effect (AME) values of 0.82, 11.53 mm $month^{-1}$ and 9.56, respectively.

Gavilan et al. [58] estimated the ET rates over a 70 km^2 stretch of land in Chile's agriculturally prominent O'Higgins region. The daily ET estimates for the plum orchards ranged between 3 and 5 mm day^{-1}. The actual and reference ET (ETo) for the season were estimated to be 331 and 525 mm, respectively. The remotely sensed estimates had a good agreement with the ground-based ET values, producing RMSE and bias values of 0.6 mm day^{-1} and −0.4 mm day^{-1}, respectively. The low ET estimate reported in the study was attributed to a water deficit during the season resulting from poor irrigation management in the area. The study also had a shorter growing season of 3 months (December–March), compared to 5–6 months in the other studies. Growing season length appeared to be the most common cause of discrepancies in the water requirement estimates. Late-season-maturing orchards have a longer growing season, meaning the trees retain their leaves for longer. This maintains the crop canopy for an extended period, facilitating continual crop water usage compared to early- and mid-season-maturing orchards, which experience leaf fall at an earlier stage. Additional causes of variation include differences in growing conditions (a combination of climate and orchard management practices) and the chosen regulated deficit regime (where applicable).

Moñino et al. [21] estimated the average annual water requirement (irrigation + effective rainfall) for a 9-year-old cv. Angeleno orchard to range between 1011 and 1187 mm a^{-1} depending on the imposed regulated deficit irrigation (RDI) regime. In another study, Sampeiro et al. [22] estimated the average water requirement (irrigation + rainfall) of the early-maturing Japanese plum cultivar cv. Red Beaut under three different regulated irrigation regimes over five seasons (2009–2013). The imposed irrigation regimes included a control regime where the trees were irrigated at the estimated crop water requirement, along with two regulated deficit irrigation (RDI) regimes, where the trees were irrigated at 60% (RDI-60) and 30% (RDI-30) of the crop water requirement. The average water requirement was estimated to range between 835 and 1159 mm a^{-1}, with the trees under the RDI-30 regime having the lowest water use and the trees under the control irrigation regime having the largest. In a second study, Sampeiro et al. [19] estimated the average water requirement (irrigation + rainfall) of a 4-year-old cv. Angeleno orchard in Badajoz, Spain, to be between 963 and 1211 mm a^{-1}, depending on the irrigation regime.

The full-bearing plum orchards reported by Sampeiro et al. [19,22] and Moñino et al. [21] were cultivated under similar growing conditions (climate and management practices] in Badajoz, Spain. Different RDI regimes were applied at each orchard, but the control plots were irrigated at 100% of the crop water requirement. The early-maturing Red Beaut orchard had the lowest water requirement (1159 mm a^{-1}) [22]. Moñino et al. [20] and Sampeiro et al. [18] reported water requirements of 1187 and 1211 mm a^{-1} for late-maturing Angeleno orchards. These orchards were well watered and thus considered to be indicative of the maximum unstressed water requirement for mature full-bearing Japanese plum orchards in the region.

Intrigliolo and Castel [14] used an adjusted Kc for canopy size to estimate the crop water requirements of the 7-year-old Japanese plum cv. Black Gold in Valencia, Spain, for three seasons (2004–2006). The seasonal water requirement, calculated as the sum of irrigation and effective rainfall from April to October, was between 432 and 525 mm, depending on the irrigation water treatment and crop load.

4. Study Limitations

During the literature search exercise, several studies were unavailable as full text, while others were written in languages other than English. This is a significant setback for trying to synthesize all studies conducted on estimating the water requirements of various plum cultivars. Additionally, the current performed literature search used the Science Direct, Scopus and Web of Science databases only. There is a strong chance that some relevant studies may have been left out of the analysis. Thus, the exclusion of these studies may have negatively impacted the accurate spatial distribution of the studies conducted to estimate the water requirements of plums. Fundamentally, it is imperative to compare the ET data estimated using other methods with the ground ET data measured using EC to evaluate accuracy and for validation purposes. Most of the studies did not perform the validation process; thus, this review did not compare the accuracies of the methods.

5. Research Gaps

Although the FAO-56 approach is the most widely used and reliable method for estimating crop water requirements, studies need to adopt and use one of the most direct and defensible micro-meteorological methods. The FAO-56 approach utilizes published crop coefficients (crop factors) that may not be representative of the different microclimates (locations) of the field orchards. Therefore, there is a need to use a more direct method of estimating the actual ET, such as the eddy covariance system. In this review, only one study used the eddy covariance system, yet it has great potential to determine the accurate ETc value. It has been widely used and performed well for other agricultural crops; thus, there is a critical need for studies to adopt the use of EC systems to estimate ETc in plum orchards. Therefore, the estimated plum ETc can also be used to calibrate and validate other methods and technologies. The EC system is mathematically complex and requires a lot of expertise to install and process data, but it is imperative to use.

Of the retrieved articles, no studies utilized ground-based plant measurements to estimate the water requirements of plum cultivars. When estimating crop water requirements, it is essential to understand the plant–water relations. Plant measurement methods such as the stem water potential (SWP) aid in monitoring plant water status and tracing the onset of water stress. Future studies should integrate soil, plant and atmospheric measurements to estimate accurate water requirements of various plum cultivars.

6. Conclusions

In recent years, the number of studies on estimating and measuring the water requirements in plum orchards has cumulatively grown. The results obtained from the literature show that the full-year water requirements for well-watered full-bearing Japanese orchards ranged between 835 and 1211 mm a^{-1}. Canopy growth and pruning appeared to be the most common causes of differences in the water requirement estimates. Growing season length also plays a role, with late-season maturing orchards having higher water requirements than their early and mid-maturing counterparts. Additional causes of variation include differences in growing conditions (combination of climate and orchard management practices) and the chosen regulated deficit regime (where applicable). Extensive research on the water-saving potential of regulated deficit irrigation (RDI) was performed in various studies from the literature, with the bulk of the work originating from Spain. Similar to South Africa, increasing water scarcity and climate change appear to be significant challenges in Spanish agriculture. Approximately 67% of the reviewed studies adopted the use of varying RDI treatments (particularly in stage II and post-harvest phenological growth stages) to reduce water use and improve fruit quality whilst maintaining commercially acceptable crop yields. The adoption of the FAO-56 coefficient approach, together with varying RDI treatments, was common in most orchards. The FAO-56 coefficient approach is widely used due to its ability to estimate ETc using environmental and crop-specific conditions. In the wake of a recent drought in the Western Cape, this methodology could assist in developing a drought resiliency framework to protect the plum industry from the effects of climate change. However, further research is required on the response of plums to water stress in the context of South Africa. Additionally, there is a need to quantify the water use of plum orchards from planting to full-bearing age for holistic, long-term water planning and the sustainability of the industry. Lastly, extensive validation of remote-sensing-based crop ET estimates against ground-based measurements is required to evaluate the performance of models. The continual validation and calibration of the models aid in improving the model accuracy.

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