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Drought Risk in Mango and Avocado Orchards: Insights Into Plant Water Relations and Irrigation-Related Agronomic Solutions

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ABSTRACT

Climate change is making water availability more uncertain, with growing consequences for the productivity and long-term sustainability of tropical and subtropical fruit orchards. *Mangifera indica* L. and *Persea americana* Mill. both require large amounts of water to sustain growth and productivity. They are among the most water-demanding perennial crops. This review summarizes recent findings on plant–water relations and irrigation management in mango and avocado, considering soil-based approaches aimed at mitigating water stress. Particular attention is given to regulated and sustained deficit irrigation, partial root-zone drying and the use of soil amendments such as biochar, zeolite and hydrogels. Recent field experiments indicate that the application of soil amendments and biostimulants can mitigate some of the constraints imposed by drought. Their effects are mainly associated with improved soil water retention and nutrient availability, as well as better root-zone functioning leading to more stable yields under water-limited conditions, especially in degraded soils. By combining physiological, agronomic and soil-based approaches, this review identifies practical opportunities to improve water-saving strategies in mango and avocado. At the same time, it points out key research gaps that need to be addressed to support the development of resilient orchard systems under increasing water stress driven by climate change.

RÉSUMÉ

Le changement climatique rend la disponibilité en eau plus incertaine, avec des conséquences croissantes sur la productivité et la durabilité à long terme des vergers fruitiers tropicaux et subtropicaux. *Mangifera indica* L. et *Persea americana* Mill.—les deux nécessitent de grandes quantités d'eau pour soutenir la croissance et la productivité. Elles sont parmi les cultures pérennes les plus exigeantes en eau. Cette revue résume les résultats récents obtenus sur les relations entre les plantes et l'eau et la gestion de l'irrigation chez la mangue et l'avocat, en tenant compte des approches basées sur le sol visant à atténuer le stress hydrique. Une attention particulière est accordée à l'irrigation déficitaire réglée et soutenue, à l'assèchement partiel des racines et à l'utilisation d'amendements du sol tels que le biochar, la zéolite et les hydrogels. Des expériences récentes menées sur le terrain indiquent que l'application d'amendements du sol et de biostimulants peut atténuer certaines des contraintes imposées par la sécheresse. Leurs effets sont principalement associés à une meilleure rétention de l'eau du sol et à une meilleure disponibilité des éléments nutritifs,

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ainsi qu'à un meilleur fonctionnement de la zone racinaire, ce qui donne des rendements plus stables dans des conditions limitées en eau, en particulier dans les sols dégradés. En combinant des approches physiologiques, agronomiques et basées sur le sol, cette revue identifie des possibilités pratiques d'améliorer les stratégies d'économie d'eau dans la mangue et l'avocat. Dans le même temps, elle souligne les principales lacunes de la recherche qui doivent être comblées pour soutenir le développement de systèmes de vergers résilients sous le stress hydrique croissant provoqué par le changement climatique.

1 | Introduction

Water relations play a crucial role in the growth, productivity and resilience of tropical tree crops. Understanding plant–water interactions helps optimize irrigation management, improve drought tolerance and maintain physiological balance under stress conditions (Beyá-Marshall et al. 2025). Tropical or subtropical tree crops are often cultivated in regions characterized by high temperatures and irregular rainfall patterns, making efficient water use essential for sustainable production (Raju et al. 2024). A broad scientific consensus indicates that tropical regions are among the earliest and most severely affected by climate change, even though historical and projected temperature shifts in the tropics may appear moderate relative to higher latitude regions (Nath et al. 2018). This vulnerability arises from a combination of factors, including widespread socioeconomic fragility, strong reliance on natural resources and ecosystem services and the typically narrow climatic tolerance ranges of tropical environments (Nath et al. 2018). The IPCC confirms that climate change does not alter global precipitation uniformly but instead redistributes rainfall patterns in heterogeneous ways by reshaping regional water cycles (IPCC 2021). As the atmosphere warms, its moisture-holding capacity increases following Clausius–Clapeyron dynamics, intensifying atmospheric water transport and amplifying existing hydro-climatic gradients (Döll et al. 2018). Consequently, humid regions tend to experience greater annual rainfall and more persistent wet spells, whereas arid and subtropical zones become drier, with prolonged dry periods and reduced seasonal precipitation. These shifts are accompanied by stronger hydrological extremes: Heavy rainfall events become more frequent and intense because of enhanced atmospheric moisture availability, while droughts deepen and lengthen in water-limited regions as evaporation demand rises (Fowler et al. 2021; Deng et al. 2024). Overall, the warming climate strengthens both ends of the precipitation spectrum, producing a pattern often summarized as 'wetter-get-wetter, drier-get-drier' and increasing the severity and occurrence of floods and droughts (Trancoso et al. 2024). For example, countries such as Chile (Beyá-Marshall et al. 2025), the Mediterranean basin (Cataldo et al. 2025), Brazil (Marengo et al. 2022) and India (Mishra and Liu 2014) have been affected by a severe reduction in water availability, especially in already semi-arid areas. Beyond changes in precipitation, rising air temperatures further intensify water stress through increased evaporative demand. Current projections suggest an increase in tropical regions' mean temperature of approximately 0.8°C–3.2°C by mid-century and 1.2°C–6°C by 2100 relative to historical baselines, accompanied by a rise in atmospheric CO_2 concentrations to 550–800 ppm by the end of the century. Climate change in the tropics is expected to manifest not as a smooth trend but through heightened variability and more extreme events (Nath et al. 2018).

Traditional tropical and subtropical growing regions for mango and avocado are increasingly constrained by climate-induced stressors. Rising temperatures during anthesis and fruit set exceed crop thermal optima, impairing pollen viability and early fruit retention. Concurrent increases in vapour pressure deficit and irregular precipitation intensify irrigation demand and heighten vulnerability to drought. Consequently, previously core production zones are becoming marginal or agronomically unsustainable without substantial adaptive inputs (Grüter et al. 2022). In parallel, warming trends are expanding the potential cultivation range towards cooler subtropical and warm-temperate environments, where historical thermal limitations are diminishing. This spatial reallocation reflects a progressive geographic and altitudinal shift in suitable agro-climatic niches for perennial tropical fruit crops (Noordam 2024). NASA's latest global temperature assessment shows that 2024 was the hottest year ever recorded. The global mean surface temperatures were approximately 1.28°C above the 1951–1980 reference period, surpassing the previous record set in 2023 (NASA 2025). When compared to pre-industrial mid-19th-century levels, the warming reached approximately 1.47°C, underscoring the continued acceleration of planetary heating (Figures 1 and 2).

Temperature anomalies indicate widespread warming, strongest at high northern latitudes and across major ocean basins. Precipitation anomalies display a heterogeneous pattern, with wetter-than-average conditions in northern Europe, East Africa and South Asia and drier-than-average conditions around the Mediterranean, Central America and Western Australia. These spatial patterns are consistent with the observed intensification of the hydrological cycle under global warming (Copernicus Climate Data Store 2023). These spatial anomalies support the broader evidence that perennial tropical fruit systems must adapt to a rapidly shifting climate envelope, integrating water-efficient systems and geographic diversification of production (Noordam 2024).

Water availability and temperature influence leaf gas exchange, stomatal conductance and photosynthetic efficiency, directly affecting biomass accumulation and fruit yield (Cataldo et al. 2025). Moreover, hydraulic conductivity within the xylem determines how efficiently water is transported from roots to leaves, impacting canopy temperature regulation and nutrient translocation. In tropical environments, prolonged water deficit can lead to cavitation, leaf shedding and reduced carbohydrate synthesis (Moreno-Pérez et al. 2024). Conversely, waterlogging-induced hypoxia rapidly depresses gas exchange and impairs root function, leading to restricted nutrient uptake and growth decline (Schaffer et al. 2006). Integrating knowledge of water potential dynamics, soil moisture and plant hydraulic characteristics allows for the development of better adaptation strategies to climate variability. Together, these hydraulic constraints

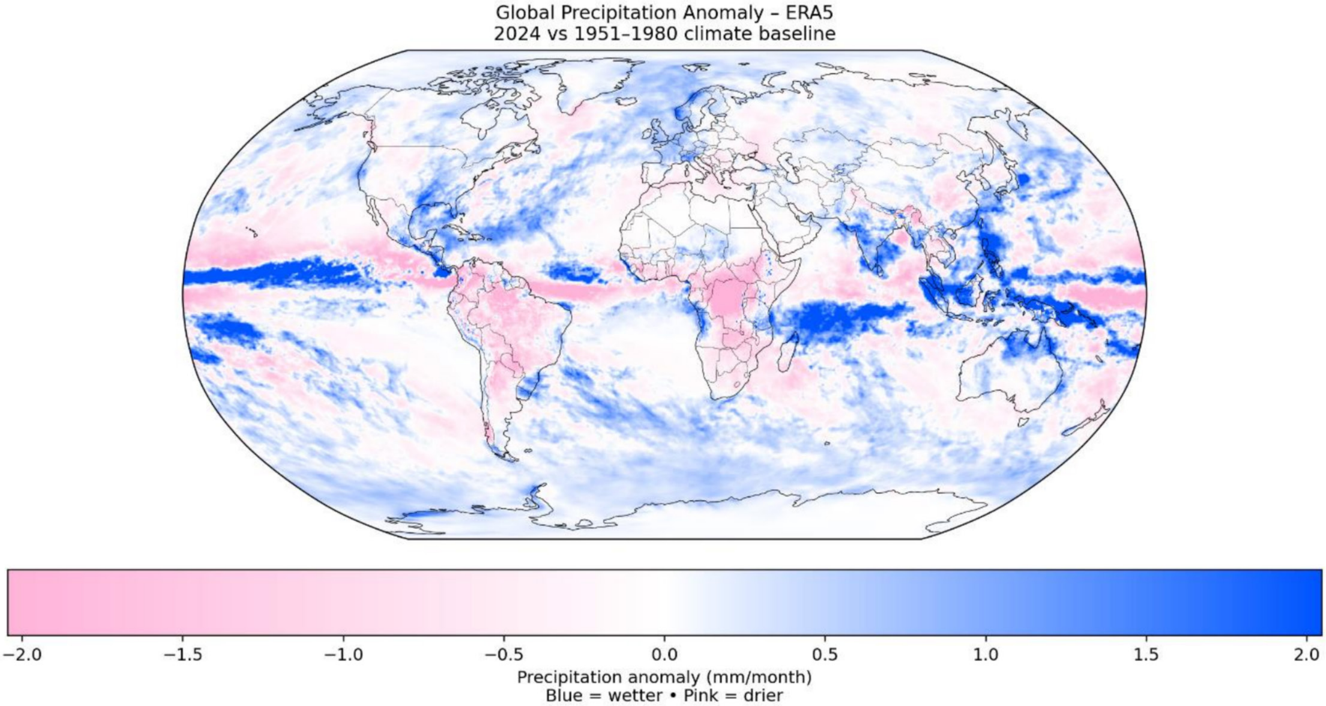

FIGURE 1 | The figure illustrates the global anomalies in total precipitation for 2024 relative to the 1951–1980 climatological baseline, derived from ERA5 reanalysis (Copernicus Climate Data Store 2023). The figure was produced by the author based on publicly available data. The Robinson projection was selected to provide a visually balanced representation across latitudes. The major producing regions discussed in this review include China, Indonesia, Mexico, Pakistan, Thailand, Brazil, Colombia, Peru, the Dominican Republic, Kenya and the Mediterranean basin.

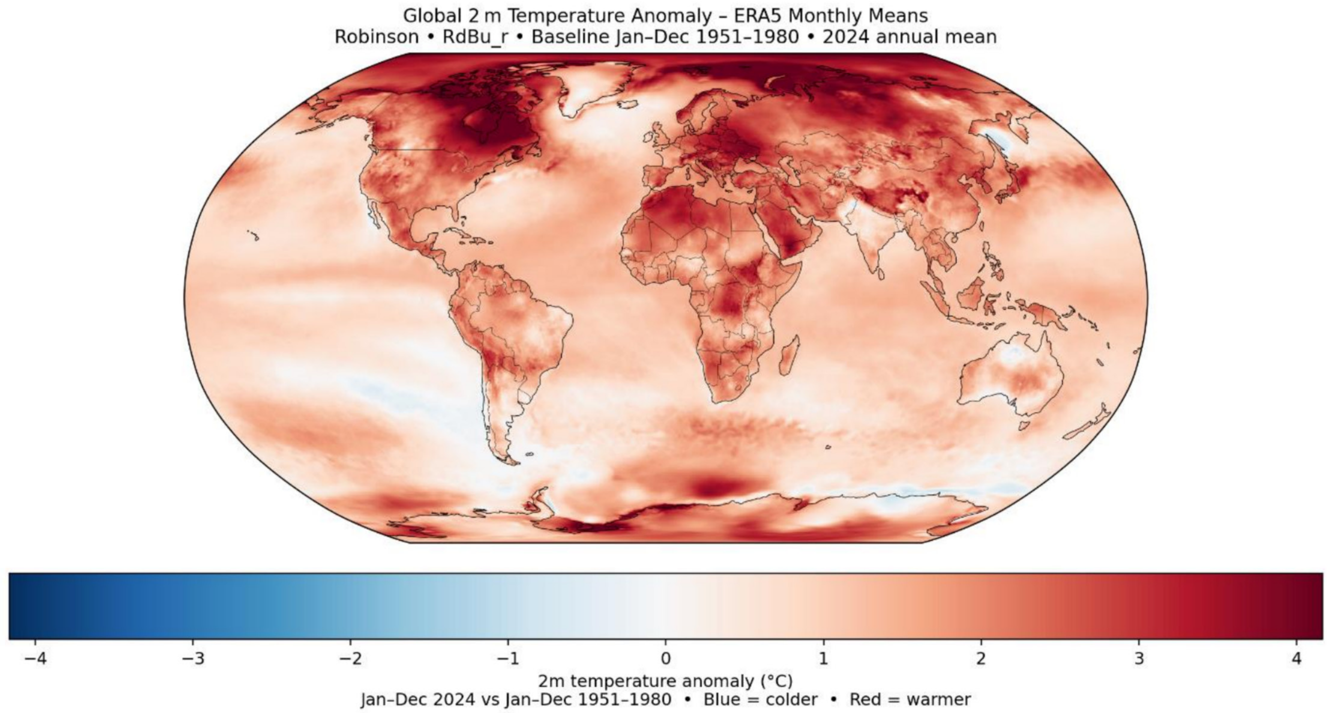

FIGURE 2 | The figure illustrates the global anomalies in mean annual 2-m air temperature for 2024 relative to the 1951–1980 climatological baseline, derived from ERA5 reanalysis (Copernicus Climate Data Store 2023). The figure was produced by the author based on publicly available data. The Robinson projection was selected to provide a visually balanced representation across latitudes. The major producing regions discussed in this review include China, Indonesia, Mexico, Pakistan, Thailand, Brazil, Colombia, Peru, the Dominican Republic, Kenya and the Mediterranean basin.

highlight the physiological margin within which tropical perennial crops must operate under increasingly variable water availability. Therefore, studying water–soil relationships is essential to improving resource efficiency, ensuring fruit quality and ensuring the long-term sustainability of tropical orchard systems.

This review focuses on mango (*Mangifera indica* L.) and avocado (*Persea americana* Mill.), two tropical–subtropical fruit tree species characterized by high water requirements and sensitivity to drought stress. Both crops are expanding in regions increasingly affected by water scarcity, emphasizing the need for sustainable water management strategies. In these systems, water deficits can severely affect not only vegetative growth but also key reproductive processes such as flowering success, fruit set and fruit retention, ultimately reducing yield stability and marketable quality. Because orchard irrigation must simultaneously sustain productivity and minimize water withdrawal, there is a growing need for management strategies that integrate plant hydraulic behaviour with agronomic solutions aimed at buffering root-zone water availability and improving irrigation efficiency. This paper analyses current practices adopted to mitigate water stress, including optimized irrigation systems and biostimulant applications. Furthermore, it explores innovative and underexplored approaches that could enhance water productivity and resilience in fruit tree cultivation. Particular attention is given to agronomic strategies capable of improving plant hydraulic performance, such as hydrogel, zeolite and biochar. This review aims to identify future directions for sustainable water management in tropical fruit orchards.

2 | Literature Search and Selection and Review Structure

This review is based on a comprehensive analysis of peer-reviewed literature addressing water relations, irrigation strategies and drought mitigation approaches in mango (*M. indica* L.) and avocado (*P. americana* Mill.). Bibliographic searches were conducted using major scientific databases, including Web of Science, Scopus and Google Scholar. Priority was given to experimental field studies and controlled environment trials articles published primarily between 2010 and 2025, with particular emphasis on studies reporting physiological, agronomic or soil-based responses to water limitation. Studies were selected based on their relevance to orchard-scale management, the clarity of experimental design and the availability of quantitative data on plant water status, yield, water productivity or water-use efficiency. The search strategy combined crop-specific terms with water-stress and irrigation-related keywords using Boolean operators. The main keyword strings included ('mango' OR '*Mangifera indica*') AND ('drought' OR 'water stress' OR 'water deficit' OR 'plant water relations') AND ('irrigation' OR 'regulated deficit irrigation' OR 'RDI' OR 'sustained deficit irrigation' OR 'SDI' OR 'partial root-zone drying' OR 'PRD' OR 'water productivity' OR 'water use efficiency'); and ('avocado' OR '*Persea americana*') AND the same set of water-related and management-related terms. Additional searches targeted soil-based mitigation practices by including ('biochar' OR 'zeolite' OR 'hydrogel' OR 'biostimulant' OR 'soil amendment' OR 'water retention') in combination with crop-specific terms. In Google Scholar, searches were performed using simplified keyword combinations, followed by an iterative screening of titles and abstracts, maintaining consistency with the thematic scope applied in the other databases. The inclusion criteria were as follows: (i) peer-reviewed journal articles written in English; (ii) studies focused on mango and/or avocado; (iii) field experiments, greenhouse trials or controlled-environment studies reporting quantitative data on plant water status, physiological traits, yield, fruit quality, evapotranspiration or irrigation performance indicators; and (iv) studies addressing deficit irrigation strategies or root-zone buffering approaches relevant to orchard management. Exclusion criteria included: (i) purely modelling studies without experimental validation; (ii) papers not related to drought/irrigation management; (iii) studies dealing exclusively with postharvest technologies unrelated to water stress or soil-based mitigation practices; and (iv) reports lacking sufficient methodological clarity or quantitative outcomes.

This review adopts an integrative and comparative approach to analyse water relations and drought-mitigation strategies in mango and avocado. In this review, 'integrative' refers to jointly analysing plant physiological responses, yield/quality outcomes, irrigation performance and soil/root-zone mitigation practices. 'Comparative' refers to contrasting mango and avocado to highlight shared mechanisms and crop-specific vulnerabilities, guiding management priorities under water-limited conditions. This manuscript is structured first to outline the climatic and physiological drivers of water stress, followed by a crop-specific analysis of water demand and sensitivity. Irrigation strategies are then critically reviewed, distinguishing between regulated, sustained and spatially differentiated deficit approaches. Soil-based mitigation options, including biochar, zeolite, hydrogels and biostimulants, are examined in relation to their effects on soil–plant water dynamics. Particular emphasis is placed on physiological mechanisms underpinning crop-specific responses, rather than on agronomic performance alone. Ultimately, this review highlights methodological limitations, knowledge gaps and research priorities for enhancing irrigation resilience, that is, the ability to maintain yield stability and fruit quality under increasingly variable and limited water availability, in the face of increasing climatic water stress.

3 | Plant Water Relations and Crop-Specific Water Demand

3.1 | Mango (*Mangifera indica* L.) Water Balance Demand

India is by far the largest producer of mango, with 2,704,000 ha yielding approximately 26,299,000 t of fruit annually. China and Indonesia are next with 301,000 ha producing 3,800,000 t and 290,000 ha producing 4,100,000 t, respectively. These countries are followed by Mexico (221,858 ha; 2,486,000 t), Pakistan (164,558 ha; 2,783,000 t), Thailand (144,000 ha; 1,399,000 t) and Brazil (100,663 ha; 1,100,000 t). The world totals are 6.1 Mha, producing 59,152,000 t. Production statistics were retrieved from the FAOSTAT commodity group 'Mangoes, guavas and mangosteens' (item code 0571), which includes mango (FAO 2025).

The mango growth cycle comprises 10 phenological stages, seven of which are particularly important for vegetative and reproductive success. These include bud initiation and expansion, leaf and shoot development, floral induction and anthesis, fruit set, enlargement and ripening. Drought can significantly delay bud break and reduce the production of new leaves and roots. Short drought episodes may provide advantages for mango grown in tropical regions where controlled water restriction can enhance floral induction. However, the same practice is less effective in subtropical climates, where lower winter temperatures inherently limit flowering (Khalid et al. 2025). More severe or prolonged water deficits impair carbohydrate accumulation in the canopy and can compromise subsequent phenological transitions (Carr 2014).

Mango trees can flower following 6–12 weeks of water stress, particularly in tropical environments, although successful development of reproductive structures thereafter requires adequate irrigation. This especially occurs in warm regions where fruit growth coincides with high evaporative demand (Carr 2014). Earlier work, approximately 20 years ago, reported that withholding irrigation for approximately 40 days after flowering increased fruit set and extended fruit longevity (Madigu et al. 2008); however, other investigations associate water deficit during initial fruit development with increased fruit drop (Spreer et al. 2007). During the rapid expansion phase, when fruit reaches up to 80% of its final mass, both cell division and cell enlargement are highly sensitive to water supply, and deficits during this stage have been associated with substantial reductions in fresh weight (Tharanathan et al. 2006). Overall, drought exerts its greatest negative impact during flowering and fruit enlargement, when the demand for photoassimilates is maximal (Khalid et al. 2025).

Numerous studies indicate that the timing and adequacy of irrigation are important determinants of mango flowering, fruit set, yield, postharvest performance and overall fruit quality (Tharanathan et al. 2006; Carr 2014; Durán Zuazo et al. 2019). Although mango is generally classified as a drought-tolerant species, sustained water deficit markedly constrains root proliferation and vegetative growth. In fact, mango is a water-demanding crop, especially during fruit set and fruit swelling. In semi-arid areas, it can consume up to 6000 m^3/ha/year, with a daily crop evapotranspiration (ETc) of 4–5 mm/d (de Azevedo et al. 2003). Early exposure to water stress typically enhances fruit abscission and reduces final fruit size, underscoring the crop's sensitivity during critical developmental windows (Spreer et al. 2007).

Water deficit also influences fruit biochemical traits. Stress conditions tend to produce firmer fruits with elevated concentrations of pigments such as anthocyanins and β-carotene, although these responses often reflect suboptimal irrigation strategies rather than adaptive advantages (Madigu et al. 2008).

The multi-omics analysis revealed three key regulatory genes, namely, WRKY3, PAO4 and MEI2-like 1, that structure the mango drought-response network. WRKY3 was strongly induced under water deficit and correlated with increases in L-tryptophan, L-phenylalanine and L-isoleucine, indicating coordinated activation of amino acid–based osmotic and antioxidant pathways. PAO4 upregulation under severe stress aligned with metabolites such as D-sphingosine and N^2-tryptophyllysine, linking polyamine catabolism to sphingolipid signalling and ROS modulation. MEI2-like 1, an RNA-associated regulator, showed strong induction alongside 2,5-dimethyl pyrazine, suggesting stress-driven post-transcriptional adjustment. Together, these genes form interconnected hubs integrating transcription, metabolite reprogramming and physiological drought tolerance (Hou et al. 2024).

From a physiological standpoint, mango exhibits notable mechanisms that contribute to its drought tolerance. The species is capable of maintaining a favourable leaf water status under declining soil moisture through osmotic adjustment (Carr 2014) but is not able to maintain a certain level of hydraulic safety thanks to latex-containing tissues, as wrongly suggested by the same author.

Osmotic adjustment is the primary mechanism underlying drought tolerance, involving the accumulation of compatible solutes (e.g., soluble sugars, proline and potassium), which lowers osmotic potential and helps sustain turgor under water deficit. Leaf elasticity, an extensive rooting system and efficient stomatal control further contribute to hydraulic stability (Perera-Castro et al. 2023).

However, the species does not rely on latex-bearing tissues to sustain hydraulic safety, contrary to what had been speculated in earlier interpretations of its drought tolerance (Carr 2014). In *M. indica* L., latex-containing resin ducts are anatomically confined to the phloem and cortical tissues rather than to the xylem and therefore cannot contribute to cavitation resistance or water transport. Their role is structural and defensive: Latex pressurization can facilitate wound sealing and provide mechanical reinforcement to surrounding soft tissues, but it does not participate in leaf-level osmotic regulation or in maintaining xylem hydraulic integrity under tension (Barceló-Anguiano et al. 2021). Briefly, mango latex is stored in an extensive network of laticiferous canals located in the fruit peel and pedicel, where ducts are particularly enlarged near the abscission zone. These secretory structures contain a biphasic exudate composed of an oily monoterpene-rich fraction and an aqueous phase with carbohydrates, proteins and defence-related enzymes. The non-aqueous phase includes alk(en)ylresorcinols with well-documented antifungal activity, explaining cultivar differences in postharvest disease resistance (John et al. 2011). Because latex exudation could interfere with pressure chamber measurements in water stress experiments, some authors have proposed using latex osmotic potential as a practical proxy for estimating leaf water potential under slow-developing drought. Leaf wilting began once the leaf water potential dropped to approximately −1.2 to −1.5 MPa, with young leaves exhibiting the earliest symptoms. As stress intensified, leaves became flaccid at approximately −2.45 MPa, and necrosis appeared on the oldest leaves near −3.2 MPa. Irreversible damage occurred close to −3.45 MPa, corresponding to an approximately 77% relative water content. Throughout the 44-day dehydration period, leaf water potential, relative water content and latex osmotic potential declined in parallel, showing strong mutual correlations (Pongsomboon et al. 1991).

Other studies demonstrated that mango leaves sustain turgor under water deficit until leaf water potential approaches approximately −1.75 MPa, and irreversible leaf injury occurs only when relative water content declines to approximately 77%; thresholds substantially lower than those reported for many other woody fruit crops. These characteristics highlight the inherent capacity of mango to buffer moderate water deficits while maintaining functional hydration of its tissues (Khalid et al. 2025). Thus, mango drought tolerance results from coordinated biochemical and physiological mechanisms.

3.2 | Avocado (*Persea americana* Mill.) Water Balance Demand

Mexico is by far the largest producer of avocado, with 236,132 ha yielding approximately 2,592,581 t of fruit annually. Colombia and Peru are next with 110,183 ha producing 1,090,664 t and 65,000 ha producing 866,457 t, respectively. These countries are followed by the Dominican Republic (23,000 ha; 737,201 t), Kenya (28,000 ha; 458,439 t), Indonesia (38,000 ha; 389,000 t) and Brazil (75,000 ha; 338,238 t). The world totals are 884,035 ha, producing 9,534,798 t (FAO 2025).

Avocado flowers are protogynous and dichogamous, meaning that the female and male phases occur at different times. Botanically, the fruit is a single-seeded berry with a thick, oily mesocarp valued for its nutritional and pharmaceutical uses. Unlike most fruits, cell division in avocado continues throughout development, for as long as the fruit remains on the tree. In addition, fruits do not ripen on the tree; only when they are picked do these fruits begin to soften. Water deficits during key developmental stages are associated with disorders such as ringneck, fruit elongation (notably in the 'Hass' cultivar) and internal quality decline (Carr 2013).

Following flowering, heavy fruit drop occurs, marking a critical phase for determining yield and fruit size. During this period, developing fruits compete with new shoot growth for assimilates, while net photosynthesis and root activity are reduced. In warm, humid subtropical environments, current photosynthesis, rather than stored reserves, plays a dominant role in supporting fruit retention and growth. Frequent irrigation has been shown to enhance calcium accumulation in avocado fruits, which in turn helps prevent various physiological disorders while improving overall fruit quality and postharvest longevity. Avocado trees develop a shallow root system concentrated within the upper 15–60 cm of soil, limiting their ability to access deeper water reserves. Consequently, effective management requires maintaining adequate moisture in the top 15–20 cm of the soil profile through rainfall or irrigation (Singh 2020).

Neuhaus et al. (2007) observed a steady reduction in sap flow over a 44-day period of soil drying (Figure 3). Trees subjected to the dry (DS) treatment exhibited markedly reduced physiological activity compared with those under well-watered (WW) conditions. After irrigation was resumed on Day 45, the leaf water potential in the DS trees recovered to levels similar to those in the WW treatment within a week, although the sap flow rates remained comparatively low. In the lower trunks of DS trees, as many as 34% of xylem vessels remained obstructed by tyloses even 84 days after rewatering, resulting in an estimated 50% decline in hydraulic conductivity. In contrast, no tyloses were observed in the xylem of well-watered trees.

The strong dependence of avocado growth on soil moisture was first demonstrated in early irrigation trials conducted in California by Richards et al. (1962).

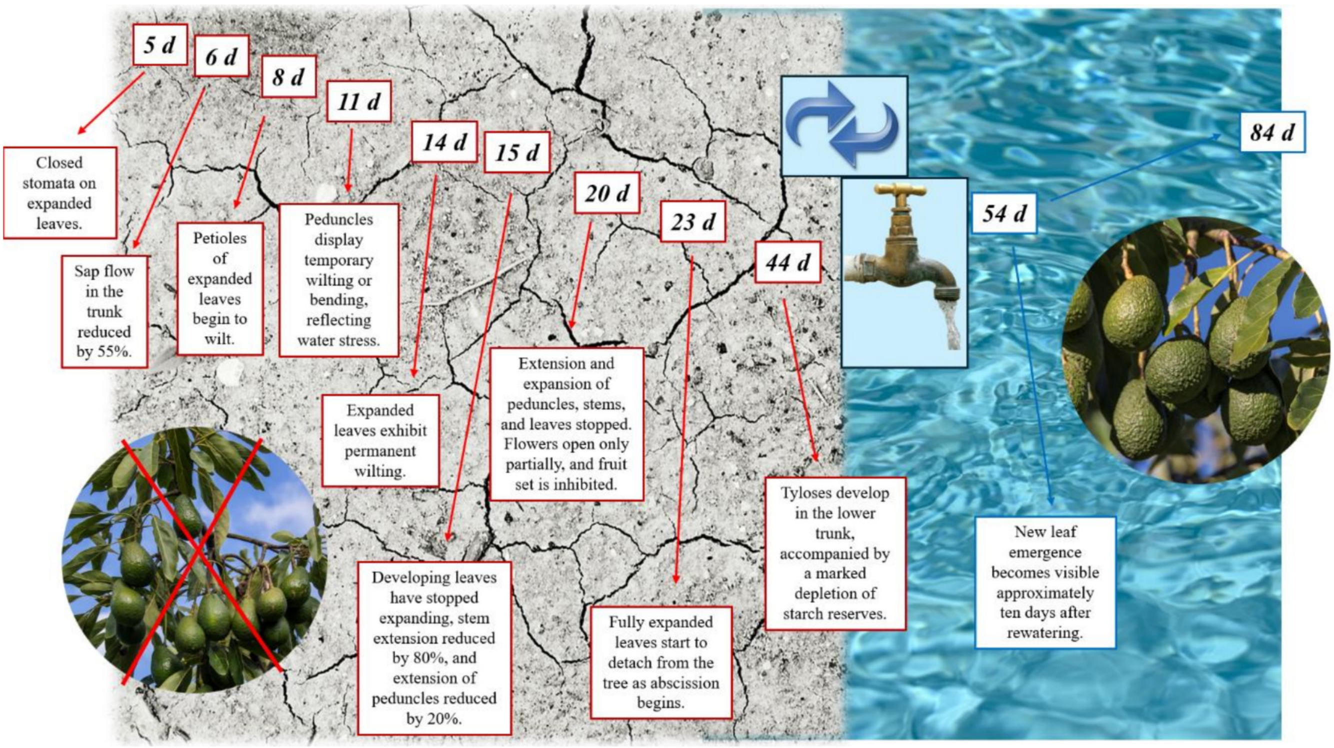

FIGURE 3 | Progressive changes were monitored over a 5- to 44-day drying period in potted avocado trees, followed by observations 10 days after rewatering, where d represents the time after drying starts.

Avocado, which is even more water dependent, is characterized by water requirements exceeding 1000 mm/year, equivalent to 10,000 m^3/ha/year, making it one of the world's 'thirstiest' fruit trees (Faber 2006; Montazar et al. 2025).

It was shown that early-season water deficits trigger leaf chlorosis, which intensifies as floral buds develop and bloom progresses, ultimately leading to substantial defoliation and increased fruit drop. The elevated fruit abscission reflects a shortage of carbohydrates available to sustain developing fruits under stress (Silber et al. 2019). Similarly, it was reported that maintaining trees under continuous water limitation (40%–60% of FAO-56 crop evapotranspiration) throughout the season reduced yields by approximately 30% and exacerbated drought stress during periods of high evaporative demand (Moreno-Ortega et al. 2019). Neuhaus et al. (2007) demonstrated that total drying of the soil profile caused tyloses to form, blocking xylem vessels of water-stressed trees but not in partially watered or well-watered trees. In the dry treatment, 33% of xylem vessels were blocked by tyloses, preventing further stress by reducing the amount of water that is required to maintain water pressure and conductance in the trunk. Tylose development may assist tree survival under severe root-zone drying, but the blockage of xylem vessels could be permanent and reduce long-term tree function and productivity.

Fruit development in avocado is strongly influenced by the tree's water status. Insufficient irrigation during the early rapid growth phase can limit final fruit size and reduce the proportion of marketable yield. Water deficits occurring at key phenological stages have also been associated with postharvest quality problems, including ring-neck and internal browning. Drought-treated trees generally show lower dry matter and oil content than well-watered trees. Because fruit moisture and oil content are closely correlated and both relate to ripening behaviour, the timing of water supply is critical. Severe soil drying can decrease fruit water content by approximately 20%, a reduction with clear implications for overall productivity (Singh 2020). Additionally, overirrigation equivalent to 120% of the FAO-56 crop evapotranspiration requirement has been shown to depress avocado productivity. Evidence from Moreno-Ortega et al. (2019) indicates that supplying water beyond the tree's calculated needs provides no yield benefit and may instead impair root function through reduced soil aeration.

Both crops, therefore, considering the above and in light of the parameters reported in Table 1, require precision irrigation and water-reduction strategies, such as biostimulants and controlled deficit irrigation.

4 | Mitigation Strategies

The mitigation strategies discussed in this review were selected based on three main criteria: (i) their direct relevance to orchard-scale water management under field conditions; (ii) the availability of quantitative evidence linking these practices to changes in plant water status, yield stability or water productivity; and (iii) their potential to modulate soil–plant water relations.

Accordingly, this section focuses on deficit irrigation strategies (regulated deficit irrigation, RDI; sustained deficit irrigation,

TABLE 1 | Water requirements and seasonal needs of mangoes and avocados. In the Bibliography column, (M) indicates references related to mango, and (A) indicates references related to avocado.

Parameters	*Mangifera indica* L.	*Persea americana* Mill.	Bibliography
Daily crop evapotranspiration (ETc)	3.10–4.9 mm per day	2.00–4.2 mm per day (a mean daily use of 3.98 mm d^{-1} in summer and 1.64 mm d^{-1} in winter)	de Azevedo et al. (2003) (M) Lahav et al. (2013) (A) Taylor et al. (2021) (A) Montazar et al. (2025) (A)
Total seasonal consumption (whole productive cycle)	551.6 and 555.1 mm by the soil water and Bowen ratio-energy balance methods, respectively	713 mm to 1028 mm 450–1500 mm irrigation +250–500 mm rainfall (California)	de Azevedo et al. (2003) (M) Faber (2006) (A) Montazar et al. (2025) (A)
Equivalent annual consumption	5000–6000 m^3 ha^{-1} $year^{-1}$	8000–13,000 m^3 ha^{-1} $year^{-1}$	de Azevedo et al. (2003) (M) Faber (2006) (A) Montazar et al. (2025) (A)
Crop coefficient (Kc)	0.65–1.05 0.43, 0.67 and 0.63 at flowering, fruit set and fruit growth, respectively	0.55–0.85	Carr (2014) (M) Durán Zuazo et al. (2019) (M) Kaneko et al. (2022) (A) Montazar et al. (2025) (A)
Peak of water demand	During fruit growth and ripening	During full leaf expansion and fruiting	Durán Zuazo et al. (2019) (M) Montazar et al. (2025) (A)
Sensitivity to water stress	High: reduction in flowering and size	Very high: flower and fruit drop, black tip disorder, root stress	Zuazo, García-Tejero, et al. (2021) (M) Carr (2013) (A) Nemera et al. (2021) (A)

SDI; partial root-zone drying, PRD) and soil strengtheners/amendments (biochar, biostimulants, hydrogels and zeolites) that have been experimentally tested in mango and/or avocado systems. These approaches were prioritized because they explicitly target the buffering capacity of the root zone, which is a key leverage point for improving drought resilience in perennial fruit orchards. Each strategy is subsequently analysed with respect to its agronomic performance, physiological implications and documented limitations.

4.1 | Terminology and Methodological Considerations (Water-Use Efficiency WUE, Water Productivity WP, and ETc-Based Scheduling)

First of all, the terms water-use efficiency (WUE) and water productivity (WP) are often used interchangeably in the irrigation literature, generating conceptual ambiguity and inconsistencies in reporting across studies. Oweis and Hachum (2006) highlighted that WUE has been defined in several ways depending on discipline and scale, frequently relating crop biomass or yield to different water terms such as transpiration, evapotranspiration or irrigation water applied (e.g., WUET and WUEET). They further proposed WP as a broader, scale-dependent concept defined as the return per unit of water consumed (depleted), emphasizing the need to distinguish between water supplied/diverted and water actually consumed by the production system.

At the physiological scale, WUE is often used to describe the relationship between carbon gain and water loss (e.g., assimilation/transpiration or intrinsic WUE as A/gs) (Yi et al. 2006; McAusland et al. 2013). At the orchard or production scale, water productivity is typically the most informative indicator, as it links agronomic output (e.g., fruit yield or marketable yield) to water input or water consumption (e.g., kg m^{-3} of irrigation water applied or evapotranspiration) (Wang et al. 2022).

This distinction is consistent with FAO terminology (FAO 2019), where 'efficiency' refers to how effectively water inputs are converted into beneficial use, whereas 'productivity' expresses the amount of output obtained per unit of water used or supplied (typically reported as kg m^{-3}). Ragab (2024) also stressed that confusing WUE with WP represents a frequent misconception in agricultural water management and clarified that productivity metrics should be explicitly expressed as output per unit of water supplied/used, while efficiency terminology should not be used as a synonym for productivity. In water management frameworks, WUE should be expressed as a dimensionless efficiency concept (e.g., as a percentage of supplied water effectively used by the crop), highlighting the importance of clearly stating the definition adopted.

In this review, the following terminology is used according to the scale of analysis: (i) WUE at the leaf/physiological level, expressed as carbon gain per unit water loss (e.g., eWUE A/E) or intrinsic IWUE (A/gs); (ii) WUE at the management level, intended as an efficiency concept and, where applicable, expressed as a dimensionless fraction or percentage of supplied water effectively used by the crop; and (iii) WP at the orchard/production level, expressed as agronomic output per unit of water input or consumption (e.g., kg m^{-3} of irrigation water applied or evapotranspiration). WP is used as a general term for yield per unit of water supplied/used and 'irrigation water productivity' (IWP) when the denominator refers specifically to irrigation water applied. Throughout this review, the terminology used in the original studies is reported to preserve consistency with the cited studies; however, whenever different or inconsistent definitions are adopted across the literature, this is explicitly stated and discussed to avoid ambiguity in interpretation (see also Chapter 5).

A second independent limitation concerns the estimation of crop evapotranspiration (ETc) as the reference variable for deficit irrigation scheduling. Ragab (2024) highlights that FAO-56–based ETc, even when derived from the Penman–Monteith equation, primarily reflects atmospheric evaporative demand rather than actual plant water use. In perennial orchards, where canopy cover is often discontinuous, root-zone wetting is localized, and transpiration is actively regulated by stomatal control, ETc may systematically overestimate crop water requirements. As a consequence, irrigation regimes defined as fixed percentages of ETc do not necessarily impose proportional levels of physiological water stress. This situation could complicate the interpretation of deficit irrigation outcomes requiring crop-, canopy- and site-specific calibration of ETc, ideally supported by direct soil or plant-based measurements.

4.2 | Regulated Deficit Irrigation (RDI), Sustained Deficit Irrigation (SDI) and Partial Root-Zone Drying (PRD)

RDIPRD are deficit-based irrigation strategies designed to improve water productivity by manipulating soil-root water availability rather than maximizing water supply. RDI is an irrigation strategy that deliberately supplies less than full crop evapotranspiration during selected phenological stages to restrain vegetative growth while preserving yield and fruit quality. PRD is a spatially regulated approach in which irrigation alternates between different halves of the root system, maintaining water uptake from wet roots while exposing other roots to drying cycles. This asymmetric soil moisture distribution reduces stomatal conductance and transpiration without inducing severe plant water stress (McCarthy et al. 2002).

In mango, both approaches have been tested at approximately 50% of ETc compared with fully irrigated controls. Field experiments showed that the PRD reduced seasonal irrigation inputs from 230–270 mm to 125–135 mm, achieving water savings of nearly 45%–50%. Despite reduced water application, PRD maintained fruit quality comparable to that of fully irrigated trees, whereas RDI resulted in moderate yield reductions. As a result, PRD markedly increased irrigation water productivity (fruit yield per unit of applied water), reaching approximately 10–11 kg m^{-3} compared with 6–6.5 kg m^{-3} under full irrigation. Fruit quality parameters, including total soluble solids, acidity, firmness and peel colour, were not negatively affected by either strategy (Spreer et al. 2007). These responses are attributed to root-to-shoot chemical signalling, primarily abscisic acid produced in drying roots, which limits stomatal conductance without restricting fruit water supply (McCarthy et al. 2002).

A possible phytohormonal regulation under repeated drying–rewetting cycles could explain ABA-induced fruit drop and a relative enhancement of cytokinin-driven fruit growth during favourable seasons (Spreer et al. 2007).

Complementary evidence from regulated deficit irrigation trials indicates that mango responses to water restriction are strongly dependent on the phenological stage at which the deficit is imposed. In field-grown 'Tommy Atkins' mango, RDI at 50% ETc applied during flowering-fruit set or early fruit expansion maintained yields comparable to full irrigation, whereas the absence of irrigation markedly reduced production. Root system analysis revealed that moderate RDI increased root length density and promoted deeper soil exploration, particularly between 0.2 and 0.9 m depth and 0.5–1.5 m from the trunk, indicating adaptive shifts in belowground architecture (Santos et al. 2014).

Available evidence in mango indicates that RDI primarily promotes drought tolerance through longer term structural and hydraulic adjustments of the root system, including increased root length density and deeper soil exploration, rather than through immediate stomatal regulation. In contrast, PRD establishes a spatially heterogeneous root environment in which drying and wet roots coexist, enabling root-to-shoot signalling that could constrain transpiration while sustaining water uptake. This fundamental difference in root-zone hydraulics helps explain why PRD generally achieves higher irrigation water productivity than RDI in mango, even when total irrigation volumes are similar.

Spreer et al. (2009) also found that irrigation water productivity (kg fruit m^{-3} irrigation water) was consistently higher under deficit treatments (Table 2) than under full irrigation because yield losses were proportionally smaller than the reduction in applied water. Both PRD and RDI were imposed at approximately 50% ETc, leading to a marked reduction in seasonal irrigation volumes while causing only moderate or negligible yield penalties. This pattern was observed across seasons and irrigation strategies, highlighting that WUE gains primarily reflected irrigation savings rather than active physiological regulation. It is important to note that this paper speaks of water-use efficiency only but uses it in a management-oriented (WP-like) sense, without making the conceptual distinction. However, the authors defined it as the yield per unit of irrigation water applied (kg m^{-3}), following FAO recommendations (Doorenbos and Kassam 1979). Although termed WUE by the authors, this metric corresponds conceptually to irrigation water productivity rather than to physiological water-use efficiency based on transpiration or evapotranspiration. However, in that historical FAO context, the term WUE was often used in an agronomic-operational sense, that is, as kg of product per m^3 of irrigation water. Therefore, the name 'WUE' is consistent with the cited FAO source but does not coincide with the physiological WUE.

In this context, deficit effects under drip irrigation are highly sensitive to wetting patterns and emitter placement; inadequate soil wetting caused by improperly designed drip irrigation systems may induce uncontrolled root-zone stress, fruit drop and yield losses, even when total irrigation volumes appear sufficient (Mirjat et al. 2011).

Unlike mango and other crops, avocado lacks a robust body of evidence supporting partial root-zone drying as an effective irrigation strategy. Available studies indicate that localized root-zone drying fails to induce sustained stomatal regulation and instead triggers strong fruit abscission, highlighting species-specific limitations of PRD in avocado and explaining the scarcity of dedicated studies (Neuhaus et al. 2009). This behaviour is consistent with the high sensitivity of avocado roots to localized stress, the rapid decline in root hydraulic functionality and the preferential maintenance of canopy gas exchange at the expense of reproductive sinks, which promotes early fruit abscission as a dominant stress response (Carr 2013). Moreover, physiological studies indicate that leaf abscisic acid concentrations do not increase under localized root stress in avocado, suggesting that ABA-mediated root-to-shoot signalling, central to PRD efficacy in other crops, is weak or uncoupled in this species, thereby limiting the capacity for controlled stomatal regulation under partial root-zone drying conditions (Gil et al. 2009).

In avocado, RDI has been evaluated mainly as a phenology-based water-saving strategy rather than a physiological regulation tool. Evidence synthesized for Mediterranean and subtropical environments indicates that RDI applications at 50%–75% ETc can reduce seasonal irrigation volumes, but yield responses are highly dependent on the timing of the deficit. Water restrictions imposed during flowering or early fruit set frequently resulted in yield losses, whereas moderate deficits applied during less sensitive vegetative or post-set phases showed limited yield penalties. Improvements in water-use efficiency were reported in some cases, although often accompanied by reduced fruit size or increased variability in production stability (Cárceles Rodríguez et al. 2023). In avocado, deficit irrigation strategies have been investigated mainly through RDI and SDI. RDI involves the application of uniform water reductions restricted to specific phenological stages to exploit periods of lower sensitivity to water stress, whereas SDI consists of a continuous, season-long reduction of irrigation across the entire root zone. The following studies summarize how these approaches affect water savings, yield stability, water productivity and water-use efficiency under contrasting environments (Table 3).

4.3 | Biochar

Biochar is a carbon-rich, micro-porous solid produced via pyrolysis of biomass under oxygen-limited conditions, yielding a stable aromatic matrix with high surface area and cation-exchange capacity. Its physicochemical properties enable long-term carbon sequestration while modifying soil hydraulic behaviour and rhizosphere redox balance. Functionally, biochar acts as a sorbent and structural amendment that enhances water status, microbial habitat and nutrient cycling (Lippi et al. 2025).

In mango grown under semi-arid conditions, soil amendments function as drought mitigation agents. Biochar at 14 kg $tree^{-1}$ produced marked gains in canopy development, leaf chlorophyll (up to +81%), nutrient status and yield and WP (+40%–56% over control), with responses strengthened where biochar was paired with hydrogel (Shaban et al. 2025). Authors report WUE term as yield per irrigation requirement (kg m^{-3}), which corresponds conceptually to IWP in this review. Another study (Eissa

TABLE 2 | Agronomic performance, water-use efficiency, water productivity (note: when the denominator is irrigation water applied, WP is referred to as irrigation water productivity, IWP) and physiological responses of mango and avocado under partial root-zone drying (PRD) and PRD-like irrigation strategies.

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Mangifera indica L.	Field experiment, arid environment (Egypt); sandy soil; hot summers, cold winters; negligible rainfall Irrigation strategies.	FI (100% ETc); DI 75% ETc; DI 50% ETc; PRD (50% ETc, alternating root sides) ± organic mulch (1–3 layers).	≈25% (DI75); ≈50% (DI50I3, PRD).	FI ≈ 10,000 $m^3 ha^{-1}$; PRD and DI50 ≈ 50% of FI (year-dependent).	PRD maintained or increased yield relative to FI PRD alone: ~10.1–10.5 $t ha^{-1}$ (vs FI ~ 9.7 $t ha^{-1}$) PRD + 3 mulch layers: 13.1–13.6 $t ha^{-1}$.	PRD: 2.1 $kg m^{-3}$ PRD + mulch (L3): up to 2.7 $kg m^{-3}$ FI: ~0.8–1.0 $kg m^{-3}$ (IWP)	Not directly measured; improved yield and water productivity under PRD and mulch were associated with enhanced soil moisture conservation and reduced salinity.	PRD increased TSS (PRD + mulch (L3): up to 14.1% FI: 10.1%), total acidity, and vitamin C relative to DI 50% (PRD + mulch (L3): up to 49.3 mg/100 mL FI: 29.8 mg/100 mL). Quality further improved with increasing mulch layers.	Strong synergistic effect of organic mulch (up to 3 layers ≈ 6.7 $t ha^{-1}$ per layer): reduced salt accumulation, higher soil moisture, increased soil organic matter.	Alhashimi et al. 2023
Mangifera indica L. cv. Zibdia (rootstock 'Sukari')	Field, arid climate, sandy soil (BD ≈ 1.65–1.67 $g cm^{-3}$), negligible rainfall. Al-Nubariya Region of Al Buhayra Governorate, Egypt.	FI (100%), DI1 (0.75FI), DI2 (0.5FI both sides), PRD (0.5FI alternating sides—alternation frequency: periodic side switching) + compost rates (NC, C12, C18, C24 ton ha^{-1}).	50% vs. FI	FI ≈ 9800–9900 $m^3 ha^{-1}$ PRD and DI2 ≈ 4900–4925 $m^3 ha^{-1}$.	PRD maintained yield (10.6–11.0 $t ha^{-1}$) ≈ FI; DI2 reduced yield to 7.9–8.5 $t ha^{-1}$.	PRD: 2.15–2.38 $kg m^{-3}$ vs. FI ≈ 1.04 $kg m^{-3}$ (IWP)	Reduced transpiration inferred from PRD-induced spatial root drying and root-to-shoot signalling. PRD improved water productivity, consistent with mechanisms described in previous studies on partial root-zone drying, although no direct physiological measurements were performed.	Higher TSS (up to 14.5%), vitamin C (≈50 mg 100 mL^{-1}) under PRD, especially with compost; lowest quality under DI2 + no compost.	Compost (24 $t ha^{-1}$) strongly enhanced PRD effects. Compost (especially C24) increased soil moisture, soil organic matter, reduced root-zone water stress, enhanced yield, and WUE.	El-Sayed et al. 2023

(Continues)

TABLE 2 | (Continued)

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Mangifera indica L. cv. Amrapalli	Field, subtropical climate (eastern India); sandy loam soil (45% sand, 24% silt, 31% clay); BD ≈ 1.44 g cm^{-3}; acidic soil (pH ≈ 5.9); monsoon rainfall concentrated Jul–Oct.	FI (100% ETc), PRD at 80%, 60%, 40% ETc, rainfed control; PRD applied by alternating laterals.	≈40% (60% PRD vs. FI)	FI ≈ ~9800–9900 $m^3 ha^{-1}$; 60% PRD ≈ ~5900–6000 $m^3 ha^{-1}$	80% PRD highest yield (9.6 t ha^{-1}); 60% PRD (9.0 t ha^{-1}) statistically ≈ FI (9.3 t ha^{-1}); 40% PRD reduced yield (5.2 t ha^{-1}).	60% PRD: +85% vs. FI (≈ 6.47 vs. 3.50 kg m^{-3}) highest water productivity at PRD60 (6.47 kg m^{-3}); FI lowest (3.50 kg m^{-3}); PRD80 intermediate (5.03 kg m^{-3}); PRD40 high WP but associated with yield loss. Although termed WUE by authors in the abstract, the indicator expressed as yield per unit of irrigation water applied (kg m^{-3}) corresponds conceptually to irrigation water productivity (IWP).	Authors describe PRD mechanism as drying-induced root signals (ABA) reducing stomatal opening and transpiration while maintaining leaf hydration and photosynthesis (no direct measurements). Increased plant height, collar diameter and canopy volume (FI). The sub-optimum soil moisture might have reduced the photosynthesis rate (lower vegetative growth PDR). The higher number of fruits probably caused lower fruit weight under full irrigation.	Best fruit quality at 60% PRD: TSS 21.7°Brix, acidity 0.42%, pulp ≈70%. PDR40 showed inferior quality due to excess stress.	PRD side alternation based on SWC threshold (switching at ~50% available soil moisture; ~15 d winter, ~7 d summer).	Mohanty et al. 2022

(Continues)

TABLE 2 | (Continued)

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Mangifera indica L. cv. Dashehari	Field, subtropical climate (Jammu, India); open field orchard.	FI (100% ETc); RDI (75% and 50% ETc, uniform); PRD (75% and 50% ETc, alternating sides); ± fertigation.	Not explicitly reported.	Not explicitly quantified (ETc-based treatments).	Yield not assessed (postharvest study)	Not reported	Not experimentally assessed; mechanisms discussed only conceptually, without physiological measurements. PRD induces partial root drying and spatially heterogeneous soil moisture, leading to delayed senescence and improved postharvest performance; RDI effects are mainly associated with uniform water-status limitation.	PRD 50% ETc + fertigation minimized physiological weight loss (≈12.8% vs. > 21% in non-irrigated fruit), maximized firmness (≈21.62–22.47 lb. $inch^{-2}$), maintained higher fruit moisture (≈75–76%) and reduced decay losses (≈35–36% vs. > 51% under no irrigation).	Fertigation with K_2SO_4 (0.5%), H_3BO_3 (0.5%), Ca $(NO_3)_2$ (1%) enhanced postharvest quality under both PRD and RDI.	Simrandeep et al. 2022
Mangifera indica L. (seedlings)	Greenhouse pot experiment; red loam soil; FC ≈ 24.4%; temperature 20–32 °C; RH 45–70% During the seedling adaptive stage, the soil moisture content in all the pots was kept at 75–85% FC, and both sides of the root zone were irrigated at the same time.	Alternate Infiltration Irrigation (AII; PRD-like): CK (85% FC both sides), AII90, AII70, AII50; irrigation alternated every 14 days between root sides.	30% (AII70) and 50% (AII50) vs. CK The irrigation quota for CK was controlled by the weighing method, and the soil moisture content was returned to 85% FC after each irrigation.	Not reported as field mm; expressed as % of CK (pot-scale study)	Not applicable (seedlings); incremental dry mass highest in AII70 (+significant vs. CK).	IWUE (irrigation water-use efficiency; g L − 1) increased by +101% in AII70, +32% in AII90, +23% in AII50 vs. CK eWUE (Pn/Tr, leaf; µmol mmol $(H_2O)^{-1}$) increased by +10.5–11.8% in AII70–AII50 vs. CK.	Reduced gs (−13.9%) and Tr (−13.8%) under stronger deficit; ABA-mediated root-to-shoot signalling under alternating root drying.	Not applicable	Enhanced lateral and fine root growth was observed under AII70. When multiple physiological and growth variables were jointly evaluated using the TOPSIS decision-analysis method, AII70 achieved the highest overall ranking.	Sun et al. 2022

(Continues)

TABLE 2 | (Continued)

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Mangifera indica L. cv. Tommy Atkins	Field, semi-arid climate (Bahia, Brazil); Fluvic Neosol; sandy texture; BD ≈ 1.3–1.6 g cm^{-3}; mean annual rainfall ≈ 680 mm (no rainfall during experiment).	RDI at 100, 75, and 50% ETc applied at specific phenological stages (flowering–fruit set, fruit development, physiological maturation) using microsprinklers; PRD at 100%, 80%, 60% and 40% ETc applied throughout the season with drip irrigation and alternation of the wetted root side every 15 days.	RDI: up to 50% ETc depending on treatment and phenological stage; PRD: 20%–60% ETc relative to full irrigation.	Expressed as a percentage of ETc; absolute seasonal irrigation volumes not reported.	PRD80–60 reduced yield (9.2–8.2 t ha^{-1}) vs. FI (16.7 t ha^{-1}); PRD40 caused strongest yield loss (7.6 t ha^{-1})	Although termed WUE by the authors (Table 7), this yield-based index (kg ha^{-1} mm^{-1}) corresponds to irrigation water productivity (IWP). Highest under PRD40 (≈ 41 kg ha^{-1} mm^{-1}); PRD60 ≈ 29.6 kg ha^{-1} mm^{-1} vs. FI (36.2 kg ha^{-1} mm^{-1}). RDI50S3 = FI (≈ 47 kg ha^{-1} mm^{-1} (eWUE) Instantaneous water-use efficiency (A/E) Under PRD, A/E reached its highest value at PRD60 (2.51), PRD40 = FI. Under RDI, the highest A/E values were observed in RDI75S2 (1.83), although most RDI treatments showed values = FI.	PRD40 induced lower stomatal conductance (≈0.12 mol m^{-2} s^{-1}), reduced photosynthesis (6.67) and carboxylation efficiency (A/Ci), indicating excessive physiological stress rather than optimized regulation.	Not evaluated.	Gas exchange strongly affected by leaf temperature; climatic conditions override irrigation effects in some periods.	Santos et al. 2016

(Continues)

TABLE 2 | (Continued)

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Persea americana Mill. cv. Hass	Field, Mediterranean climate (Western Australia); deep siliceous sandy soil; mature trees (15 years); slightly saline irrigation water.	WW (fully irrigated); WD (drying half the root zone for one season); DD (full root-zone drying); no alternation (extended drying). WD (Wet–Dry) = drying half of the root zone for one entire season. No rotation; no rewetting of the dry side; chronic and unidirectional stress.	WD ≈ 50% vs. WW	WD received ~50% of WW irrigation; DD ≈ 0% (plastic-covered soil).	Yield reduced by > 50% under WD, similar to DD; yield losses persisted into the following season. Yield reduction was proportionally greater than water reduction.	Reduced irrigation efficiency under WD and DD (yield loss exceeded water saving). Irrigation efficiency is discussed conceptually as economic yield per unit of irrigation water applied, but it is not reported as an explicit numerical index (kg m^{-3}).	Partial root-zone drying did not induce sustained stomatal closure in avocado. Leaf water potential and leaf gas exchange parameters did not indicate severe leaf-level water stress under PRD, whereas fruit abscission increased markedly, indicating that the effects of root-zone drying were not mediated by leaf-level water stress but were expressed primarily at the reproductive level.	No effect on fruit Ca concentration, suggesting no improvement in fruit quality	Strong fruit abscission driven by root-zone drying rather than canopy water status; avocado reproductive sinks highly sensitive to root dehydration.	Neuhaus et al. 2009
Mangifera indica L. cv. Chok Anan (rootstock 'Talap Nak')	Field, tropical–subtropical climate (Chiang Mai, Thailand); Regosol with high stone content and low water-holding capacity; 350 m a.s.l.; pronounced dry season with variable in-season rainfall.	FI (100% ETc); PRD (50% ETc, alternating sides of the root system every ~14 days); RDI (50% ETc); no irrigation.	≈50% (RDI and PRD vs. FI)	PRD ≈ 1.6–1.9 m^3 $tree^{-1}$ $season^{-1}$ vs. FI ≈ 3.0–3.6 m^3 $tree^{-1}$ (year-dependent; rainfall included)	Over 4 years, mean yield: FI 83.35 kg $tree^{-1}$; RDI 80.16 kg $tree^{-1}$; PRD 80.85 kg $tree^{-1}$; NI 66.1 kg $tree^{-1}$. Yield differences between RDI and PRD generally small; in dry years PRD > RDI, while in wet years RDI ≥ PRD	Consistently higher under PRD (e.g., 10.6–17.0 kg m^{-3}) vs. FI (~4.5–9.0 kg m^{-3}, year-dependent). Although termed WUE by the authors, the yield-based indicator expressed per unit of irrigation water applied (kg m^{-3}) corresponds conceptually to IWP.	Increased WUE explained by lower marginal yield response to water near optimum availability; PRD did not induce reduced stomatal aperture; plants under PRD did not experience drought stress.	PRD increased average fruit weight and shifted fruit size distribution towards larger classes; no negative effects on ripening or quality reported.	Yield mainly driven by fruit number rather than fruit size; alternate bearing not affected by irrigation treatment; frequent alternation (≈2 weeks) required to maintain PRD effects.	Spreer et al. 2009

TABLE 3 | Performance and limitations of deficit irrigation (RDI and SDI) in avocado under water-limited conditions.

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Persea americana cv. Hass	Field experiment; arid–semi-arid climate (Egypt); sandy soil; drip irrigation.	RDI at 100%, 80%, 70% of IR (ETo × Kc) combined with soil absorbents (biopolymer or zeolite at 500–1500 g tree^{-1}).	20% (IR80); 30% (IR70).	2070, 1656, 1451 L tree^{-1} yr.$^{-1}$ (100%, 80%, 70% IR).	Moderate RDI (80%) reduced yield in control, but yield losses were mitigated by amendments; high-dose amendments increased yield up to ≈30% vs. control under full IR and maintained higher yields under deficit.	Not explicitly reported as WUE index. Improved productivity per unit water inferred under IR80 + amendments.	Soil amendments increased RWC (+17%–18%) and partially alleviated stomatal limitation under deficit irrigation, maintaining higher gs values (≈225 vs. ≈ 160 mmol m^{-2} s^{-1}) compared with nonamended trees at the same irrigation level, thereby reducing stress intensity and fruit drop risk.	Biopolymer or zeolite increased fruit weight (up to 274 g), size, carbohydrates (≈15%–16%), and oil content (≈12%–13%), especially with 1000–1500 g tree^{-1}, under both full and moderate deficit irrigation.	Strong dose-dependent response; biopolymer generally more effective than zeolite under RDI; sandy soil context.	Abdelzaher et al. 2025a
Persea americana Mill. (grafted seedlings)	Greenhouse experiment; controlled conditions; potted plants; long-term trial (≈180 days).	Uniform water regimes: • Control (100% irrigation) • Moderate deficit (−25%) • Severe deficit (−50%) • Moderate excess (+25%) • Severe excess (+50%) (uniform application to entire root system; no spatial or phenological regulation; RDI/SDI-like, not field-managed irrigation).	25% and 50% vs. control (constant water application of 222 mL day^{-1} plant^{-1})	Not expressed as field ETc or mm; irrigation volumes defined relative to control (% basis).	Not applicable (seedlings; no reproductive stage).	Not reported	Water deficit strongly reduced vegetative growth and biomass accumulation, inducing marked carbon reallocation towards stem and root tissues (> 90% of total C; ANRR88 rootstock), reduced leaf area (up to −60%) and dry mass (up to −57%), indicating high sensitivity of avocado to sustained, non-buffered water limitation.	Not applicable.	Vegetation indices (NDVI, MTCI) detected stress responses early; spectral sensitivity around ~720 nm highlighted as effective for monitoring avocado water stress under uniform deficit conditions.	Rondón et al. 2024

(Continues)

TABLE 3 | (Continued)

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Persea americana Mill. cv. Hass	Field experiment under semi-arid conditions (central Chile); alluvial loam to sandy-loam soil; mature commercial orchards managed under drip irrigation.	Fully irrigated control (FI) versus uniform sustained deficit irrigation with a seasonal water reduction of 25% and 29%, applied across the entire root zone without spatial alternation.	≈ 29%–30% relative to full irrigation.	FI: ≈ 10,300–11,600 $m^3 ha^{-1}$; RDI: ≈ 7300–8300 $m^3 ha^{-1}$ (year-dependent).	Moderate yield reduction under SDI (≈ 4%–6% relative to FI), with no significant increase in fruit abscission and > 90% of fruit meeting export quality standards.	Substantially increased under SDI, reaching values up to ≈ 6.0 $kg m^{-3}$ compared with ≈ 3.5–4.5 $kg m^{-3}$ under full irrigation (WP, irrigation applied + effective rainfall).	Uniform water restriction induced a predominantly hydraulic response, with tree water status strongly regulated by atmospheric demand (VPD) rather than by root-derived chemical signalling; improvements in WUE were mainly driven by reduced water inputs rather than optimized stomatal control.	Fruit dry matter content, ripening behaviour and commercial quality were not negatively affected by SDI.	Introduction of a soil water 'breaking point' concept to define non-stress thresholds for avocado irrigation scheduling under field conditions.	Beyá-Marshall et al. 2022
Persea americana Mill. cv. Hass (rootstock Lula)	Field experiment; arid–semi-arid environment (South El-Tahreer, Egypt); newly reclaimed sandy soil; drip-irrigated orchard; mulched soil; hot arid summers and mild winters; negligible rainfall.	FI (100% ETo); sustained deficit irrigation (SDI) at 90%, 80%, 70% and 60% ETo (uniform reduction over the entire root zone); drip irrigation + organic mulch.	≈10% (SDI90), 20% (SDI80), 30% (SDI70), 40% (SDI60) vs. FI.	FI: ≈7319 m^3 $fed^{-1} yr.^{-1}$ SDI90: ≈6737 m^3 fed^{-1} SDI80: ≈5935 m^3 fed^{-1} SDI70: ≈5072 m^3 fed^{-1} SDI60: ≈4441 m^3 fed^{-1}.	Progressive yield reduction with increasing deficit: SDI90: −3% SDI80: −11% SDI70: −18% SDI60: −35% (FI: 7.76 t fed^{-1}; SDI60: 5.03 t fed^{-1}).	Crop water productivity, highest at SDI70 (≈1.24 kg fruit m^{-3}), followed by SDI80 (≈1.18 $kg m^{-3}$), compared with FI (≈1.06 $kg m^{-3}$) CWP in kg/m^3 = yield/total water requirement corresponding to IWP.	No direct physiological regulation assessed	Fruit quality remained suitable for export at all SDI levels; no severe deterioration reported even at 60% ETo.	Organic mulch improved soil moisture conservation. Increasing SDI intensified soil salinity at deeper layers (25–75 cm) ($EC_{1:2.5}$ up to ≈1.04 dS m^{-1} at 60% ETo); high irrigation frequency recommended to limit salt accumulation.	Sokkar et al. 2022

(Continues)

TABLE 3 | (Continued)

Crop	Environment and soil	Irrigation strategies	Water saving (%)	Seasonal water applied	Yield response	Water-use efficiency (WUE) and/or water productivity (WP)	Proposed physiological mechanism	Fruit quality effects	Additional factors	Reference
Persea americana Mill. cv. Hass	Field experiment; subtropical Mediterranean climate (SE Spain, Almuñécar); terraced orchard; shallow, well-drained Xerorthent soil; mean annual rainfall ≈ 449 mm.	C100 (100% ETc); SDI75, SDI50, SDI33 (sustained deficit irrigation at 75%, 50% and 33% ETc; uniform reduction over the entire root zone).	≈ 25% (SDI75); 50% (SDI50); 67% (SDI33) vs. C100	Not reported as absolute mm; expressed as % ETc (100%, 75%, 50% and 33%). The average irrigation per season: 7868 (C100), 5837 (SDI75), 4057 (SDI50) and 2714 (SDI33) m3 ha^{-1}.	Average yield over 3 seasons: • C100: 47.5 kg tree^{-1} • SDI75: 43.8 kg tree^{-1} (−8%, not statistically significant) • SDI50: 38.3 kg tree^{-1} (−19%) • SDI33: 31.6 kg tree^{-1} (−33%)	• C100: 1.51 kg m^{-3} • SDI75: 1.87 kg m^{-3} • SDI50: 2.34 kg m^{-3} • SDI33: 2.90 kg m^{-3} Authors define WUE as fresh yield per total seasonal irrigation water applied (kg m^{-3}), which corresponds conceptually to IWP.	Uniform water limitation reduces canopy growth and fruit size proportionally to irrigation level. Compared with C100 (Ψstem ≈ − 0.6 to −0.8 MPa), SDI50 and SDI33 reduced Ψstem to −1.2 and −1.5 MPa, respectively, accompanied by reductions in stomatal conductance (SDI50: ~150–180 mmol m^{-2} s^{-1} SDI33: ~100–130 mmol m^{-2} s^{-1}). SDI75 maintained comparatively higher.	SDI75 and SDI33 increased unsaturated fatty acids (oleic, omega-3 and omega-6); SDI33 negatively affected fruit size and weight.	SDI75 maintained comparatively higher Ψstem and only moderate reductions in gs, supporting the identification of this treatment as a threshold beyond which physiological stress becomes limiting for growth and yield.	Zuazo, Lipan, et al. 2021
Persea americana Mill. cv. Hass	Central Chile; clay loam to sandy-loam alluvial soil; mature commercial orchard; microsprinkler irrigation over three consecutive seasons.	Uniform deficit irrigation treatments at 25%, 50%, 75% and 100% ETo (entire root zone wetted; no spatial alternation; sustained deficit irrigation, SDI).	25%, 50% and 75% relative to full irrigation.	Seasonal water application ranged from ≈2100 to ≈10,100 m^3 ha^{-1} yr.$^{-1}$ depending on treatment and season.	Fruit yield and size increased with irrigation level; highest and most stable yields obtained at 75%–100% ETo, while severe deficits (25%–50% ETo) caused strong yield penalties, particularly in off-crop years.	Not explicitly expressed as WP or WUE index; moderate deficit (≈75% ETo) improved productivity per unit water by maintaining yield with reduced irrigation volumes.	Yield responses were governed primarily by hydraulic limitations associated with the shallow avocado root system (0–0.6 m); insufficient soil water storage under severe deficit enhanced fruit abscission and intensified alternate bearing.	Fruit size (polar and equatorial diameter) increased proportionally with irrigation level; severe deficits reduced fruit number and size.	Deficit irrigation amplified alternate bearing intensity; maintaining adequate irrigation even in off-crop years was critical to orchard stability.	Holzapfel et al. 2017

et al. 2025) demonstrated that potassium-enriched biochar markedly enhances drought resilience in mango by simultaneously improving soil biochemical functionality and leaf physiological status. Under 50% irrigation, biochar increased microbial biomass carbon by up to 73%, dehydrogenase activity by 100% and soil organic carbon by 34%, strengthening the soil's capacity to buffer water and nutrient fluctuations. At the leaf level, biochar elevated chlorophyll by up to 40%, soluble carbohydrates by > 60% and proline accumulation, indicating improved osmotic adjustment and sustained photosynthetic efficiency under water deficit. These coordinated soil–plant responses translated into up to 97% higher yield and > 100% improvement in yield/ETc, kg m^{-3}, confirming enriched biochar as a potent drought-mitigation tool in mango orchards. In this case, the biochar was produced by slow pyrolysis of a maize straw–banana peel mixture (1:3, w/w) at 500°C for 3 h, yielding a K-rich lignocellulosic char.

Beyond yield and water-use efficiency, biochar application also exerts a measurable influence on mango fruit quality through enhanced carbon allocation. Independent studies conducted under non-drought conditions have shown that biochar significantly increases soluble sugars and total soluble solids in mango fruit, consistent with improved sink strength (Iqbal et al. 2021). This biochemical response is supported at the molecular level by the up-regulation of sucrose metabolism genes, including MiSS1, MiSS2 and MiSPS, which control sucrose synthesis and partitioning during fruit development (Sun et al. 2024). Although these transcriptional effects have not yet been investigated under drought stress, they suggest that biochar-induced improvements in fruit carbohydrate status are mediated by coordinated soil–plant–fruit interactions.

Although biochar has been investigated in avocado systems, direct evidence for its role in mitigating water deficit remains largely unexplored. In the field study by Joseph et al. (2020), soil incorporation of biochar (5%–20% v/v in the upper 50 cm) increased avocado fruit yield by up to 97% in one season and enhanced soil organic carbon, dissolved organic carbon and total dissolved nitrogen relative to unamended controls. These improvements indicate a substantial strengthening of rhizosphere structure and nutrient buffering capacity, factors that are known to influence plant water relations. However, because irrigation was not restricted and no plant water-status parameters (e.g., Ψleaf, RWC or WUE) were measured, this study cannot directly link biochar application to drought alleviation in avocado. Consequently, despite clear gains in productivity and soil quality, quantitative evidence demonstrating biochar-mediated mitigation of water stress in avocado orchards is still lacking and warrants targeted deficit irrigation experiments.

4.4 | Biostimulants

Foliar biostimulants can play a significant role in reducing abiotic stress in mango trees grown under semi-arid conditions. When applied during the shoot maturation phase, a period in which trees naturally face high temperatures and reduced water availability, these products help stabilize key physiological processes. Treated trees with three yeast extract and amino acid biostimulant applications, followed by one application of potassium sulfate spaced at 10-day intervals, showed improved accumulation of osmoprotective metabolites such as soluble carbohydrates, amino acids and proline, which support osmotic adjustment and protect cellular structures during water deficit (Silva et al. 2020). The biostimulant also enhanced the plant's antioxidant defence system, leading to more stable activities of enzymes such as ascorbate peroxidase and catalase compared with untreated plants. This suggests a better capacity to detoxify reactive oxygen species generated under drought stress, thereby limiting oxidative damage. A recent article (Almutairi et al. 2023) shows that foliar biostimulants such as putrescine, brassinosteroids and chitosan can enhance mango growth, yield and fruit quality, suggesting that these compounds may reinforce tree resilience under stress conditions. Putrescine (100 mg/L) is highlighted as a regulator of physiological processes and abiotic stress responses, improving photosynthesis, nutrient accumulation and fruit set, mechanisms that are relevant for trees exposed to drought-induced limitations. Brassinosteroids (2 mg/L) are described as natural phytohormones that not only stimulate growth but also help plants cope with environmental stresses, including water deficits, by supporting photosynthesis, enzyme activity and reproductive development. Chitosan (1500 mg/L) is reported to act as both a growth stimulator and anti-transpirant, improving water availability, leaf water status and nutrient uptake, which are key features for drought tolerance. While the experiment was not designed as a drought trial, the authors discuss these compounds within a broader framework of abiotic-stress physiology, noting that they are widely reported to mitigate water-related stress. Chitosan and nano-chitosan function both as growth enhancers and stress protectants, enabling the detoxification of reactive oxygen species that accumulate when drought impairs cellular metabolism (Muthuramalingam et al. 2023). This review also reinforces that silicon, potassium silicate, tocopherol and engineered nanoparticles (e.g., ZnO + nano-Si) enhance antioxidant activity, osmotic adjustment, nutrient assimilation and defence signalling in response to salinity and drought stress by depositing silicon in cell walls. Seaweed extracts (particularly *Ascophyllum nodosum*) enhance stress tolerance, including water scarcity, by improving metabolic performance and shoot maturation under semi-arid conditions. At the molecular level (Ali et al. 2023), *A. nodosum* treatment triggered the up-regulation of stress-responsive genes, including those encoding late embryogenesis abundant (LEA) proteins, Δ^1-pyrroline-5-carboxylate synthase (P5CS, a key enzyme in proline biosynthesis), lipid-transfer proteins involved in membrane repair and metacaspases associated with programmed cell protection. These gene expression changes are consistent with enhanced osmoprotection, membrane stabilization and reactive oxygen species (ROS) detoxification, which together support plant survival under drought. A soybean study (Shukla et al. 2018) provides clear molecular evidence that *A. nodosum* extract (AN) enhances drought tolerance by selectively activating stress-responsive gene networks. Under water deficit, at the hormone-regulation level, AN increased the expression of abscisic acid (ABA) catabolism regulators (GmCYP707A1a and GmCYP707A3b), suggesting a potential role in controlling ABA turnover during dehydration and recovery. AN also stimulated the transcription of GmRD22 and GmDREB1B, two ABA-dependent drought regulators involved in osmotic adjustment and cell wall protection. In addition, the extract enhanced transcripts linked to photoprotection and membrane stabilization, including FIB1a (supporting PSII tolerance) and GmBIP (a molecular chaperone associated with delayed senescence). Notably, AN elevated the expression of GmPIP1b, an aquaporin gene associated with maintaining water transport during stress, and induced GmTP55, an antiquitin-like aldehyde dehydrogenase linked to the detoxification of lipid peroxidation products.

Beyond *A. nodosum*–based products ($3\,g\,L^{-1}$), other natural biostimulants have shown protective effects under water-related stress in perennial fruit crops. For example, in mango seedlings irrigated with low-quality agricultural drainage water, foliar application of garlic extract ($5\,mL\,L^{-1}$; obtained through grinding, 1:10 w/v aqueous steeping, and filtration) significantly buffered oxidative and physiological damage. Drainage water increased malondialdehyde and proline accumulation, indicating membrane degradation and osmotic stress, whereas garlic and seaweed extract markedly reduced these stress indicators, promoted chlorophyll synthesis and improved antioxidant status (Mahmoud et al. 2024).

Products containing amino acids, proline, humic substances or yeast extract have shown the ability to reduce the negative effects of heat and limited water availability, supporting growth, water uptake and nutrient status (Muthuramalingam et al. 2023).

Evidence from avocado production systems also suggests beneficial effects of biostimulant-based nutritional inputs on orchard performance. In the study by Rojas-Rodríguez et al. (2023), water stress was not experimentally imposed; however, the application of a nutrient-based biostimulant formulation significantly increased the total fruit weight and the proportion of extra-quality fruits without negatively affecting postharvest behaviour. The applied formulation combined high levels of soluble potassium ($100\,g\,L^{-1}$) and phosphorus ($65\,g\,L^{-1}$) with boron ($2.5\,g\,L^{-1}$), silicon ($20\,g\,L^{-1}$) and secondary metabolites ($50\,g\,L^{-1}$) and included oxidizable organic carbon from seaweed extracts as well as free amino acids (600 ppm), including phenylalanine and methionine (300 ppm each). Overall, this composition reflects a combined nutritional and bioactive profile aimed at supporting physiological performance and fruit quality. A two-season field experiment demonstrated that drought mitigation in avocado is strongly dependent on the amendment type. Among all root-zone treatments, *A. nodosum* extract ($24\,L\,ha^{-1}$ total per season) consistently produced the lowest accumulated stress values and maintained leaf water status. Its effectiveness was attributed to improved soil water availability, enhanced fine root proliferation and greater soil exploration depth, allowing sustained water uptake under restriction. Humic acids ($83\,kg\,ha^{-1}$) and arbuscular mycorrhizal fungi ($2\,kg\,ha^{-1}$) also contributed to stress reduction, albeit with less pronounced effects. Treatments with nitrogen-fixing bacteria ($1\,kg\,ha^{-1}$) showed no benefit, underscoring that successful drought mitigation requires amendments that simultaneously modify soil structure and stimulate root functionality (Beyá-Marshall et al. 2025). Similarly, a multi-stage trial (Cano-Benitez et al. 2024) demonstrated that foliar or soil-applied *A. nodosum* extract at $\geq 5\,mL\,L^{-1}$ consistently increased stomatal conductance, chlorophyll accumulation, hydraulic conductivity and nutrient uptake, ultimately improving dry matter accretion and fruit yield. Both application routes were effective, indicating flexibility for integration into crop management programs aimed at reinforcing avocado resilience under heat and water imbalances.

Long-term field experiments in Australia (Arioli et al. 2024) further support the relevance of seaweed-based biostimulants for avocado resilience. Regular soil fertigation with an *A. nodosum/Durvillaea potatorum* extract increased yield by 38%, enhanced fruit firmness and colour and stimulated root biomass (+21.8%). Although this study did not impose controlled drought, these responses mirror classical drought-acclimation traits, improved rooting capacity, nutrient mobilization (notably calcium) and delayed postharvest senescence, suggesting a functional role in buffering stress episodes frequently encountered under tropical field conditions. Moreover, transcriptomics evidence (research on *Arabidopsis*) associated with the same extract indicates activation of systemic acquired resistance pathways and defence-related genes (PR1 and MLO), supporting a priming mechanism that can enhance tolerance to biotic and abiotic challenges. Together, these findings reinforce the role of seaweed biostimulants as tools for strengthening avocado physiology under environmentally stressful conditions.

Overall, the treatments using biostimulants demonstrated greater metabolic stability and reduced sensitivity to fluctuations in environmental stressors. Together, these roles indicate that biostimulants can support mango and avocado trees in coping with adverse conditions by improving water-use efficiency and water productivity, maintaining photosynthetic function and stabilizing physiological performance. However, despite avocado's expanding global importance, dedicated research on biostimulants in this species, particularly under abiotic stress, remains fragmented and largely restricted, representing a clear knowledge gap. This scarcity contrasts sharply with mango (Almutairi et al. 2023), soybean (Shukla et al. 2018), tomato (Ali et al. 2023) or grapevine (Salvi et al. 2020), where diverse biostimulant categories and stress models have been investigated extensively.

4.5 | Hydrogel

Hydrogels are cross-linked hydrophilic polymers capable of absorbing and retaining large quantities of water relative to their dry mass. In soil applications, they act as biodegradable water-holding agents, swelling upon hydration and slowly releasing stored water as the soil dries. Their performance depends on their polymer structure, swelling pressure and release tension, which determines whether the water they store is accessible to plant roots (Ramírez-Brewer et al. 2025).

Recent findings support the concept that polyacrylamide-based hydrogels can mitigate transient water limitations in young mango orchards. In experimental planting pits, under Mediterranean-desert conditions receiving only 26 mm annual rainfall, hydrogel addition increased field capacity by 22%–35%, extended the period of plant-available water from 3–4 to 8–10 days and enhanced volumetric water content around roots by 18%–32%, translating into 25%–40% higher seedling survival under fluctuating irrigation regimes (Alshallash et al. 2022).

In mature Zebda mango orchards, soil application of hydrogel at 50 g $tree^{-1}$ increased IWP from 1.69–1.57 to 1.85–1.66 kg fruit m^{-3} and raised yield from 28.3–25.9 to 31–27 kg $tree^{-1}$, whereas the higher dose (100 g $tree^{-1}$) elevated it to 2.07–1.78 kg fruit m^{-3} and yield to 34.5–29.4 kg $tree^{-1}$, demonstrating clear dose-dependent enhancement of productivity under semi-arid irrigation (Shaban et al. 2025). Authors report WUE term in their paper as yield per irrigation requirement (kg m^{-3}), which corresponds conceptually to irrigation water productivity in the present review. Although irrigation volumes in semi-arid Egyptian orchards exceed 4300 m^3 per feddan (approximately 10,200 m^3 ha^{-1}), sandy desert soils exhibit low water-holding capacity and rapid percolation losses, creating intermittent water stress. Under these conditions, hydrogel application acts not by supplying additional water but by stabilizing soil moisture availability around the roots and improving WP (Shaban et al. 2025).

Beyond agronomic use, hydrogels have also shown clear physiological benefits during mango storage. Gelatin-based hydrogel films limited postharvest dehydration, with wrapped fruit losing only 3%–7% mass over 7 days compared with 19% in untreated controls, and softened more slowly, indicating delayed senescence. Fruit coated in hydrogel exhibited smaller shifts in pH and titratable acidity, consistent with reduced metabolic aging, and accumulated 1.5–2.0 nmol g^{-1} FW of malondialdehyde versus 3.18 nmol g^{-1} in controls, reflecting lower lipid peroxidation and better membrane integrity (Gang et al. 2025).

While hydrogels are widely proposed to support fruit crops such as mango by increasing planting-zone water availability, their functional success depends on whether stored water is released at tensions accessible to the root system, a limitation also observed in avocado, where excessive retention increased drought stress (with 83 kg ha^{-1} application) (Beyá-Marshall et al. 2025). Instead, different results were found under 500–1500 g $tree^{-1}$ doses, where a soil-applied water-retaining biopolymer markedly improved drought resilience in 'Hass' avocado. At 1500 g, under moderate deficit irrigation, the polymer improved the plant water status and yield components. The leaf relative water content increased from approximately 63%–65% in untreated trees to approximately 80%–83% in biopolymer-amended treatments, depending on the irrigation level and season. Fruit number per tree increased under both full and deficit irrigation, with higher values consistently observed in amended treatments compared with the non-amended control. Fruit biochemical traits were also enhanced, with the total carbohydrate concentration reaching approximately 14.6%–15.7% and the oil content increasing to approximately 11.5%–12.7%, depending on the irrigation regime. This study also evaluated zeolite amendments, which showed comparable or higher responses for several parameters (Abdelzaher et al. 2025a). Under 70% irrigation (IR3), the application of 1000 g biopolymer maintained leaf nitrogen above 2.15%, whereas control and zeolite-treated trees declined below 1.90%. Similar trends were observed for phosphorus ($>$ 0.20%), potassium (up to 1.40%), calcium (1.45%–1.52%) and magnesium ($\geq$ 0.32%), indicating a marked mitigation of nutrient depletion under deficit irrigation. Yield-based IWP (kg m^{-3}; calculated per unit of irrigation water applied) was lowest in the unamended control under IR3 ($\approx$ 5.9–6.0 kg m^{-3}), while biopolymer and zeolite treatments significantly improved this parameter across irrigation regimes, with the highest values recorded at high amendment doses under full irrigation ($\approx$ 11.0–11.2 kg m^{-3}). This demonstrates that the biopolymer buffered rhizosphere moisture, sustained nutrient acquisition and supported metabolic function under restricted irrigation, contributing to improved orchard-scale water productivity, aligning with avocado's isohydric regulation strategy (Abdelzaher et al. 2025b). Although termed WUE by the authors, this yield-based index expressed per unit of irrigation water applied (kg m^{-3}) corresponds conceptually to irrigation water productivity.

Notably, beyond recent drought-amendment trials, no other published studies have evaluated hydrogel application as a mitigation strategy in avocado under water stress. The literature referring to 'hydrogel and avocado' almost exclusively concerns postharvest coatings or the use of avocado residues to manufacture hydrogel materials rather than agronomic deployment on avocado trees.

For example, in a photothermal materials study, avocado peel was carbonized and embedded within a sodium-alginate hydrogel, producing a highly efficient solar evaporator. Under solar irradiation, the resulting composite achieved a 1.44 kg m^{-2} h^{-1} evaporation rate with 90.26% photothermal conversion efficiency. The system showed stable performance over multiple evaporation cycles, including operation in saline solutions, and effectively reduced dissolved inorganic ions to concentrations below WHO and EPA drinking-water standards, demonstrating efficient solar-driven desalination and water purification (Roy et al. 2025). This contrast underscores a substantial research gap in hydrogel-avocado systems for field drought resilience.

4.6 | Zeolite

Zeolites are natural or synthetic aluminosilicate minerals with a crystalline three-dimensional framework characterized by high cation exchange capacity and internal microporosity. In soils, they function as ion exchangers and buffering agents, improving nutrient retention and modulating ammonium and moisture dynamics (Cataldo et al. 2024).

The soil application of zeolite markedly improved mango performance, enhancing trunk diameter from 2.3 to 4.1 cm, leaf chlorophyll from 43–44 to 55–58 SPAD units, fruit yield from 59–62 to 87–90 kg $tree^{-1}$ and fruit weight from 260 to 310 g. Treatments with higher zeolite rates showed a consistent increase in total soluble solids, rising from 18.5%–18.3% in the control to 26.9%–28.5%. In parallel, total sugars increased from ≈10.7% to ≈18.5%–19.8%, with both reducing sugars and non-reducing sugars contributing to this rise. At the same time, vitamin C content and carotene concentration markedly increased. The strongest responses were obtained when zeolite was combined with biochar (3 kg zeolite + 3 kg biochar) rather than applied individually, demonstrating its capacity to improve water availability, nutrient retention and stress resilience under low irrigation quality (Harhash et al. 2022).

Under hyper-arid field conditions, soil-applied zeolite improved drought resilience in 'Hass' avocado. At 1500 g of $tree^{-1}$, zeolite increased the leaf relative water content from 63%–65% in untreated trees to 78%–81%, raised the fruit number from < 55–60 to 210–250 fruits tree^{-1}, and under full irrigation elevated the total soluble carbohydrates in pulp from 12.0% to 15.2%–15.5% under full irrigation. Additionally, the fruit oil concentration increased from 8.7%–8.8% in the stressed control (trees under severe deficit irrigation, 70% IR) to 12.1%–12.5%, indicating improved assimilate allocation and fruit metabolic status. These responses occurred even under a 20%–30% irrigation deficit, indicating that zeolite enhanced water availability and nutrient efficiency sufficiently to sustain canopy function, fruit set and biochemical quality indices under restricted water inputs (Abdelzaher et al. 2025a). Its strongest contribution was highlighted in yield (kg/tree)/irrigation water applied (m^3/tree) and proline. This mineral increased the IWP from 5.9–6.0 kg m^{-3} in stressed controls to 9.5–10.6 kg m^{-3}, confirming its ability to enhance root-zone moisture availability and support physiological resilience under irrigation deficit. In addition, increased proline showed a better osmotic adjustment capacity (Abdelzaher et al. 2025b).

Although zeolite-based amendments have been tested on avocado and mango, the number of peer-reviewed studies remains surprisingly small. This underscores the need for more targeted research across environments and soil types. Existing trials indicate that zeolite alone does not reliably alleviate drought stress in avocado. Its benefits tend to manifest through improved soil structure, cation exchange capacity and incremental gains in water-use efficiency, particularly when combined with other amendments such as biochar or hydrogels. This limited adoption is difficult to reconcile with zeolite's low cost and wide availability, suggesting that the material remains underutilized in commercial orchards. Moreover, even though exchange capacity, porosity and water retention properties differ widely among different kinds of minerals, most studies seldom address variability in zeolite mineralogy or particle size. Future work should therefore incorporate detailed information on zeolite type, purity and granulometry, enabling agronomists to match amendment characteristics with orchard requirements rather than assuming uniform performance across sources.

5 | Limits and Critical Issues

i. To what extent do deficit irrigation strategies defined as fixed percentages of ETc accurately reflect plant water stress in perennial fruit orchards?

An important methodological aspect highlighted by recent studies is that the effectiveness of deficit irrigation strategies expressed as a percentage of ETc is strongly dependent on the accuracy of ETc estimation. Several authors have reported that FAO-56–based approaches, even when using the Penman–Monteith equation (Allen et al. 1998), may overestimate actual crop water requirements in perennial fruit orchards, particularly under localized irrigation systems and partial canopy cover, as they reflect atmospheric demand rather than plant-regulated transpiration (de la Antonia Gonzalez 2023; Ragab 2024, 2025). As a consequence, irrigation treatments defined as a fixed fraction of ETc (e.g., 50%–75% ETc) do not necessarily correspond to proportional levels of physiological water stress. This potential overestimation may partly contribute to the apparent success of some deficit irrigation regimes and highlights the need for crop- and site-specific calibration of ETc estimates, ideally supported by direct measurements of plant or soil water status.

A second source of ambiguity in deficit irrigation studies arises from the inconsistent use of water-use efficiency (WUE) and water productivity (WP). Ragab (2024) highlights that 'efficiency' should be treated as a dimensionless concept (often expressed as a percentage) describing how effectively supplied water is converted into beneficial crop use, whereas 'productivity' refers to output per unit of water supplied or applied (e.g., kg m^{-3}). When efficiency and productivity metrics are conflated, deficit irrigation strategies may appear 'more efficient' simply because water inputs are reduced, even when plant water use or physiological performance is not proportionally improved. In some orchard studies, including Spreer et al. (2009), 'WUE' is calculated as yield per unit of irrigation water (kg m^{-3}), which conceptually corresponds to irrigation water productivity rather than physiological WUE (Kilemo 2022).

ii. Which sensing approaches can be integrated with ETc-based irrigation to validate and calibrate imposed water deficits at the plant level?

A key limitation of deficit irrigation expressed as fixed fractions of ETc is that the resulting level of physiological stress is not necessarily proportional and is strongly modulated by canopy development, wetting pattern and atmospheric demand. For this reason, successful deficit management should require crop-specific validation of stress thresholds. Precision sensing could partially resolve this gap by tracking plant and soil water status in real time and adjusting irrigation to actual stress dynamics.

In mango, stem/trunk dendrometers have been proposed as sensitive indicators of irrigation regime effects on tree hydration dynamics. However, their sensitivity is highest under stable, rain-free conditions with elevated evaporative demand, whereas rainfall and cloud cover can obscure stress-related signals by inducing rapid passive stem rehydration (Hahn and García 2022).

In avocado, spectral vegetation indices such as NDVI (normalized difference vegetation index) and MTCI (MERIS terrestrial chlorophyll index), particularly those based on red-edge wavelengths of approximately 720 nm, have been shown to detect water stress rapidly and discriminate between stress intensities at early developmental stages (Rondon et al. 2024). Likewise, in mango, UAV-derived NDVI and red-edge (NDRE) indices have proven effective for detecting irrigation-induced stress and differentiating deficit intensity, particularly during early stress development (Sillero-Medina et al. 2025). These non-destructive sensing approaches could enable timely identification of plant water status alterations. Although primarily tested under controlled conditions, such sensor-based tools hold strong potential to support deficit irrigation management by improving stress monitoring and reducing the risk of unintended hydraulic stress associated with fixed ETc-based irrigation schedules.

iii. Why do deficit irrigation strategies, particularly partial root-zone drying, elicit contrasting physiological and agronomic responses in mango and avocado?

While mango can exploit deficit irrigation through coordinated osmotic adjustment, root plasticity and hormonal regulation when water deficits are imposed at tolerant phenological stages (El-Sayed et al. 2023), avocado exhibits markedly lower physiological plasticity. Its shallow root system and weak coupling between root-derived ABA signals and stomatal regulation result in a limited capacity to control transpiration under soil water heterogeneity, often leading to premature fruit abscission rather than adaptive water-use regulation (Gil et al. 2009; Neuhaus et al. 2009; Carr 2013). This explains why PRD works best in mangoes but not in avocados.

These limitations indicate that deficit irrigation strategies cannot be transferred across species without accounting for fundamental differences in root physiology and signalling pathways. In avocado, deficit-based approaches require buffering through soil amendments or real-time physiological monitoring, whereas in mango, they can be exploited more directly when phenology and stress intensity are carefully aligned. This explains why PRD works best in mangoes but not in avocados.

iv. Which aspects of avocado water relations remain poorly resolved under deficit irrigation conditions?

Compared with mango, avocado remains underrepresented in mechanistic irrigation research, particularly regarding hormonal signalling, root hydraulics and recovery dynamics following stress. Many conclusions on avocado sensitivity are inferred indirectly rather than derived from targeted physiological experiments. This lack of mechanistic depth constrains the development of species-specific irrigation models and partly explains the inconsistent performance of deficit-based strategies in avocado orchards.

v. To what extent do current deficit irrigation studies capture the internal carbon constraints underlying fruit growth and retention?

A major limitation of many deficit irrigation studies is the predominant focus on yield and irrigation water productivity, with little consideration of how carbon is allocated within the tree. In mango and avocado, fruit growth and retention depend on the balance between assimilate supply, vegetative growth and internal carbon reserves. Without measurements of non-structural carbohydrates, shoot growth or fruit abscission dynamics, it is difficult to determine whether yield reductions under deficit irrigation reflect a temporary and reversible physiological adjustment or a deeper structural imbalance that may compromise future productivity. In this context, assessment of non-structural carbohydrates, particularly soluble sugars (sucrose, glucose and fructose) and starch pools in leaves, perennial organs and roots, would be essential to distinguish between short-term physiological adjustment and long-term depletion of carbon reserves under deficit irrigation (Nawaz et al. 2025).

vi. Are current biochar studies sufficient to predict its long-term effectiveness as a soil amendment for drought mitigation in perennial fruit orchards?

One major limitation in biochar application is the high variability in biochar physicochemical properties, which strongly depend on feedstock origin, pyrolysis temperature and enrichment procedures (Lippi et al. 2025). Often, biochars used in different studies differ in surface area, porosity, ash content, nutrient composition and hydrophobicity. This heterogeneity could complicate cross-study comparisons and limit the generalization of results, particularly in perennial orchard systems where soil and biochar interactions evolve over multiple seasons.

In addition, although biochar has been shown to improve soil water-holding capacity in controlled experiments, its long-term effectiveness in maintaining plant-available water under field conditions remains uncertain. Few orchard studies extend beyond two to three seasons, limiting the assessment of biochar durability under repeated wet and dry cycles.

vii. Which research gaps currently limit the development of zeolite-based drought-mitigation strategies for mango and avocado orchards?

An additional and still poorly addressed gap in the literature concerns the limited number of studies about zeolite applications for mitigating water stress in mango and avocado. This underrepresentation is unexpected, given that natural and synthetic zeolites are non-toxic, chemically stable and environmentally sustainable materials, characterized by high cation-exchange capacity, strong water adsorption/desorption properties and relatively low costs (Cataldo et al. 2024, 2025). Moreover, a wide range of synthetic zeolites with tunable pore size, surface chemistry and granulometry is already available, potentially allowing optimization for specific conditions (de Carvalho Izidoro et al. 2024).

6 | Conclusions

Climate change–driven water scarcity poses a significant threat to the long-term sustainability of mango and avocado orchards, particularly in semi-arid and marginal production areas. This review highlights that although both crops are highly water-demanding, they exhibit different physiological responses to soil water limitation, which strongly conditions the effectiveness of irrigation and mitigation strategies. Mango demonstrates a relatively high capacity to exploit controlled water deficits when restrictions are applied at phenologically tolerant stages, benefiting from osmotic adjustment, root system plasticity and coordinated metabolic regulation that allow yield and fruit quality to be maintained under reduced water inputs. In contrast, avocado shows pronounced sensitivity to both uniform and localized soil drying, driven by its shallow root system, weak root-to-shoot hormonal signalling and high susceptibility of reproductive sinks to hydraulic stress, which severely limits the applicability of strategies such as partial root-zone drying.

Across both crops, deficit irrigation alone rarely provides a robust solution under increasing climatic variability. Instead, the most consistent gains in water-use efficiency and yield stability emerge when irrigation strategies are coupled with soil amendments and biostimulants capable of buffering root-zone moisture, enhancing nutrient retention and sustaining root functionality. Biochar, zeolite, hydrogels and seaweed-based biostimulants show clear potential, particularly in sandy or degraded soils. However, their agronomic deployment remains fragmented and highly context dependent. Notably, for avocado, quantitative field evidence linking these amendments to drought mitigation is still scarce, and existing studies often lack direct physiological measurements of plant water status.

Overall, the literature reveals a critical need for integrated, crop-specific strategies that combine precise irrigation scheduling (e.g., remote sensing approaches) with soil and physiological buffering approaches. Future research should prioritize long-term field experiments, mechanistic investigations of plant hydraulic responses and comparative assessments of amendment types, doses and physical properties. Without such advances, current water-management practices risk being insufficient to prevent climate-change hazards from jeopardizing the productivity and resilience of mango and avocado orchard systems.

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