Plant Archives Vol. 25, No. 1, 2025 pp. 1653-1664 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.1.241

SMART WATER MANAGEMENT IN HORTICULTURAL CROPS: A REVIEW

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(Date of Receiving : 10-02-2025; Date of Acceptance : 13-04-2025)

ABSTRACT

Water is a basic resource for plant life, playing a crucial role in several biochemical and physiological processes essential for plant growth. Long-term horticulture output depends on irrigation, yet social fairness, environmental sustainability, and economic viability are all threatened by high water consumption demands and diminishing water supplies due to climate change. The world economy and food security depend heavily on the horticultural industry. The extensive use of technology provides a way to supply precisely the right amount of water for crops and plants. In horticulture, sustainable water management entails making effective use of water to reduce waste. Water shortage can be avoided by making sure that water is used efficiently, particularly in areas that are prone to drought and aridity. This review article encompasses the smart ways to mange water in the production of horticultural crops.
***Keywords*:** water management, approaches, horticulture, IoT.

Introduction

Horticulture is a significant agricultural sector that contributes to food security, high returns, and employment, making it an essential part of the world economy (Touil *et al*., 2022). Horticulture has had significantly more economic growth in recent decades than the majority of agricultural commodities (Kour *et al*., 2022). Growing populations and changes in consumer lifestyles have led to a rise in the demand for horticultural products. Fruits and vegetables are consumed in greater quantities due to their low-fat content and high levels of various nutritional compounds (such as vitamins, minerals, fibres, and antioxidants), which are supported by growing awareness of the connection between diet and health (USDAID; ISHS, 2005). The expansion of supermarkets and the increased market demand for exotic food items also contributed to the growth of horticulture product production (Manzoor *et al*., 2024).

A vital component of many physiological and biochemical processes necessary for plant development and health, water is a basic resource for plant life. According to Scharwies and Dinneny (2019), water has a role in initiating seed germination, promoting the uptake of minerals and nutrients from the soil, and then transferring them throughout different plant organs.

Additionally, water is essential for maintaining turgor pressure, giving plant cells stiffness, preserving their vigour and form, and avoiding wilting (Sevik and Cetin, 2015).

Irrigation is a common practice in horticulture, especially for high-value horticultural products, such as vegetables and fruit (Bogdan and Kulshreshtha, 2021). Typically, it includes water from freshwater resources and/or groundwater, depending on water availability and existent technology and/or hydraulic infrastructures to exploit the actual water resources. The expansion of horticultural activities and associated water requirements can exert substantial pressure on water resources, including both quantity and quality. Increasing water demand for irrigation has contributed to the depletion of water resources (Guo *et al.*, 2023) and to conflicts in scarce water regions (Lanari *et al*., 2018). Irrigated agriculture accounts for 85–90 % of global water consumption (Qin *et al*., 2019). Specific water consumption for horticulture alone is difficult to point out due to varying methods of measurement and regional practices, and the significant differences in crop requirements (e.g., tomatoes, lettuce, and citrus fruits are particularly water-intensive, whereas ornamental plants require less but frequent watering), but is estimated to represent 20–30% of the agricultural water use (Molden, 2007).

Reducing water consumption in horticulture without sacrificing output (both yield and quality) has become crucial (Stefanelli *et al*., 2010). Unacceptable water losses are linked to traditional irrigation techniques, such as flood irrigation. Furthermore, in order to maximize yields and financial returns, farmers typically choose irrigation based on their personal experiences, field observations of plant canopy, water availability, and/or generalised regional evapo-transpiration tables (Bierer, 2023). This leads to excessive irrigation. However, a number of strategies have been developed in recent decades to increase water usage efficiency and give irrigation water savings. Implementing water conservation strategies and raising productivity per area has benefited from strategies centred on improving soil water retention, more effective irrigation technologies (such as drip irrigation and subsurface irrigation), and developing decision support systems that use, for example, sensor technologies to improve and automate data collection of soil water status and physiological stress (Guo *et al*., 2023).

In horticulture, sustainable water management entails making effective use of water to reduce waste (Russo *et al*., 2014). Preventing water scarcity, particularly in dry and drought-prone areas, as well as excessive freshwater extraction and pollution, requires efficient water usage. This is crucial for maintaining ecosystems, promoting human welfare, and guaranteeing the long-term supply of water resources. Its significance encompasses social, economic, and environmental aspects both today and in the future. The implementation of better water management techniques and technologies by farmers can aid in food security, climate change adaption, and the accomplishment of many SDGs (Sustainable Development Goals). Artificial intelligence and data-driven and sensor-based irrigation are examples of recent technological developments that present a chance to address the present issues in horticulture.

Approaches for Improving Water Management in Horticulture

Mulching

In horticulture, natural options are being investigated more and more to lower the need for water irrigation. To improve soil qualities, retain water, and promote plant growth, these solutions frequently include the application of both organic and inorganic mulches together with other agronomic practices. By increasing the amount of water available to plants and reducing direct soil water evaporation, mulching a layer of material applied to the soil surface is a method for conserving soil moisture (Alharbi *et al*., 2024). Horticulture has been using it more and more lately (Gava *et al*., 2023). Organic mulches, such as straw, bark, wood chips, and compost, have been demonstrated to improve soil physical properties (e.g., reducing soil bulk density and increasing porosity), favoring water infiltration and increasing soil organic matter content, which further aids in water retention (Gholami *et al*., 2023). Organic mulches contribute to regulating soil temperature, thus reducing evaporation (Liao *et al*., 2021). The use of mulch can reduce 20 to 50% of evapo-transpiration from soil when compared with non-mulched soils (Kuehny and Bowers, 2006; Chai *et al*., 2016; Bai *et al.*, 2018)

Various organic mulches have been investigated in ornamentals (Berríos and Nielsen, 2006), fruits (e.g., strawberry, apple) (Wavhal and Giri, 2014), vegetables (e.g., pepper) (Hossain and Ryu, 2009) and aromatics (e.g., turmeric, basil) (Wang *et al.*, 2009; Agyarko *et al*., 2006). In horticulture, plastic mulches are the most widely used, including in fruits (e.g., strawberry), vegetables (e.g., pepper), herbs, and ornamentals, but gravel mulches and geotextiles have been also applied. For example, in a commercial adult mandarin orchard located in southeastern Spain, the black polypropylene raffia geotextile mulch reduced the intensity of water stress by 18% (Bai *et al.*, 2018). Some studies have revealed that inorganic mulches may be more effective in increasing soil water content than organic mulches (Montague *et al*., 2007). The choice of mulch material depends on several factors, including availability, climate, durability, cost-effectiveness, and environmental impact (Khan, 2018). Given the wide number of variables affecting soil water retention (e.g., soil type, rainfall patterns, evaporative demands), it is challenging to generalize about the efficiency of mulching in reducing water requirements in horticulture (Alharbi *et al*., 2024).

Agronomical Practices

In horticulture, other crop management techniques like cover crops, organic amendments, and reduced tillage have been applied, for example, to increase water-holding capacity (Diacono and Montemurro, 2011; Singh and Sharma, 2003). Depending on the type of compost, crop nutrient requirements, soil properties, and local practices, the annual application rates of compost in horticulture typically range from 20 to 40 t/ha in vegetable crops (Alharbi *et al*., 2024), 10 to 30 t/ha in orchards and (Ronga *et al*., 2016), and 10 to 20 t/ha in both ornamental (Glover *et al*., 2000) and aromatic (Corato *et al*., 2020).

Greenhouses and Hydrophonics

Horticulture plants, however, have been increasingly grown on soilless media, with compost being used as a substitute of soil in greenhouse crops (Singh and Sharma, 2003). Soilless systems, i.e., cultivation on substrates such as peat moss, perlite, vermiculite, and expanded clay pellets, provide a supportive environment for plant roots and have higher water use efficiency than soil cropping, given the better water retention properties of substrates compared to soil (Herrero-Hernández *et al*., 2020).

Soilless media are widely used in horticulture, particularly in controlled environments like greenhouses, vertical farms, and hydroponic systems. In hydroponic systems, water recirculation provides enhanced water use efficiency (Carotti *et al*., 2023). Various types of horticultural crops are successfully grown in soilless media, such as lettuce, tomatoes, blueberries, roses, and orchids. Savvas and Gruda (2018) provided a literature review on the application of soilless technologies in greenhouse industry.

Biochar

Biochar, a carbon-rich solid byproduct with a porous structure obtained from pyrolysis (Corato, 2020), is a soil amendment with high potential to increase water storage by improving soil structure (e.g., reducing soil bulk density) (Kavitha *et al*., 2018). It can also mitigate the negative impacts of horticulture on water quality by immobilizing nutrients and contaminants (Gökalp and Bulut, 2022). Biochar has been applied in fruit (e.g., strawberry, citrus, apple) (Álvarez *et al*., 2018; Akhtar, 2015; Ortiz-Liébana *et al*.,2023), vegetable (e.g., tomato and pepper) (Genesio *et al*., 2015), herbs (sweet basil, mint, and oregano) (Graber *et al*., 2010), and ornamental (e.g., calendula, marigold, petunia, and geranium) production (Rowland *et al*., 2018).

Cover Crops

Cover crops, planted between the growth cycles of main crops or during fallow periods, can improve water infiltration and retention by enhancing soil structure and increasing organic matter content (Arif *et al*., 2017). Cover crops have been used, e.g., in orchards and vineyards (Boulet *et al*., 2021), ornamentals (Steenwerth and Belina, 2008), and herbs (Hartwing and Ammon, 2002), but knowledge on their contribution to reducing water-irrigation requirements is very limited. Intercropping has been shown to increase the water use efficiency of horticulture crops (e.g., moth bean between paired rows of pearl millet and green gram between paired rows of pigeon pea) because of higher yields in intercropping systems (Alharbi *et al*., 2024). Reduce tillage improves soil water retention by maintaining soil cover and promoting better water infiltration (Mohammed *et al*., 2020). It has been applied in different horticulture crops (e.g., tomato, strawberry) (Ferreira *et al*., 2020; Wang *et al*., 2004).

The use of nature-based solutions has been identified as innovative solutions to improve water resources management under climate change. The above-mentioned management practices lead to improved soil structure and water holding capacity, relevant to decreasing irrigation water demand, but also providing improvements to soil health (e.g., fertility), reduced nutrient losses, and soil erosion, relevant to mitigate the environmental impacts of horticulture on water resource quality. However, generalizations on their effectiveness in reducing horticultural water irrigation are difficult, given the several factors affecting water availability and crop requirements in different regions. Future studies should focus on the effectiveness of different nature-based solutions in horticulture water savings to support water management.

Emerging Technologies and Tools for Water Management

Irrigation Technologies and Methods

Irrigation is a technical measure used to replenish water necessary for crop growth. It has been used for thousands of years to maximize the performance, efficiency, and profitability of crops, and it is a science that is constantly developing (Gil *et al*., 2023). Several authors advocate for water use efficiency as a crucial aspect to decrease water demand (Carr, 2012; Nikolaou *et al*., 2020), which can be achieved using efficient irrigation methods (Kang *et al*., 2021). Generally, drip irrigation has a water application efficiency of 65–95%, whereas sprinkler and furrow irrigation methods have efficiencies of 50–90% and 50–70%, respectively (Lakhiar *et al*., 2024).

Traditionally, both flood and furrow irrigation has been used in vegetable, fruit, ornamental, and herb crops. Generally, flood irrigation is used in areas with abundant water resources for the cultivation of, e.g., leafy greens (e.g., spinach and lettuce), citrus trees, flower beds, and mint (Ferreira *et al.*, 2024; Singh, 1992). Furrow irrigation has been used in different horticulture crops, including vegetable (e.g., tomatoes, cucumbers, and lettuce), fruit (e.g., melons, strawberries), ornamental (e.g., shrubs and hedges), and aromatics (e.g., mint, thyme) (Ferreira *et al.*, 2024; Singh, 1992). Both flood and furrow irrigation are easy to implement and require relatively low initial investment, but they tend to overwater and are less efficient in water use compared to other irrigation systems, thus contributing to the depletion of water resources. Over irrigation using these systems is quite common and can result in nitrogen leaching and pollution of water resources, low fertilizer use efficiency, and increased production costs (Mwinuka *et al.*, 2022).

Environmental, economic, and social drivers have been placing great pressure on horticultural systems to improve water use efficiency (Devitt and Morris, 2007), which has led to the application of a range of irrigation technologies and methods, such as drip irrigation systems, subsurface irrigation systems, and controlled drainage (Bogdan and Kulshreshtha, 2021). Sprinkler irrigation systems have been used in horticulture, e.g., in apples (Hamilton *et al.*, 2005), blueberries (Fereres and Evans, 2006), lettuce (Strik and Buller, 2005), and basil (Simonne *et al.*, 2005). Sprinkler technology uses stationary sprinklers, moving sprinklers, or center-pivot systems to spray water over the crops.

In small-acreage irrigation, methods such as micro irrigation are commonly used. The use of micro irrigation systems, such as drip irrigation, is a key factor in achieving higher yields and better-quality product in open-field (McDonald *et al.*, 2022) and greenhouse (Senapti *et al.*, 2021) vegetable cultivation. Drip irrigation diverts water near the root zone through a network of pipes, tubes, and emitters. It has been proposed as a potential alternative to traditional methods as it can significantly increase yield and water use efficiency due to lower water loss through seepage and evaporation (Zhang *et al*., 2024; Sebastian *et al.*, 2021). For example, a literature review focused on crops irrigated in China revealed that for the same amount of water applied, drip irrigation increases crop yields by 29%, 8%, 5%, and 2% comparing to the yields from flooding, furrow, micro-sprinkler, and two-sprinkler irrigation, respectively (Guo *et al.*, 2023).

Numerous horticulture farmers use drip irrigation technologies (Webb *et al.*, 2014). Several forms of automated micro-irrigation systems, including drip irrigation, have been used in water management methods such as deficit irrigation (Seema *et al.*, 2022). Deficit irrigation methods are based on the reaction of signaling molecules transported by xylem tissue, since water is first sent by the roots and provides the signal to leaves to retard the standard development and prevent water loss (Kaldate *et al.*, 2021). Based on this principle, water-management techniques such as partial root-zone drying (PRD) and regulated deficit irrigation (RDI) have been successfully used to improve yield and quality in horticulture (Wen *et al*., 2024). PRD involves alternately wetting and drying different parts of the root zone, effectively exposing only half of the root system to water stress at any given time (Chen *et al.*, 2023). In PRD, irrigation is applied to one side of the plant's root system while the other side is allowed to dry. After a certain period, typically one to two weeks, irrigation is switched to the previously dry side. This alternation helps to stimulate physiological responses in the plant that improve water use efficiency and can lead to benefits such as improved drought-tolerance mechanisms and reduced transpiration rates (Kaldate *et al.*, 2021).

PDR has been effectively implemented in a number of horticultural corps, resulting in a 30–50% decrease in irrigation for crops such as citrus (Yactayo *et al.*, 2013), potatoes (Giuliani *et al.*, 2017), and tomatoes (Shahnazari *et al.*, 2007). RDI is a technique that purposefully lowers the quantity of water given to crops during particular phases of growth. By applying water deficits at noncritical growth stages, plants can be conditioned to use water more efficiently, leading to considerable reductions in water use with minimal impacts on yield and quality (Consoli *et al.*, 2017). RDI has led to water savings of up to 20–30% in horticultural crops such as tomato (Loveys *et al*., 2004), grapes (Savic *et al*., 2011), and bean (Faci *et al.*, 2014). Water savings in horticulture are particularly relevant in arid and semiarid areas (Alharbi *et al.*, 2024). Nevertheless, both RDI and PDR are strategies that could be further explored in some horticultural cropping regimes (Webb *et al*., 2014).

Research on subsurface irrigation for open-air horticulture crops has shown promising results. In subsurface irrigation, water is delivered into the crop root zone, through a pipe network system laid below the surface layer. This method reduces deep seepage and soil evaporation and improves water use efficiency (Guo *et al.*, 2023). Oron *et al.* (1991) found that a subsurface drip system can be used for years without failure, with increased yields compared to surface microirrigation systems. Ayars *et al.* (1999) reported significant yield and water use efficiency increases in various crops, including tomato, cotton, and cantaloupe, when using subsurface drip irrigation. Brown *et al.* (1981) demonstrated the practical advantages of subsurface drip irrigation for multiple cropping, with higher yields in cantaloupe and dry onion. Lamm *et al*. (2015) in their work highlighted the increased usage of subsurface drip irrigation in the USA, particularly for cotton, tomato, and onion production.

In order to maximise growing conditions and boost crop production, controlled drainage is a water management technique that includes controlling the water table to increase water availability during dry spells and avoid water logging during wet spells (Strock *et al.*, 2007). It has been applied to minimise drought stress in orchards as well as water logging in horticulture crops like tomatoes and strawberries (Ayars *et al.*, 2006; Feset *et al*., 2010) Controlled drainage is mainly used in countries like the Netherlands and Denmark. Controlled drainage can be a valuable tool in water management, its limitations and potential trade-offs should be carefully considered in horticultural crops.

Recent research in horticulture irrigation methods has focused on improving water and nutrient management in greenhouse vegetable crops (Drury *et al.*, 2009). This includes the use of fertigation and advanced technologies such as hydroponics. Fertigation, i.e., the application of fertilizers through irrigation systems, provides an efficient method to optimize water and nutrient management in intensive horticultural systems, such as strawberries, lettuce, roses, and mint (Koukounaras, 2020; García-Ruiz *et al.*, 2017). Hydroponic is a soilless farming technique using mineral nutrient solutions in an aqueous solvent, with minimum evaporative losses. It is gaining attention in horticulture for its potential to provide increased yields, higher growth rates, efficient use of water and nutrients, higher plant density and allowing for vertical farming, thus addressing food demand and environmental challenges (Incrocci *et al.*, 2017). However, hydroponic also presents challenges, including high initial investment, technical knowledge requirements, and reliance on consistent electricity and water supply (Carrubba and Militello, 2013). Despite these limitations, the future of hydroponic farming looks promising, with the potential to provide high-quality, locally grown products (Pomoni *et al.*, 2023).

The challenge of adapting water management to a changing climate, including the need to reduce water consumption and improve water quality, involves improving irrigation efficiency (Zhang *et al.*, 2023). The best irrigation practice to implement, however, can vary with crop morphology, land availability, and soil type [2]. In addition to water use efficiency, the selection for the irrigation technology and method should consider the water accessibility and availability and the associated costs for both technology and water abstraction (O'Neill and Dobrowolski, 2011). Previous studies focusing on economic aspects of irrigation have shown that low-cost and moderate- to high-efficiency irrigation infrastructures may best suit farmers targeting area-based income (Xudayev *et al*. 2021).

The Potential of IoT and Artificial Intelligence in Supporting Water Management

The most recent technological advances in irrigation involve smart irrigation and precision irrigation, based on the adoption of a new generation of technology and information tools, such as Internet of Things (IoT) and artificial intelligence (AI). Smart irrigation is more focused on time aspects (scheduling), involving the automation and optimization of irrigation processes using real-time data (Muleke *et al*., 2023), whereas precision irrigation is more focused on the spatial distribution of water supply, targeting the precise application of water based on detailed analysis of field variability (Lephondo *et al.*, 2024).

The Internet of Things (IoT) emerges as the natural choice for smart water management applications, even though the integration of different technologies required for making it work seamlessly in practice is still not fully accomplished. The emergence of IoT is a phenomenon that owes to the conjunction of several factors such as inexpensive devices, low-power wireless technologies, availability of cloud data centers for storage and processing, management frameworks for dealing with unstructured data from social networks, high-performance computing resources in commodity platforms, and computational intelligence algorithms to deal with this monumental amount of data (aka big data analytics). (Atzori *et al*., 2010)

Additionally, irrigation system leaks can be found using IoT sensors (Pomoni *et al*., 2023), facilitating better water management. The important problem of water management in horticulture could be greatly addressed by the quickly developing domains of IoT and AI (Ludwig-Ohm *et al.*, 2023). By employing IoT sensors to gather data in real time (such as soil moisture content, weather, and plant water requirements) and sending the information to data centres, these solutions can assist precision irrigation (Keates, 2023). IoT includes actuators (e.g., to operate valves and pumps) and connected electronic devices (nodes) to support smart irrigation (Muleke *et al*., 2023). Apart from this hardware side, IoT comprises cloud computing for system feedback, based, e.g., on the water budget approach for personalized and farm-directed alerts (Singh *et al*., 2023; Bwambale *et al*., 2022) Remote control of the irrigation system allows farmers to control irrigation and other water management systems from anywhere (especially considering the 6G wireless systems), providing timely interventions by farmers, flexibility, and efficiency (Kaburuan and Jayadi, 2019).

Advancements in the field of horticulture include, e.g., the design of intelligent drip irrigation network control systems, which can monitor soil humidity, air temperature, and light and provide feedback through wireless sensor networks (Chen, 2011; Jiménez and Asano, 2008; Yao *et al*., 2005; Leão *et al.*, 2020; Zhang *et al.*, 2021; Kumar *et al.*, 2024). Several studies have used soil moisture sensors for real-time optimization of irrigation systems (scheduling) in both open-field and indoor horticulture (Bwambale *et al.*, 2022). Pardossi and Incrocci, (2011) used a new generation of dielectric sensors that can also measure electrical conductivity and nutrient microenvironment for controlled fertigation. Kumar *et al*., (2024) provided a literature review on the application of IoT technologies in agriculture, including irrigation in some horticultural crops.

Horticultural crops' water use efficiency has significantly increased due to automation based on wireless sensor network technologies (Bierer *et al.*, 2023). A literature assessment on the use of wireless communication technologies (such as 5G, WiFi, and ZigBee) in agricultural irrigation control was presented by Tang *et al*., (2024). Horticulture has seen a rise in the use of emerging decision support systems that use sensor technologies to enhance and automate data collection of soil water status, screen for drought tolerance within speciality cropping systems, and adopt climate-smart, responsive irrigation programs (Bierer *et al.*, 2023; Pomoni *et al.*, 2023). Sensor technology has been utilised to maximise crop yields and water savings in crops like cabbage (Zhang and Kong, 2021), lettuce, and tomatoes (Li *et al.*, 2018).

Other Methods

Drought-Tolerant Cultivars

Many strategies have been employed to increase horticultural yield and quality while reducing the negative impacts of water stress. These include, for instance, choosing crops, varietals, and rootstock to grow plants with low water requirements. Crop improvement techniques, such as genome editing and molecular breeding, have advanced to create drought-tolerant cultivars of horticulture crops by inducing a variety of physiological, morphological, and biochemical changes (Kaldate *et al*., 2021). These advances involve, for example, genetic improvements by stimulating gene activity through nanotechnology (e.g., zinc oxide nanoparticles), adjusting levels of hormones to produce growth regulators, enhancing water uptake, improve root hydraulic conductance, and preventing oxidative damage (Hayat *et al.*, 2023). Recent studies on physiological phenotyping have monitored water relations in the soil–plant-atmosphere continuum of multiple horticultural crops under dynamic environmental conditions (Mpakairi *et al*., 2024). Physiological phenotyping is a tool used to identify and select plant traits that enhance water-use efficiency and reduce water requirements in horticultural crops. This approach involves assessing various physiological parameters of plants, such as their ability to maintain growth under water-limited conditions, their water uptake and transport mechanisms, and their overall response to drought stress (Dalal *et al*., 2019). By integrating these phenotypic traits into breeding programs, water-scarcity-resilient horticultural crops can be developed. Breeding programs have used physiological phenotyping to select for traits such as improved water use efficiency, leading to tomato, lettuce, and grape varieties that require less water (Mir *et al*., 2019).

Grafting

In horticultural crops, grafting has also been effectively utilized to reduce water stress (Grieves *et al*., 2017). In order for two plants to grow as one, their tissues must be joined. This tried-and-true method frequently uses scions chosen for particular fruit or vegetable output traits and rootstocks that can withstand drought. In the Cucurbitaceae and Solanaceae families as well as grapevines, grafting has been employed (Grieves *et al*., 2017; Yang *et al*., 2022). Grafting's capacity to increase water intake, control water loss, promote root-to-shoot communication, and offer resilience against oxidative stress brought on by drought is what makes it effective at reducing water stress. Given the effects of climate change and water shortages, this strategy is becoming more and more crucial for sustainable gardening (Coskun, 2023).

Microbial Inoculants

Adaptive microbial inoculants are increasingly recognized as effective tools for mitigating water stress in horticultural crops. These inoculants consist of beneficial microorganisms, such as bacteria, fungi, or a combination of both, that enhance plant resilience to drought. Examples of microbial inoculants include (i) arbuscular mycorrhizal fungi, widely used to enhance drought tolerance in tomatoes, peppers, and strawberries (Wahab *et al.,* 2023) (ii) plant-growth-promoting rhizobacteria for promoting root growth, enhancing nutrient uptake, and inducing systemic tolerance to drought in crops like lettuce, carrots, and cucumbers (Kaldate *et al*., 2021); and (iii) phosphate-solubilizing bacteria and rhizobium inoculation, used to improve water use efficiency in crops such as chickpea (Alharbi *et al.,* 2024). Kour *et al.,* (2022) provided a literature review on adaptive microbial inoculants for alleviation of water stress in horticultural crops. As research advances, the development and application of tailored microbial consortia could become a key strategy in sustainable horticulture, particularly in regions prone to drought.

Nanotechnology

Innovative approaches to managing water stress in horticulture are provided by nanotechnology. These include hydrogel nanocomposites, materials that improve soil water retention and release water gradually based on plant needs, silicon nanoparticles that improve drought tolerance by increasing water uptake and decreasing transpiration, and silver nanoparticles that improve plant growth under oxidative stress related to drought (Gupta *et al.,* 2023). A overview of the literature on nanotechnology-based horticultural techniques, including water stress tolerance, was given by Manzoor *et al*. (2024). A literature assessment on the application and promise of nanoparticles for enhancing plants' tolerance to drought stress was presented by Hayat *et al.,* (2023). As research progresses, these technologies are likely to become increasingly integrated into sustainable agricultural practices, helping to mitigate the effects of climate change and water scarcity on horticulture.

Conclusion and Future Prospective

A vital industry for both the global economy and food security is horticulture. In recent decades, there has been a growing social demand for horticultural crops, such as fruits, vegetables, aromatic herbs, and ornamental plants. Particularly in arid and semiarid areas, these crops demand a significant amount of water and frequently require irrigation. One major issue facing horticulture is the growing scarcity of water brought on by population expansion, climate change, and conflicting demands from other sectors (such as industry and urbanisation). Another significant obstacle to water management in horticulture is ineffective irrigation techniques. Flood irrigation and other conventional irrigation techniques are frequently linked to overwatering, nutrient leaching, and soil deterioration (such as salinisation).

A comprehensive strategy that combines sustainable agricultural methods with technological innovation to enhance water management in horticulture is needed to address water scarcity and increase water usage efficiency. However, farmers' ignorance of their crops' water needs is one of the main obstacles to effective water management in horticulture. Instead, then considering the true water requirements of crops, farmers frequently base their decisions on their assessment of crop health and water availability. The water requirements of many horticultural crops, such as lettuce and tomatoes, have been thoroughly studied. However, less is known about many other crops, particularly some ornamentals, aromatics, and perennials. Furthermore, research on agricultural water requirements is created in particular settings, and data for many locations is still insufficient (e.g., the Mediterranean). A global database about crop water requirements in different environments, easily accessible to farmers, would be useful.

By increasing the soil's capacity to hold water and decreasing evaporation losses, the use of natural solutions based on best agricultural practices such as mulching, organic amendments, and cover crops can improve soil moisture and reduce the need for water irrigation. For example, using hydrogels can cut evaporation losses by as much as 50%. Although studies of large-scale application are still limited, other methods to lessen the need for irrigation, such as approaches based on nanotechnology for water stress tolerance, seem promising. The creation of crop types resistant to drought can lessen reliance on water and sustain output in difficult circumstances. A crucial area of research is the breeding and genetic engineering of crops that can flourish in low-water environments and are more drought-resistant.

An essential component of water management in horticulture is the utilization of non-traditional water sources, which are being investigated more and more. Particularly in areas with limited water supplies, water sources like desalination and treated wastewater offer a viable substitute for freshwater resources. These sources are more costly than natural water supplies, though, and poor management can result in salt buildup, which degrades soil and lowers crop yields. For horticulture, this is a significant problem, particularly in arid and semiarid areas. Given the possibility of food contamination and the potential health effects, the quality of treated wastewater is still another significant concern for horticulture. The extent of soil degradation and food safety problems have not been sufficiently investigated. Future research should focus on developing cost-effective technologies to improve the water quality of alternative sources.

To increase horticulture's water, use efficiency, better irrigation methods are crucial. Adopting more effective technologies, such drip irrigation, can maximize water use by supplying the root zone with the right amount of water. However, to properly optimize water management, new techniques and technologies are required. In order to enhance irrigation, new research areas include automation and remote sensing. Farmers are able to optimize irrigation through the real-time integration of weather forecasts and sensor data, which provides information about the water status of crops. By adjusting irrigation schedules and spatial variability, respectively, to the unique requirements of crops, precision irrigation and smart irrigation have a great potential to increase water use efficiency. The use of IoT with 6G wireless systems has the potential to revolutionize horticulture, given the high capacity of 6G to support large-scale operations with numerous IoT devices. Other innovative tools, such as data analytics, predictive modeling, and digital twins, provide remarkable improvements in decision support systems. The practical implementation of these technologies, however, has been limited. The high cost of the technology and the complexity of implementation are barriers to the widespread adoption of these water-efficient tools. Additionally, farmers are often resistant to change their established practices. Efforts to develop more cost-effective and user-friendly technologies and tools and to educate and engage farmers will be crucial in driving the widespread adoption of water-efficient practices. Smart irrigation and the safeguarding of water resources are essential to adapt to climate change, ensure food security, and achieve some of the Sustainable Development Goals.

In order to meet the increasing demands for horticulture crops, this paper focusses on demand-driven water management, which control and reduces the demand for water through conservation practices, drought-tolerant crops, and more efficient use. However, other demand-driven strategies are also available (e.g., water pricing policies). Supply-driven tactics and actions, such as building infrastructure like dams, reservoirs, and irrigation canals to store and supply water to horticulture as needed, are also essential to effective water management in agriculture. To deal with the growing water shortage, which is made worse by both rising societal demand and climate change, and to guarantee sustainable water management which is necessary for food security a comprehensive strategy combining supply-driven and demand-driven tactics is needed.

References

Agyarko, K., Asiedu, E.K., Tachie-Menson, J. (2006). Effect of mulching materials on soil temperature, nutrient concentration, growth and yield of turmeric (*Curcuma longa*). *Int. J. Plant Prod. **2***, 63–75.

Akhtar, S.S. (2015). Biochar stimulates plant growth but not fruit yield of processing tomato in a fertile soil. *Sci. Hortic. **264***, 109184.

Alharbi, S., Felemban, A., Abdelrahim, A., Al-Dakhil, M. (2024). Agricultural and Technology-Based Strategies to Improve Water-Use Efficiency in Arid and Semiarid Areas. *Water*, ***16***, 1842

Álvarez, J., Pasian, C., Lal, R., López, R., Díaz, M., Fernández, M. (2018). Morpho-physiological plant quality when biochar and vermicompost are used as growing media replacement in urban horticulture. *Urban For. Urban Gree.*, ***34***, 175–180.

Arif, M., Jan, M.T., Khan, M.Q., Saeed, M., Khan, N.U. (2017). Biochar improves growth, physiology, and ornamental quality of Calendula (*Calendula officinalis* L.). *J. Plant Nutr. **40***, 272–281

Atzori, L., Iera, A., Morabito, G. (2010). The Internet of Things: A survey. *Comput. Netw. **54***, 2787–2805

Ayars, J., Phene, C., Hutmacher, R., Davis, K., Schoneman, R., Vail, S., Mead, R. (1999). Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. *Agric. Water Manag. **42***, 1–27.

Ayars, J.E., Christen, E.W., Hornbuckle, J. (2006). Controlled drainage for improved water management in arid regions irrigated agriculture. *Agric. Water Manag.* ***86***, 128–139.

Bai, Z., Caspari, T., Gonzalez, M.R., Batjes, N.H., Mäder, P., Bünemann, E.K., de Goede, R., Brussaard, L., Xu, M., Ferreira, C.S.S. (2018). Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. *Agric. Ecosyst. Environ.* ***265***, 1–7.

Berríos, L.R., Nielsen, K.F. (2006). Crop response to irrigation Vegetables. *Irrig. Agric. Crop.* ***33***, 791–820.

Bierer, A.M. (2023). Development of an open-source soil water potential management system for horticultural applications, “Open_Irr”. *HardwareX* , ***15***, e00458

Bogdan, A.M., Kulshreshtha, S.N. (2021). Canadian horticultural growers’ perceptions of beneficial management practices for improved on-farm water management. *J. Rural Stud.* ***87***, 77–87.

Boulet, A.K., Alarcão, C., Ferreira, C., Kalantari, Z., Veiga, A., Campos, L., Ferreira, A., Hessel, R. (2021). Agro-ecological services delivered by legume cover crops grown in succession with grain corn crops in the Mediterranean region. *Open Agric.* ***6***, 609–626

Brown, M., Bondurant, J., Brockway, C. (1981). Subsurface trickle irrigation management with multiple cropping. *Trans. ASAE*, ***24***, 1482–1489.

Bwambale, E., Abagale, F.K., Anornu, G.K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agric. Water Manag.* ***260***, 107324.

Carotti, L., Pistillo, A., Zauli, I., Meneghello, D., Martin, M., Pennisi, G., Gianquinto, G., Orsini, F. (2023). Improving water use efficiency in vertical farming: Effects of growing systems, far-red radiation and planting density on lettuce cultivation. *Agric. Water Manag.* ***285***, 108365.

Carr, M.K. (2012). *Advances in Irrigation Agronomy: Plantation Crops*, Cambridge University Press: Cambridge, UK, 2012, Volume 317.

Carrubba, A., Militello, M. (2013). Growing peppermint (*Mentha piperita* L.) in hydroponics: A review. *J. Med. Plants Res.* ***7***, 3021–3029.

Chai, Q., Gan, Y., Zhao, C., Xu, H.-L., Waskom, R.M., Niu, Y., Siddique, K.H. (2016). Regulated deficit irrigation for crop production under drought stress. A review. *Agron. Sustain. Dev.* ***36***, 3.

Chen, Y. (2011). The design of intelligent drip irrigation network control system. In Proceedings of the 2011 International Conference on Internet Technology and Applications, Wuhan, China, 16–18 August 2011, pp. 1–3.

Chen, Y., Zhang, J.-H., Chen, M.-X., Zhu, F.-Y., Song, T. (2023). Optimizing water conservation and utilization with a regulated deficit irrigation strategy in woody crops: A review. *Agric. Water Manag.* ***289***, 108523.

Consoli, S., Stagno, F., Vanella, D., Boaga, J., Cassiani, G., Roccuzzo, G. (2017). Partial root-zone drying irrigation in orange orchards, effects on water use and crop production characteristics. *Europ. J. Agron.* ***82***, 190–202.

Corato, U.D. (2020). Agricultural waste recycling in horticultural intensive farming systems by on-farmcomposting and compost-based tea application improves soil quality and plant health: A review under the perspective of a circular econom. *Sci. Total Environ.* ***738***, 139840.

Coskun, Ö.F. (2023). The Effect of Grafting on Morphological, Physiological and Molecular Changes Induced by Drought Stress in Cucumber. *Sustainability* ***15***, 875.

Dalal, A., Bourstein, R., Haish, N., Shenhar, I., Wallach, R., Moshelion, M. (2019). Dynamic Physiological Phenotyping of Drought-Stressed Pepper Plants Treated With “Productivity-Enhancing” and “Survivability-Enhancing” Biostimulants. *Front. Plant Sci.* ***10***, 905.

Devitt, D.A., Morris, R.L. (2007). Water use of landscape plants in an arid environment. *HortScience* ***42***, 68–74.

Diacono, M., Montemurro, F. (2011). Long-term effects of organic amendments on soil fertility. *Sustain. Agric.* ***2***, 761–786.

Drury, C.F., Tan, C.S., Reynolds, W.D., Welacky, T.W., Calder, W., McLaughlin, N.B. (2009). Reducing nitrate loss in tile drainage water with cover crops and water-table management systems. *J. Environ. Qual.* ***38***, 1193–1204.

Faci, J.M., Blanco, O., Medina, E.T., Martínez-Cob, A. (2014). Effect of post veraison regulated deficit irrigation in production and berry quality of autumn royal and crimson table grape cultivars. *Agric. Water Manage.* ***134***, 73–83.

Fereres, E., Evans, R.G. (2006). Irrigation of fruit trees and vines: Principles and practices. *Irrig. Agric. Crop.* ***33***, 781–808

Ferreira, C.S.S., Veiga, A., Caetano, A., Gonzalez-Pelayo, O., Karine-Boulet, A., Abrantes, N., Keizer, J., Ferreira, A.J.D. (2020). Assessment of the Impact of Distinct Vineyard Management Practices on Soil Physico-Chemical Properties. *Air Soil Water Res.* **2020**,

Feset, S.E., Strock, J.S., Sands, G.R., Birr, A.S. (2010). Controlled drainage to improve edge-of-field water quality in southwest Minnesota, USA. In Proceedings of the 9th International Drainage Symposium Held Jointly with CIGR and CSBE/SCGAB Proceedings, Québec City, QC, Canada, 13–16 June 2010, p. 1.

García-Ruiz, J.M., López-Bermúdez, F., Jordán, A. (2017). The effects of soil erosion and sediment transport on soil fertility and plant productivity. *Agriculture* ***7***, 119

Gava, O., Antón, A., Carmassi, G., Pardossi, A., Incrocci, L., Bartolini, F. (2023). Reusing drainage water and substrate to improve the environmental and economic performance of Mediterranean greenhouse cropping. *J. Clean. Prod.* ***413,*** 137510.

Genesio, L., Miglietta, F., Baronti, S., Vaccari, F.P. (2015). Biochar increases vineyard productivity without affecting grape quality: Results from a four years field experiment in Tuscany. *Agric. Ecosyst. Environ.* ***201***, 20–25.

Gholami, R., Hoveizeh, N., Zahedi, S., Arji, I. (2023). Effect of organic and synthetic mulches on some morpho-physiological and yield parameters of ‘Zard’ olive cultivar subjected to three irrigation levels in field conditions. *S. Afr. J. Bot.* ***162***, 749–760.

Gil, J., González, R., Sánchez-Molina, J., Berenguel, M., Rodríguez, F. (2023). Reverse osmosis desalination for greenhouse irrigation: Experimental characterization and economic evaluation based on energy hubs. *Desalination* ***574***, 117281.

Giuliani, M.M., Nardella, E., Gagliardi, A., Gatta, G. (2017). Deficit irrigation and partial root-zone drying techniques in processing tomato cultivated under Mediterranean climate conditions. *Sustainability* ***9***, 2197.

Glover, J.D., Reganold, J.P., Andrews, P.K. (2000). Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. *Agric. Ecosyst. Environ.**80***, 29–45

Gökalp, Z., Bulut, S. (2022). Potential use of biochar in wastewater treatment operations and soil improvement. *Curr. Trends Nat. Sci.* ***11***, 161–169.

Graber, E.R., Meller Harel, Y., Kolton, M., Cytryn, E., Silber, A., Rav David, D., Tsechansky, L., Borenshtein, M., Elad, Y. (2010). Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant Soil*, ***337***, 481–496.

Grieves, M., Vickers, J. (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems*, Springer: Cham, Switzerland, pp. 85–113

Guo, J., Zheng, L., Ma, J., Li, X., Chen, R. (2023). Mata-Analysis of the effect of subsurface irrigation on crop yield and water productivity. *Sustainability* ***15***, 15716.

Gupta, A., Rayeen, F., Mishra, R., Tripathi, M., Pathak, N. (2023). Nanotechnology applications in sustainable agriculture: An emerging eco-friendly approach. *Pant Nano Biol.**4***, 100033.

Hamilton, A., Boland, A., Stevens, D., Kelly, J., Radcliffe, J., Ziehrl, A., Dillon, P., Paulin, B. (2005). Position of the Australian horticultural industry with respect to the use of reclaimed water. *Agric. Water Manag.* ***71***, 181–209.

Hartwig, N.L., Ammon, H.U. (2002). Cover crops and living mulches. *Weed Sci.* ***50***, 688–699.

Hayat, F., Khanum, F., Li, J., Iqbal, S., Khan, U., Javed, H.U., Razzaq, M.K., Altaf, M.A., Peng, Y., Ma, X., *et al*. (2023). Nanoparticles and their potential role in plant adaptation to abiotic stress in horticultural crops: A review. *Sci. Hortic.* ***321***, 112285.

Herrero-Hernández, E., Simón-Egea, A.B., Sánchez-Martín, M.J., Rodríguez-Cruz, M.S., Andrades, M.S. (2020). Monitoring and environmental risk assessment of pesticide residues and some of their degradation products in natural waters of the Spanish vineyard region included in the Denomination of Origin Jumilla. *Environ. Poll.*, ***264***, 114666.

Hossain, M.D., Ryu, K.N. (2009). Effects of mulching on yield, quality and soil properties in strawberry. *Sci. Hortic*, ***124***, 282–286.

Incrocci, L., Massa, D., Pardossi, A. (2017). New trends in the fertigation management of irrigated vegetable crops. *Horticulturae*, ***3***, 37.

Jiménez, B., Asano, T. (2008). *Water Reuse: An International Survey of Current Practice, Issues and Needs*, IWA Publishing: London, UK.

Kaburuan, E.R., Jayadi, R. (2019). A Design of IoT-based Monitoring System for Intelligence Indoor Micro-Climate Horticulture Farming in Indonesia. *Procedia Comput. Sci.*, ***157***, 459–464

Kaldate, R., Singh, S., Guleria, G., Soni, A., Aikwad, D., Kumar, N., Meshram, S., Rana, M. (2021). Current approaches in horticultural crops to mitigate the effect of drought stress. *Stress Toler. Hortic. Crop.*, ***13***, 213–240.

Kang, J., Hao, X., Zhou, H., Ding, R. (2021). An integrated strategy for improving water use efficiency by understanding physiological mechanisms of crops responding to water deficit: Present and prospect. *Agric. Water Manag.*, ***255***, 107008.

Kavitha, B., Reddy, P.V.L., Kim, B., Lee, S.S., Pandey, S.K., Kim, K.-H. (2018). Benefits and limitations of biochar amendment in agricultural soils: A review. *J. Environ. Manag.*, ***227***, 146–154.

Keates, O. (2023). Actionable insights for horticulture supply chains through advanced IoT analytics. *Procedia Comput. Sci.*, ***217***, 1631–1640.

Khan, F.A. (2018). A review on hydroponic greenhouse cultivation for sustainable agriculture. *Int. J. Agric. Environ. Food Sci.*, ***2***, 59–66.

Koukounaras, A. (2020). Advanced greenhouse horticulture: New technologies and cultivation practices. *Horticulturae*, *7*, 1.

Kour, D., Khan, S., Kaur, T., Kour, H., Singh, G., Yadav, A., Yadav, A. (2022). Drought adaptive microbes as bioinoculants for the horticultural crops. *Heliyon*, *8*, e09493.

Kuehny, J.S., Bowers, R. (2006). Mulch effects on evapotranspiration and growth of herbs in container production. *J. Plant Nutr.* ***29***, 585–600

Kumar, V., Sharma, K., Kedam, N., Patel, A., Kate, T., Rathnayake, U. (2024). A comprehensive review on smart and sustainable agriculture using IoT technologies. *Smart Agric. Techn.* ***8***, 100487.

Lakhiar, I., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., Han, Y., Wang, B., Bao, R., Syed, T., *et al*. (2024). A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints. *Agriculture*, ***14***, 1141.

Lamm, F.R., Stone, K., Dukes, M., Howell, T., Robbins, J., Mecham, B. (2015). Emerging technologies for sustainable irrigation: Selected papers from the 2015 ASABE and IA irrigation symposium. *Trans. ASABE*, ***59***, 155–161

Lanari, N., Schuler, R., Kohler, T., Liniger, H. (2018). The Impact of Commercial Horticulture on River Water Resources in the Upper Ewaso Ng'iro River Basin, Kenya. *Mt. Res. Dev.*, ***38***, 114–124

Leão, T., Costa, B., Bufon, V., Aragón, F. (2020). Using time domain reflectometry to estimate water content of three soil orders under savanna in Brazil. *Geoderma Reg.*, ***21***, e00280. [

Lephondo, A., Telukdariea, A., Muniena, I., Onkonkwoa, U., Vermeulena, A. (2024). The Outcomes of Smart Irrigation System using Machine Learning to minimize water usage within the Agriculture Sector Itumeleng. *Procedia Comput. Sci.* ***237***, 525–532.

Li, Y., Liu, P., Li, B. (2018). Water and fertilizer integration intelligent control system of tomato based on internet of things. In Proceedings of the Cloud Computing and Security: 4th International Conference, ICCCS 2018, Haikou, China, 8–10 June 2018, Revised Selected Papers, Part VI 4. Springer International Publishing: Berlin/Heidelberg, Germany, pp. 209–220.

Liao, Y., Cao, H.-X., Liu, X., Li, H.-T., Hu, Q.-Y., Xue, W.-K. (2021). By increasing infiltration and reducing evaporation, mulching can improve the soil water environment and apple yield of orchards in semiarid areas. *Agric. Water Manag.*, ***253***, 106936.

Loveys, B., Stoll, M., Davies, W. (2004). Physiological approaches to enhance water use efficiency in agriculture: Exploiting plant signalling in novel irrigation practice. In *Water Use Efficiency in Plant Biology*, Wiley: Hoboken, NJ, USA, pp. 113–141.

Ludwig-Ohm, S., Hildner, P., Isaak, M., Dirksmeyer, W., Schattenberg, J. (2023). The contribution of Horticulture 4.0 innovations to more sustainable horticulture. *Procedia Comput. Sci.*, ***217***, 465–477.

Manzoor, M., Xu, Y., Iv, Z., Xu, J., Shah, I., Sabir, I., Wang, Y., Sun, W., Liu, X., Wang, L., *et al*. (2024). Horticulture crop under pressure: Unraveling the impact of climate change on nutrition and fruit cracking. *J. Environ. Mang.*, ***357***, 120759.

McDonald, E.M., Linde, C. (2022). The impact of sprinkler irrigation on the development of foliar diseases in horticultural crops. *Australas. Plant Pathol.*, ***31***, 117–123.

Mir, R., Reynolds, M., Pinto, F., Khan, M., Bhat, M. (2019). High-throughput phenotyping for crop improvement in the genomics era. *Plant Sci.*, ***282***, 60–72.

Mohammed, A., Oloyede, F.M., Adeniran, O.M. (2020). Effect of cover cropping on soil properties and growth performance of basil (*Ocimum basilicum*) in a derived savanna ecology. *Acta Hortic.* ***1273***, 341–348.

Molden, D. (2007). *Water for Food, Wate for Life: A Comprehensive Assessment of Water Management*, Routledge: London, UK, 2007, ISBN 978-1-84407-397-9.

Montague, T., Kjelgren, R., Rupp, L., Allen, R. (2007). Tree growth and aesthetics for different mulch types in a landscape setting. *Arboric. Urban For.* ***33***, 343–349.

Mpakairi, K., Dube, T., Sibanda, M., Mutanga, O. (2024). Remote sensing crop water productivity and water use for sustainable agriculture during extreme weather events in South Africa. *Int. J. Appl. Earth Obs. Geoinf.* ***129***, 103833.

Muleke, A., Harrison, M.T., Eisner, R., Voil, P., Yanotti, M., Liu, K., Monjardino, M., Yin, X., Wang, W., Nie, J., *et al*. (2023). Sustainable intensification with irrigation raises profit despite burgeoning climate emergency. *Plants People Planet* ***5***, 368–385.

Mwinuka, P.R., Mourice, S.K., Mbungu, W.B., Mbilinyi, B.P., Tumbo, S.D., Schmitter, P. (2022). UAV-based multispectral vegetation indices for assessing the interactive effects of water and nitrogen in irrigated horticultural crops production under tropical sub-humid conditions: A case of African eggplant. *Agric. Water Manag.* ***266***, 107516.

Nikolaou, G., Neocleous, D., Christou, A., Kitta, E., Katsoulas, N. (2020). Implementing Sustainable Irrigation in Water-Scarce Regions under the Impact of Climate Change. *Agronomy* ***10***, 1120

O'Neill, M.P., Dobrowolski, J.P. (2011). Water and agriculture in a changing climate. *HortScience* ***46***, 155–157.

Oron, G., DeMalach, J., Hoffman, Z., Cibotaru, R. (1991). Subsurface microirrigation with effluent. *J. Irrig. Drain. Eng.* ***117***, 25–36.

Ortiz-Liébana, N., Zotti, M., Barquero, M., González-Andrés, F. (2023). Biochar + AD exerts a biostimulant effect in the yield of horticultural crops and improves bacterial biodiversity and species richness in the rhizosphere. *Sci. Hortic.* ***321***, 112277.

Pomoni, D.I., Koukou, M.K., Vrachopoulos, M.G., Vasiliadis, L. (2023). A review of hydroponics and conventional agriculture based on energy and water consumption, environmental impact, and land use. *Energies* ***16***, 1690.

Pomoni, D.I., Koukou, M.K., Vrachopoulos, M.G., Vasiliadis, L. (2023). A review of hydroponics and conventional agriculture based on energy and water consumption, environmental impact, and land use. *Energies* ***16***, 1690.

Qin, Y., Mueller, N.D., Siebert, S., Jackson, R.B., AghaKouchak, A., Zimmerman, J.B., Tong, D., Hong, C., Davis, S.J. (2019). Flexibility and intensity of global water use. *Nat. Sustain.* ***2***, 515–523.

Ronga, D., Francia, E., Allesina, G., Pedrazzi, S., Pane, C., Francia, M., Lovelli, S. (2016). Using compost in horticulture: A tool to increase sustainability. *Agroecol. Sustain. Food Syst.* ***40***, 1–23.

Rowland, L., Smith, H., Taylor, G. (2018). The potential to improve culinary herb crop quality with deficit irrigation. *Sci. Hortic.* ***242***, 44–50.

Russo, T., Alfredo, K., Fisher, J. (2014). Sustainable Water Management in Urban, Agricultural, and Natural Systems. *Water* ***6***, 3934–3956.

Savic, S., Stikic, R., Zaric, V., Vucelic-Radovic, B., Jovanovic, Z., Marjanovic, M., Djordjevic, S., Petkovic, D. (2011). Deficit irrigation technique for reducing water use of tomato under polytunnel conditions. *J. Cent. Eur. Agric.* ***12***, 597–607.

Scharwies, J.D., Dinneny, J.R. (2019). Water transport, perception, and response in plants. *J. Plant Res.* ***132***, 311–324

Sebastian, K., Bindu, B., Rafeekher, M. (2021). Performance of papaya variety 'Surya'under fertigation and foliar nutrition. *Plant Sci. Today* ***8***, 718–726

Seema Dahiya, R., Prakash, R., Roohi Sheoran, H.S. (2022). Drip Irrigation as a Potential Alternative to Traditional Irrigation Method for Saline Water Usage in Vegetable Crops- A Review. *Int. J. Econ. Plants* ***9***, 115–120.

Senapti, S., Santosh, D., Pholane, L. (2021). Techno economic feasibility of drip irrigation for vegetable cultivation. *Int. J. Agric. Sci.* ***17***, 636–643

Sevik, H., Cetin, M. (2015). Effects of Water Stress on Seed Germination for Select Landscape Plants. *Pol. J. Environ. Stud.* ***24***, 689–693.

Shahnazari, A., Liu, F., Andersen, M.N., Jacobsen, S.E., Jensen, C.R. (2007). Effects of partial root-zone drying on yield, tuber size, and water use efficiency in potato under field conditions. *Field Crop. Res.* ***100***, 117–124.

Simonne, E.H., Hochmuth, G.J., Dukes, M.D., Pitts, D.J. (2005). *Irrigation Management for Vegetable Crops in Florida*, University of Florida IFAS Extension: Homestead, FL, USA, 2005.

Singh, D., Biswal, A., Samanta, D., Singh, V., Kadry, S., Khan, A., Nam, Y. (2023). Smart high-yield tomato cultivation: Precision irrigation system using the Internet of Things. *Front. Plant Sci.* ***14***, 1239594.

Singh, R., Sharma, R.R. (2003). Effects of various organic soil amendments on growth, yield and quality of strawberry. *Biol. Agric. Hortic.* ***21***, 37–48.

Singh, R., Singh, B. (1992). Effect of different irrigation methods on growth and yield of mint (*Mentha arvensis* L.). *J. Herbs Spices Med. Plants* ***1***, 45–51.

Steenwerth, K., Belina, K. (2008). Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. *Appl. Soil Ecol.* ***40***, 359–369.

Stefanelli, D., Goodwin, I., Jones, R. (2010). Minimal nitrogen and water use in horticulture: Effects on quality and content of selected nutrients. *Food Res. Int.* ***43***, 1833–1843.

Strik, B.C., Buller, G. (2005). The impact of early cropping on subsequent growth and yield of highbush blueberry. *HortScience* ***40***, 1998–2001.

Strock, J.S., Dell, C.J., Schmidt, J.P. (2007). Drainage water management for water quality protection. *J. Soil Water Conserv.* ***62***, 144A–153A.

Tang, P., Liang, Q., Li, H., Pang, Y. (2024). Application of Internet-of-Things Wireless Communication Technology in Agricultural Irrigation Management: A Review. *Sustainability* ***16***, 3575.

Touil, S., Richa, A., Fizir, M., García, K., Gómez, A. (2022). A review on smart irrigation management strategies and their effect on water savings and crop yield. *Irrig. Drain.* ***71***, 1396–1416.

USDAID, (2005) ISHS. *Global Horticulture Assessment*, International Society for Horticultural Science: Leuven, Belgium, 2005, ISBN 9066053674

Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., Reddy, S.P.P. (2023). Role of Arbuscular Mycorrhizal Fungi in Regulating Growth, Enhancing Productivity, and Potentially Influencing Ecosystems under Abiotic and Biotic Stresses. *Plants* ***12***, 3102.

Wang, Q., Klassen, W., Li, Y. (2009). Influence of cover crops and organic mulches on soil properties and the growth of bell pepper. *HortTechnology* ***19***, 58–64

Wavhal, E., Giri, M. (2014). Intelligent Drip irrigation system using linear programming and interpolation methodology. *Int. J. Comput.* ***2306***, 1–11.

Webb, L., Darbyshire, R., Goodwin, I. (2014). Climate Change: Horticulture. *Encycl. Agric. Food Syst.* ***2,*** 266–283.

Wen, S., Cui, N., Wang, Y., Gong, D., Xing, L., Wu, Z., Zhang, Y., Zhao, L., Fan, J., Wang, Z. (2024). Optimizing deficit drip irrigation to improve yield, quality, and water productivity of apple in Loess Plateau of China. *Agric.Water Manag.* ***296***, 108798.

Xudayev, I., Fazliev, J.S., Ayusupova, A. (2021). Water saving up-to-date irrigation technologies. *IOP Conf. Ser. Earth Environ. Sci.* ***868***, 12–14.

Yactayo, W., Ramírez, D.A., Gutiérrez, R., Mares, V., Posadas, A., Quiroz, R. (2013). Effect of partial root-zone drying irrigation timing on potato tuber yield and water use efficiency. *Agric. Water Manage.*, ***123***, 65–70.

Yang, L., Xia, L., Zeng, Y., Han, Q., Zhang, S. (2022). Grafting enhances plants drought resistance: Current understanding, mechanisms, and future perspectives. *Front. Plant Sci.* ***13***, 1015317

Yao, S., Merwin, I.A., Bird, G.W., Abawi, G.S., Thies, J.E. (2005). Orchard floor management practices that build soil quality and improve tree performance. *HortScience* ***40***, 2101–2106.

Zhang, J., Xiang, L., Liu, Y., Jing, D., Zhang, L., Liu, Y., Li, W., Wang, X., Li, T., Li, J. (2024). Optimizing irrigation schedules of greenhouse tomato based on a comprehensive evaluation model. *Agric. Water Manag.* ***295,*** 108741.

Zhang, L.L., Kong, G.L. (2021). Design of farmland irrigation water quality monitoring and control system based on DSP and ZigBee. *Agric. Mech. Res.* ***43,*** 229–232.

Zhang, L.L., Kong, G.L. (2021). Design of farmland irrigation water quality monitoring and control system based on DSP and ZigBee. *Agric. Mech. Res.* ***43***, 229–232.

Zhang, M., Han, Y., Li, D., Xu, S., Huang, Y. (2023). Smart Horticulture as an Emerging Interdisciplinary Field Combining Novel Solutions: Past Development, Current Challenges, and Future Perspectives. *Hortic. Plant J.* **2023**.

Zinkernagel, J., Maestre-Valero, J.F., Seresti, S.Y., Intrigliolo, D.S. (2020). New technologies and practical approaches to improve irrigation management of open field vegetable crops. *Agric. Water Manag.* ***242***, 106404.