# Advanced Precision Irrigation Techniques for Enhanced Protected Cultivation Systems

## Abstract:

Precision irrigation techniques have revolutionized protected cultivation systems worldwide by optimizing water use efficiency, reducing resource consumption, and enhancing crop yield and quality.Key technologies covered include drip irrigation, micro-sprinklers, subsurface irrigation, sensors for monitoring soil moisture and crop water status, automated irrigation scheduling software, and the integration of these tools with fertigation systems. Case studies from leading horticultural regions illustrate best practices and the benefits of precision irrigation, such as water savings of 40-70%, fertilizer reductions of 30-50%, and yield improvements of 20-40% compared to conventional irrigation. However, challenges remain in terms of high initial costs, maintenance requirements, and the need for grower training and technical support. In Asia and India, government initiatives and public-private partnerships are driving the expansion of protected cultivation with precision irrigation to boost productivity, conserve resources, ensure food security, and increase smallholder incomes. Future directions emphasize sensor-based automation, data-driven decision support systems, crop-specific precision irrigation strategies, and the integration of precision irrigation with other technologies like hydroponics, vertical farming, and renewable energy to further enhance the sustainability and profitability of protected cultivation.

**Keywords:**Precision Irrigation, Protected Cultivation, Greenhouse Horticulture, Water Use Efficiency, Sensors

## Introduction

Precision irrigation techniques have emerged as a critical tool for enhancing the productivity, efficiency, and sustainability of protected cultivation systems worldwide [1]. In the context of protected cultivation, where crops are grown in greenhouses, high tunnels, or other controlled environments, precision irrigation becomes even more important due to the intensive nature of production, the high value of crops, and the need to maximize resource use efficiency [2-3]. In 2020, the precision irrigation market was valued at USD 8.50 billion and is projected to reach USD 20.99 billion by 2026, at a CAGR of 16.3% during the forecast period [4]. Protected cultivation, including greenhouse horticulture, is a key application segment for precision irrigation technologies, accounting for over 30% of the global market share [5].

Asia and India are among the fastest-growing regions for precision irrigation adoption in protected cultivation. With a large and expanding population, limited arable land, and increasing pressure on water resources, these regions are turning to protected cultivation as a means to ensure food security, increase agricultural productivity, and improve farmers' incomes [6]. Governments and private sector players are investing heavily in the development of greenhouse and precision irrigation infrastructure, supported by policies, subsidies, and research and development initiatives [7].

## Global Overview of Precision Irrigation in Protected Cultivation

Protected cultivation, including greenhouse horticulture, has emerged as a key strategy for increasing agricultural productivity, quality, and profitability while minimizing the environmental impact of crop production [8 to11].

**The scope of precision irrigation in protected cultivation encompasses a wide range of technologies and practices, including:**

- Drip irrigation systems that deliver water and nutrients directly to the root zone of plants through a network of pipes, emitters, and filters [12].
- Micro-sprinklers and foggers that provide localized irrigation and humidity control in greenhouses [13].
- Substrate moisture sensors that monitor the water content and availability in soilless growing media [14].
- Plant-based sensors that measure indicators of crop water status, such as stem diameter variations or leaf temperature [15].
- Automated irrigation controllers that adjust irrigation schedules based on sensor feedback and weather data [16].
- Fertigation systems that integrate precision irrigation with nutrient management to optimize crop nutrition [17].
- Data analytics and decision support tools that help growers interpret sensor data and make informed irrigation decisions [18].

Studies have shown that precision irrigation can reduce water use by 40-70% compared to conventional irrigation methods, while increasing crop yields by 20-40% [19-22]. Precision irrigation also enables more efficient use of fertilizers, as nutrients can be delivered directly to the root zone in synchrony with plant uptake, reducing leaching and runoff [23-27].These include:

- Government policies and subsidies that support the adoption of precision irrigation technologies, such as tax incentives, low-interest loans, or grants for equipment purchases [28].
- Public-private partnerships that bring together research institutions, technology providers, and growers to develop and disseminate precision irrigation solutions adapted to local needs and conditions [29].
- Capacity building and training programs that provide growers with the knowledge and skills needed to effectively implement and manage precision irrigation systems [30].
- Research and development initiatives that focus on improving the performance, affordability, and user-friendliness of precision irrigation technologies, such as low-cost sensors, wireless communication protocols, or mobile apps for irrigation scheduling [31].
- Market-based incentives that reward growers for adopting precision irrigation and other sustainable practices, such as certification schemes, premium prices, or payments for ecosystem services [32].

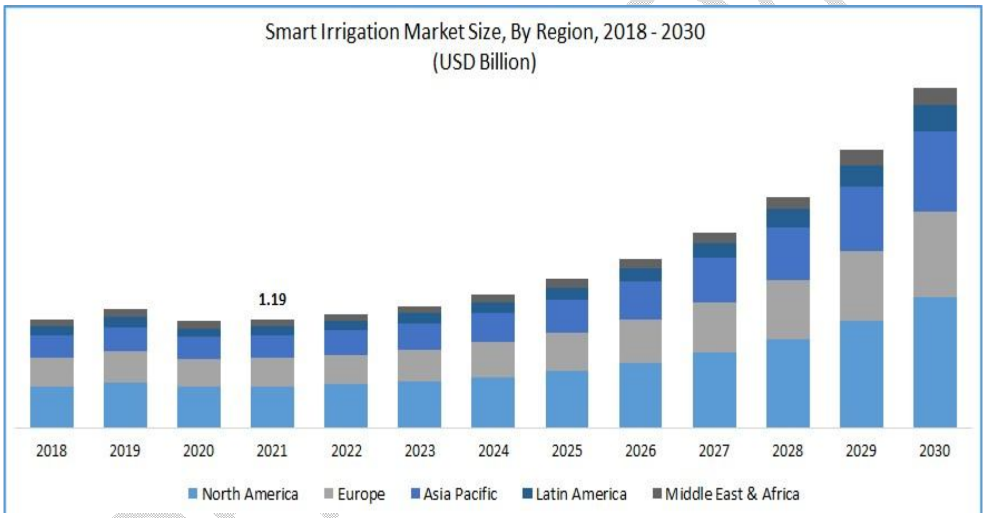
**Table 1. Global adoption of precision irrigation in protected cultivation by region and crop type.**

| Region | Greenhouse Area | Precision Irrigation | Main Crops |
|---|---|---|---|

|  | (ha) | Adoption (%) |  |
|---|---|---|---|
| Europe | 175,000 | 60-80% | Tomato, pepper, cucumber, herbs |
| North America | 25,000 | 50-70% | Tomato, lettuce, berries, flowers |
| Asia | 450,000 | 30-50% | Tomato, cucumber, strawberry, melon |
| Latin America | 20,000 | 20-40% | Tomato, pepper, flower, medicinal plants |
| Africa | 30,000 | 10-30% | Rose, tomato, cucumber, herbs |
| Oceania | 5,000 | 40-60% | Tomato, cucumber, lettuce, herbs |

**Sources:** [33], [34], [35], [36]. [37].

**Figure 1. Global precision irrigation market size and growth forecast by application, 2020-2026 (USD Billion).**



## Precision Irrigation Techniques

Precision irrigation in protected cultivation involves a range of techniques and technologies designed to deliver water and nutrients to crops in a highly controlled and efficient manner. These techniques can be broadly classified into three categories: drip irrigation, micro-irrigation, and substrate-based irrigation [38-39].

### 3.1. Drip Irrigation

Drip irrigation involves the slow and frequent application of water and nutrients directly to the root zone of plants through a network of pipes, emitters, and drippers [40-42].

### 3.1.1. Surface Drip Irrigation

**Surface drip systems typically consist of the following components:**

- A water source, such as a well, reservoir, or municipal supply, equipped with a pump and filtration system to prevent clogging of the emitters [43-44].
- A main line that conveys the water from the source to the field, usually made of PVC or polyethylene pipes [45].
- Submains and laterals that distribute the water across the field, with emitters or drippers spaced at regular intervals to match the plant spacing [46].
- Pressure regulators and valves that maintain a constant operating pressure and allow for zoning and automation of the irrigation system [47].
- Optional components such as fertilizer injectors, water meters, and sensors that enable fertigation and monitoring of the irrigation performance [48].

Surface drip irrigation is suitable for a wide range of protected cultivation systems, including row crops, raised beds, and potted plants [49-51].

**Table 2. Comparison of surface drip irrigation and traditional irrigation methods for tomato production in greenhouses.**

| **Irrigation Method** | **Water Use (L/plant/season)** | **Yield (kg/plant)** | **Water Use Efficiency (kg/m^3^)** |
|---|---|---|---|
| Surface Drip | 150-200 | 8-12 | 40-60 |
| Furrow | 400-600 | 6-10 | 10-20 |
| Sprinkler | 300-500 | 7-11 | 15-30 |

Sources: [52], [53], [54].

### 3.1.2. **Subsurface Drip Irrigation**

Subsurface drip irrigation (SDI) is a variation of drip irrigation where the emitters are buried below the soil surface, typically at depths of 5 to 45 cm depending on the crop root zone and soil properties [55].

**SDI offers several advantages over surface drip irrigation, including:**

- Reduced evaporation losses, as the soil surface remains dry and the water is applied directly to the root zone [56 and 68].
- Reduced weed growth, as the lack of surface wetting minimizes the germination and survival of weed seeds [57].
- Improved fertilizer use efficiency, as the nutrients are placed in the root zone and are less prone to leaching or runoff [58 and 69].
- Enhanced crop quality, as the dry soil surface reduces the incidence of fruit rot and other diseases associated with wet foliage [59].
- Increased system longevity, as the buried emitters are protected from damage by UV radiation, pests, and cultural practices such as pruning or harvesting [60 and 70].

**However, SDI also presents some challenges and limitations, such as:**

- Higher installation costs, as the emitters need to be buried and the system requires careful design and management to prevent clogging and ensure uniform water distribution [61-62].
- Difficulty in monitoring and maintaining the system, as the emitters are not visible and any leaks or malfunctions may go unnoticed until crop symptoms appear [63-64].
- Limited suitability for shallow-rooted crops or those with high water requirements, as the emitter depth and spacing may not match the crop needs [65-66].
- Potential for root intrusion and clogging of the emitters, especially in fine-textured soils or with poor water quality [66-67].

### 3.2. **Micro-sprinklers**

Micro-sprinklers are another type of precision irrigation technique used in protected cultivation, especially for crops with high water requirements or those grown in substrates with low water-holding capacity [71-72].

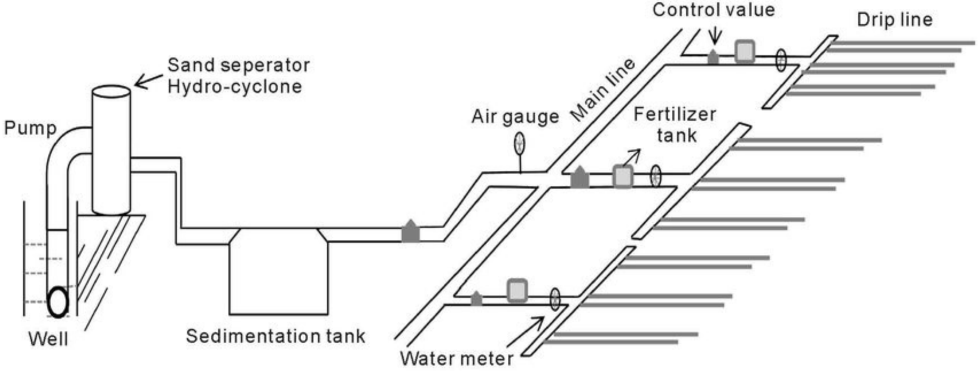


**Figure 2. Schematic diagram of a subsurface drip irrigation system in a greenhouse. Source: [70].**

**Compared to drip irrigation, micro-sprinklers have the following advantages:**

- Better coverage and uniformity, as the water is distributed over a larger area and can reach the entire root zone of the crop [73-74].
- Enhanced microclimate control, as the evaporative cooling effect of the mist can reduce the air and leaf temperature and increase the relative humidity in the greenhouse [75-76].
- Reduced clogging and maintenance, as the larger nozzle size and higher flow velocity of micro-sprinklers make them less prone to blockage by particles or biofilm [77-78].
- Versatility and adaptability, as micro-sprinklers can be used for a wide range of crops and growing systems, from tree crops to potted plants, and can be easily moved or adjusted to match the changing crop needs [79-80].

**To maximize the benefits and minimize the drawbacks of micro-sprinklers, some best practices include:**

- Using micro-sprinklers with adjustable nozzles and flow rates, and matching the sprinkler type and spacing to the crop architecture and water needs [81].
- Installing the micro-sprinklers at the correct height and orientation, and using stakes or hangers to keep them stable and prevent damage to the crop [82].
- Scheduling the irrigation based on the crop evapotranspiration and substrate moisture, and using sensors or models to optimize the irrigation frequency and duration [83].
- Combining micro-sprinklers with other irrigation methods, such as drip or subsurface irrigation, to provide a more efficient and targeted water delivery to the root zone [84].
- Implementing disease management strategies, such as pruning, ventilation, or fungicide applications, to reduce the risk of foliar diseases associated with micro-sprinkler irrigation [85].

**Table 3. Comparison of micro-sprinkler and drip irrigation for rose production in greenhouses.**

| Irrigation Method | Water Use (L/plant/day) | Yield (stems/plant/year) | Disease Incidence (%) |
|---|---|---|---|
| Micro-sprinkler | 2-4 | 200-250 | 10-20 |
| Drip | 1-2 | 180-220 | 5-10 |

Sources: [86], [87], [88].

### 3.3. **Capillary Mats and Wicks**

Capillary mats and wicks are a type of precision irrigation technique that relies on the capillary action of water to deliver moisture to the plant roots [89]. Capillary mats are thin, porous materials made of synthetic fibers or foam that are placed under the plant containers and connected to a water reservoir [90-92].

**Capillary mats and wicks have several advantages for protected cultivation, such as:**

- Low cost and simplicity, as they require minimal equipment and can be easily installed and maintained by unskilled labor [93].
- Water and nutrient efficiency, as the capillary action delivers the water directly to the root zone and minimizes losses by evaporation or leaching [94].
- Uniform moisture distribution, as the porous material provides a consistent water supply to all the plants, regardless of their position or size [95].
- Reduced disease risk, as the absence of water on the foliage and the use of well-drained substrates minimize the growth and spread of pathogens [96].
- Suitability for small-scale and hobby growers, as capillary mats and wicks can be used in greenhouses, grow rooms, or even indoors, without the need for electricity or plumbing [97].

**However, capillary mats and wicks also have some limitations and challenges, such as:**

- Limited water holding capacity, as the porous material can only store a finite amount of water and may require frequent refilling or a large reservoir for long-term use [98].

- Sensitivity to water quality, as the presence of salts, algae, or other contaminants in the water can clog the pores and reduce the capillary action over time [99].
- Difficulty in controlling the moisture level, as the capillary action depends on the substrate properties and the evaporative demand, and may result in over- or under-watering if not properly managed [100].
- Incompatibility with some growing media, such as coarse or water-repellent substrates that do not allow for good capillary contact or water retention [101].
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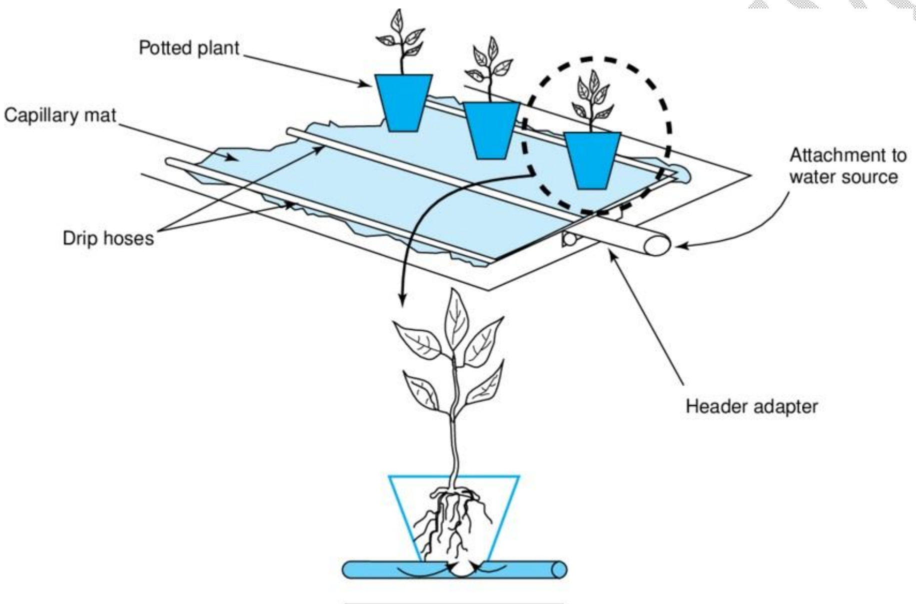

**Figure 3. Diagram of a capillary mat irrigation system for potted plants in a greenhouse.**

**To overcome these limitations and optimize the use of capillary mats and wicks, some best practices include:**

- Choosing high-quality, durable, and inert materials for the mats and wicks, such as polyester, polypropylene, or fiberglass, and avoiding materials that can degrade or release toxins over time [102].
- Using compatible and well-draining growing media, such as peat moss, coir, perlite, or vermiculite, and ensuring good contact between the mat/wick and the substrate [103].
- Monitoring the water level and quality in the reservoir, and using filters, disinfectants, or nutrients as needed to maintain a clean and balanced supply [104].
- Adjusting the mat/wick size and spacing to the plant size and water needs, and using multiple mats/wicks for larger containers or higher evaporative demand [105].

- Combining capillary mats and wicks with other irrigation methods, such as drip or sprinklers, to provide additional water and nutrients as needed, especially during peak growth stages or stress periods [106-107].

**3.4.Hydroponic Systems with Precision Irrigation** Hydroponic systems are a type of protected cultivation where the plants are grown in a nutrient solution instead of soil, with the roots either suspended in the solution or supported by an inert medium such as rockwool, perlite, or coconut fiber [108].

**Hydroponic systems offer several advantages over soil-based cultivation, such as:**

- Higher yields and quality, as the plants have access to an optimal and balanced supply of water and nutrients, and are not limited by soil-borne pests or diseases [109].
- Faster growth and shorter cycles, as the plants can allocate more resources to vegetative and reproductive growth, and are not stressed by fluctuations in soil moisture or temperature [110].
- Greater water and nutrient efficiency, as the solution is recirculated and reused, and the nutrients are precisely delivered to the roots based on the crop needs [111].
- Reduced environmental impact, as the closed-loop systems minimize the leaching and runoff of water and nutrients, and the absence of soil eliminates the need for fumigation or herbicides [112].

**However, hydroponic systems also have some challenges and requirements, such as:**

- Higher initial and operational costs, as the systems require specialized equipment, materials, and infrastructure, and consume more energy and labor than soil-based cultivation [113].
- Greater technical complexity and management skills, as the growers need to monitor and control multiple parameters such as pH, EC, temperature, oxygen, and nutrient ratios, and respond to any deviations or malfunctions in a timely manner [114].
- Dependence on external inputs and resources, as the systems rely on a constant supply of water, electricity, and fertilizers, and are vulnerable to disruptions or shortages in these inputs [115].
- Limited buffer capacity and resilience, as the plants are more sensitive to stresses or imbalances in the root zone, and any mistakes or failures in the system can quickly lead to crop damage or loss [116-117].

**Some common precision irrigation techniques used in hydroponic systems include:**

- Drip irrigation, where the nutrient solution is delivered to each plant or container through a network of emitters and tubes, with the flow rate and frequency adjusted based on the crop water use and growth stage [118].
- Ebb and flow irrigation, where the plants are periodically flooded with the nutrient solution and then drained back to a reservoir, with the timing and duration of the cycles optimized based on the substrate properties and the crop requirements [119].

- Nutrient film technique (NFT), where the plants are grown in channels or tubes with a thin film of nutrient solution flowing over the roots, with the flow rate and composition adjusted based on the crop uptake and environmental conditions [120].
- Aeroponics, where the roots are suspended in air and misted with the nutrient solution at regular intervals, with the droplet size and frequency optimized based on the root morphology and the crop water stress [121- 122].

**Some examples of these tools include:**

- pH and EC sensors that measure the acidity and salinity of the nutrient solution, and trigger the addition of acids, bases, or fertilizers to maintain the optimal ranges for the crop [123].
- Dissolved oxygen sensors that monitor the oxygen level in the solution and activate aeration or oxygenation systems to prevent root hypoxia or anoxia [124].
- Temperature sensors that control the heating or cooling of the solution to maintain the optimal root zone temperature for the crop growth and development [125].
- Moisture sensors that detect the water content or matric potential in the substrate and adjust the irrigation frequency or duration to prevent over- or under-watering [126].
- Spectral sensors that assess the crop health and nutrient status based on the leaf color or reflectance, and guide the fertigation and crop management decisions [127].
- Automated control systems that integrate the sensor data and the crop models to optimize the irrigation and nutrient delivery based on the environmental conditions and the crop growth stage [128].

**Table 4. Comparison of different hydroponic systems with precision irrigation for lettuce production.**

| **Hydroponic System** | **Water Use Efficiency (kg/L)** | **Yield (kg/m^2^/cycle)** | **Nutrient Use Efficiency (%)** |
|---|---|---|---|
| Drip irrigation | 20-30 | 5-8 | 70-90 |
| Ebb and flow | 15-25 | 4-7 | 60-80 |
| NFT | 25-35 | 6-9 | 80-95 |
| Aeroponics | 30-40 | 7-10 | 85-100 |

Sources: [129], [130], [131], [132].

## 4. Sensors and Monitoring Tools

Sensors and monitoring tools are essential components of precision irrigation systems in protected cultivation, as they provide real-time data on the crop, substrate, and environmental conditions that can be used to optimize the irrigation scheduling and management [133]. By using sensors to monitor key parameters such as soil moisture, nutrient content, plant water status, and microclimate, growers can make informed decisions on when, where, and how much to irrigate, based on the actual needs of the crop rather than fixed schedules or visual assessments [134]. This data-driven approach to irrigation can lead to significant improvements in water and nutrient use efficiency, crop yield and quality, and resource conservation, as well as reduced labor and energy costs [135-137].

**Some common types of sensors used in precision irrigation are described below.**

## 4.1. **Soil Moisture Sensors**

Soil moisture sensors are devices that measure the water content or potential in the growing medium, which can be soil, substrate, or hydroponic solution [138]. Soil moisture sensors provide direct feedback on the irrigation status and can be used to trigger or stop irrigation events based on predefined thresholds or setpoints [139].

**There are several types of soil moisture sensors, including:**

### 4.1.1. **Tensiometers**

Tensiometers are sensors that measure the soil water potential, which is the force required to extract water from the soil pores [140]. Tensiometers consist of a porous ceramic cup filled with water and connected to a pressure gauge or transducer [141]. As the soil dries out, the water in the cup is pulled out, creating a suction that is measured by the gauge [142]. Tensiometers are simple and reliable sensors that can be used to monitor the soil moisture status and schedule irrigation based on the crop- and soil-specific thresholds [143]. However, they have a limited measurement range and require regular maintenance and refilling to function properly [144].

### 4.1.2. **Capacitance and Time-Domain Reflectometry Sensors**

Capacitance and time-domain reflectometry (TDR) sensors are electronic devices that measure the soil water content by detecting the changes in the dielectric properties of the soil [145]. Capacitance sensors use the soil as a dielectric between two electrodes and measure the capacitance, which is proportional to the soil water content [146]. TDR sensors emit an electromagnetic pulse through the soil and measure the time it takes for the pulse to reflect back, which is related to the soil water content [147]. Capacitance and TDR sensors are more accurate and versatile than tensiometers, as they can measure a wider range of soil moisture levels and are less affected by soil salinity or temperature [148]. However, they are also more expensive and require a power source and data logger to operate [149].

**Table 5. Comparison of soil moisture sensors for precision irrigation in protected cultivation.**

| Sensor Type | Measurement Range (kPa) | Accuracy (%) | Cost (USD) | Maintenance |
|---|---|---|---|---|
| Tensiometer | 0 to -85 | ±10 | 50-200 | High |
| Capacitance | 0 to -1000 | ±2 | 100-500 | Low |
| TDR | 0 to -1500 | ±1 | 500-2000 | Low |

Sources: [150], [151], [152].

## 4.2. **Plant Water Status Sensors**

Plant water status sensors are devices that measure the water content, potential, or stress level of the plant tissues, such as leaves, stems, or fruits [153]. Plant water status sensors provide direct information on the crop water needs and can be used to optimize the irrigation scheduling based on the physiological responses of the plants to the environment [154]. There are several types of plant water status sensors, including:

### 4.2.1. **Leaf and Stem Water Potential Sensors**

Leaf and stem water potential sensors are devices that measure the negative pressure or suction in the plant xylem, which reflects the water status of the plant [155-156]. The most common method to measure leaf water potential is the pressure chamber, where a leaf is cut and placed in a sealed chamber, and the pressure required to force the xylem sap out of the cut surface is measured [157-158].

### 4.2.2. **Sap Flow Sensors**

Sap flow sensors are devices that measure the rate and direction of water movement in the plant stem, which is related to the transpiration and water uptake of the plant [159]. Sap flow sensors use heat as a tracer and measure the velocity of the heat pulse or the temperature difference between two probes inserted into the stem.

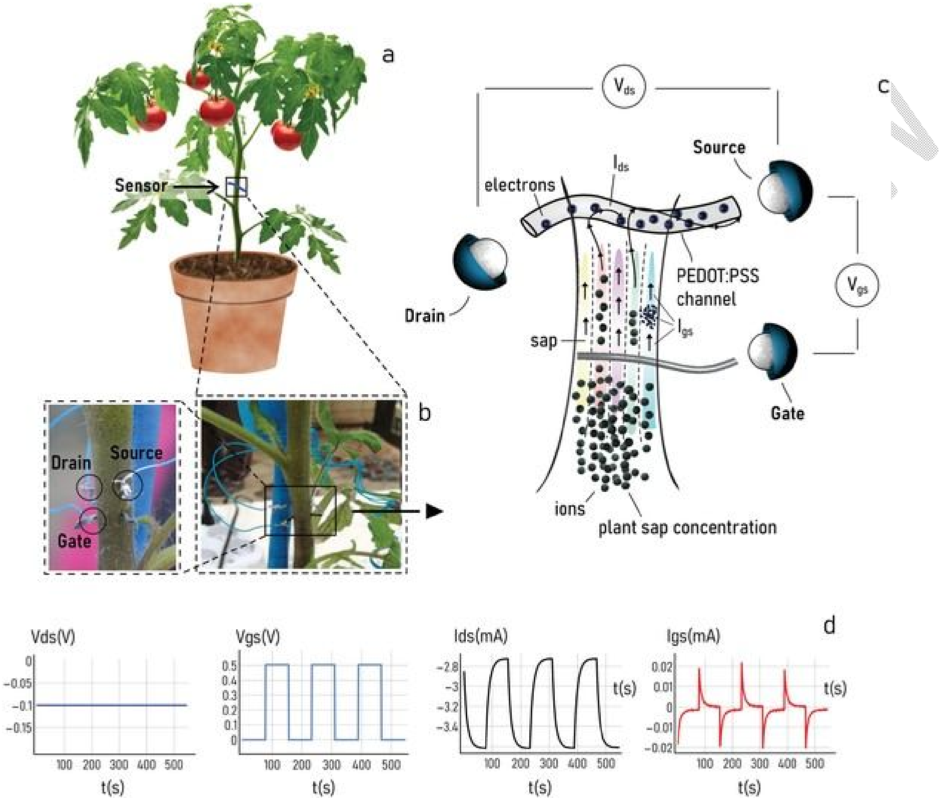

**Figure 4. Example of a sap flow sensor installed on a tomato plant stem in a greenhouse**

## 4.3. **Microclimate Sensors**

Microclimate sensors are devices that measure the environmental conditions in the plant canopy or root zone, such as temperature, humidity, light, and $CO_2$. Microclimate sensors provide information on the factors that influence the crop water use and can be used to adjust the irrigation and ventilation systems to optimize the growing conditions.

**There are several types of microclimate sensors, including:**

### 4.3.1. **Temperature and Humidity Sensors**

Temperature and humidity sensors are devices that measure the air or substrate temperature and relative humidity, which affect the crop evapotranspiration and water demand. Temperature sensors include thermocouples, thermistors, and infrared sensors, while humidity sensors include capacitive, resistive, and dew point sensors. Temperature and humidity sensors are widely available and relatively inexpensive, but they require proper placement and shielding to avoid errors due to radiation or air movement.

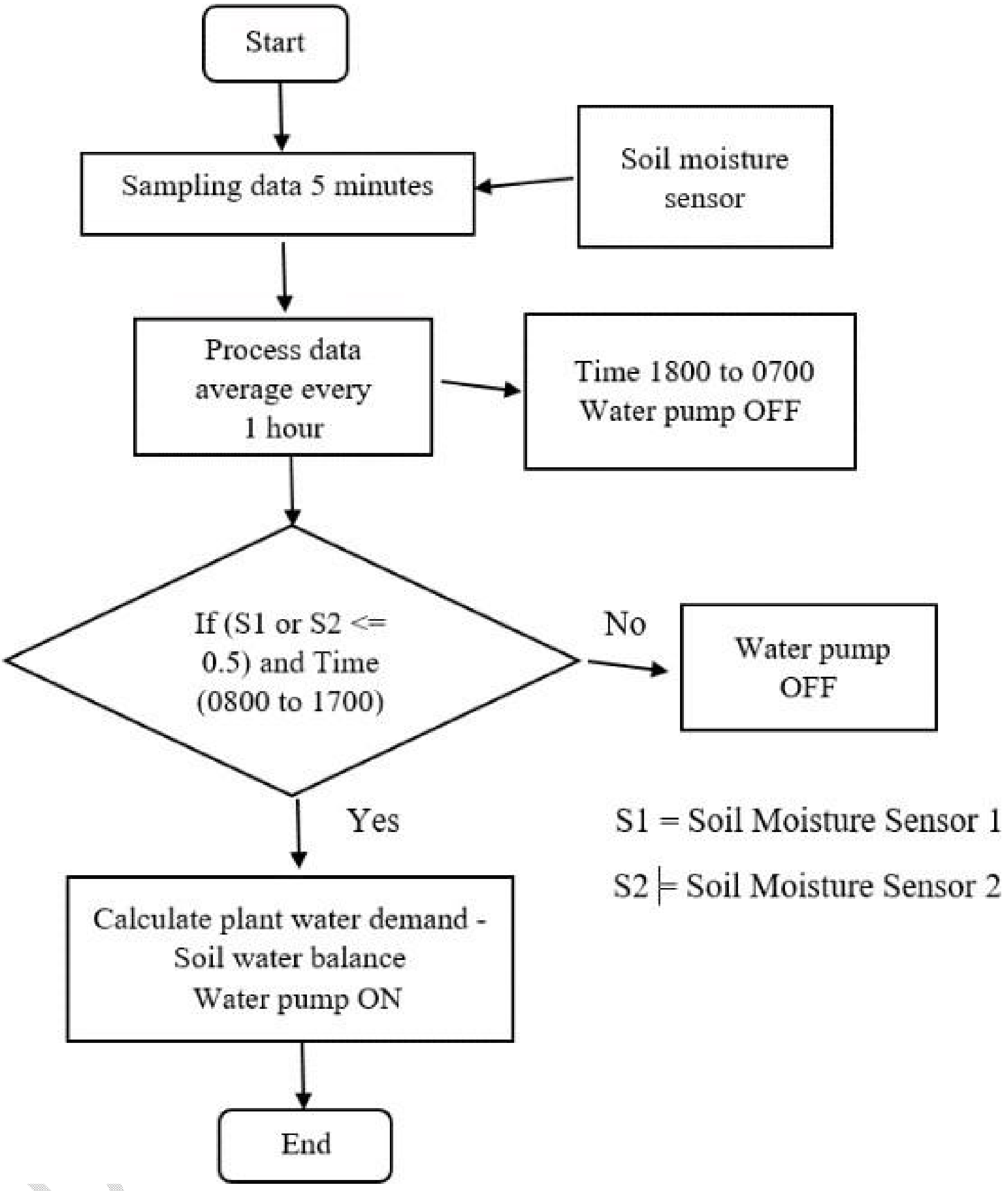

**Figure 5. Schematic diagram of a soil moisture-based irrigation control system.**

### 4.3.2. Solar Radiation and PAR Sensors

Solar radiation and photosynthetically active radiation (PAR) sensors are devices that measure the amount and quality of light available for crop growth and photosynthesis. Solar radiation sensors include pyranometers and quantum sensors, while PAR sensors include quantum meters and line quantum sensors. Solar radiation and PAR sensors are important for estimating the crop water use and potential yield, as well as for controlling the supplemental lighting and shading systems in greenhouses. However, they are more expensive and require regular calibration and maintenance to ensure accurate measurements.

**Table 6. Examples of microclimate sensors used in protected cultivation.**

| Sensor Type | Parameter | Unit | Range | Accuracy |
|---|---|---|---|---|
| Thermocouple | Air temperature | °C | -200 to 1000 | ±0.5 |
| Capacitive humidity | Relative humidity | % | 0 to 100 | ±2 |
| Pyranometer | Solar radiation | $W/m^2$ | 0 to 2000 | ±5 |
| Quantum meter | PAR | $\mu mol/m^2/s$ | 0 to 3000 | ±5 |

Sources: [172], [173], [174], [175].

## 5. Irrigation Scheduling and Control0

Irrigation scheduling and control are the core components of precision irrigation in protected cultivation, as they determine the timing, amount, and frequency of water application based on the crop water requirements and the available resources. Irrigation scheduling involves deciding when to irrigate and how much water to apply, while irrigation control involves implementing those decisions using the appropriate hardware and software. The goal of irrigation scheduling and control is to optimize the crop water use efficiency, yield, and quality, while minimizing the water losses, energy costs, and environmental impacts.

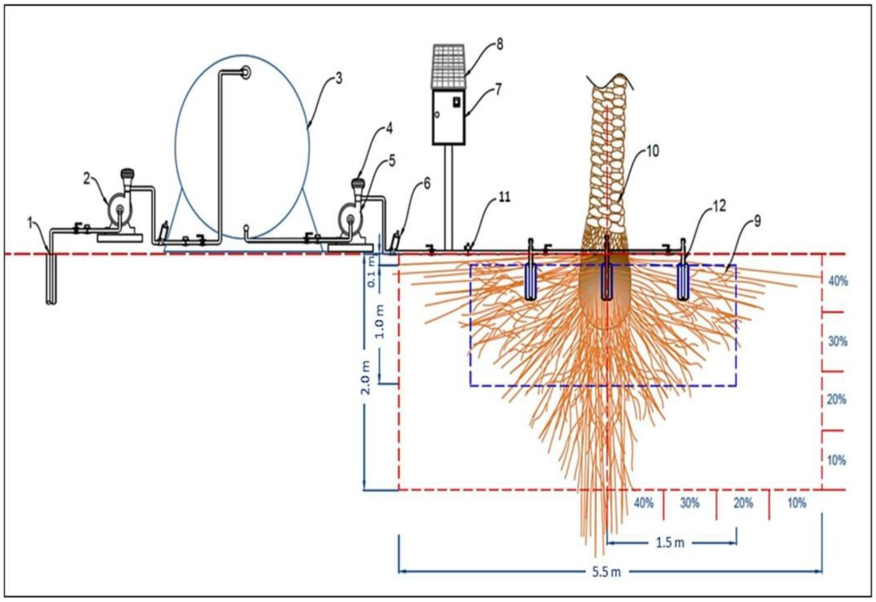

**Figure 6. Example of a sensor-based automated irrigation controller for greenhouse**

**Some common irrigation scheduling and control methods are described below.**

### 5.1. Evapotranspiration-based Methods

Evapotranspiration (ET) is the combined process of water loss from the crop and soil through evaporation and transpiration

- Reference evapotranspiration (ETo): the ET rate of a reference crop (usually grass or alfalfa) under standard conditions, which can be estimated using weather data and standardized equations, such as the FAO Penman-Monteith method
- Crop coefficient (Kc): a dimensionless factor that relates the actual crop ET to the reference ET, based on the crop type, growth stage, and management practices
- Effective rainfall (Re): the portion of rainfall that is available for crop use, after accounting for losses due to runoff, deep percolation, and canopy interception
- Irrigation efficiency (Ei): the ratio of the water beneficially used by the crop to the water applied by the irrigation system, which depends on the system design, maintenance, and operation

The basic equation for calculating the irrigation requirement (IR) using the ET-based method is:

$$IR = (ETo \times Kc - Re) / Ei$$

For example, if the reference ET is 5 mm/day, the crop coefficient is 1.2, the effective rainfall is 2 mm/day, and the irrigation efficiency is 0.8, the irrigation requirement would be:

$$IR = (5 \text{ mm/day} \times 1.2 - 2 \text{ mm/day}) / 0.8 = 5 \text{ mm/day}$$

This means that the crop would need to be irrigated with 5 mm of water per day to meet its water requirements under the given conditions.

**ET-based irrigation scheduling methods have several advantages, such as:**

- They are based on the actual crop water use and climatic conditions, rather than fixed schedules or subjective judgments
- They can be adapted to different crops, growth stages, and management practices by using specific crop coefficients and adjustment factors
- They can be automated using weather stations, sensors, and computer models to calculate and implement the irrigation requirements in real-time

**However, ET-based methods also have some limitations and challenges, such as:**

- They require accurate and reliable weather data, which may not be available or representative of the specific site conditions
- They assume that the crop coefficients and other parameters are constant and uniform, which may not be true for all crops, varieties, and management practices
- They do not account for the spatial variability of soil moisture and crop water status within the field, which can lead to over- or under-irrigation in some areas.

**Table 7. Example of crop coefficients (Kc) for tomato at different growth stages.**

| Growth Stage | Duration (days) | Kc |
|---|---|---|
| Initial | 30 | 0.6 |
| Development | 40 | 0.8 |

| | | |
|---|---|---|
| Mid-season | 50 | 1.2 |
| Late season | 30 | 0.9 |

### 5.2. **Soil Moisture-based Methods**

Soil moisture-based irrigation scheduling methods use measurements or estimates of soil water content or potential to determine when and how much to irrigate [194]. Soil moisture-based methods are based on the principle that the crop water uptake and growth are directly related to the availability of water in the root zone, and that maintaining the soil moisture within an optimal range can maximize the crop yield and quality [195].

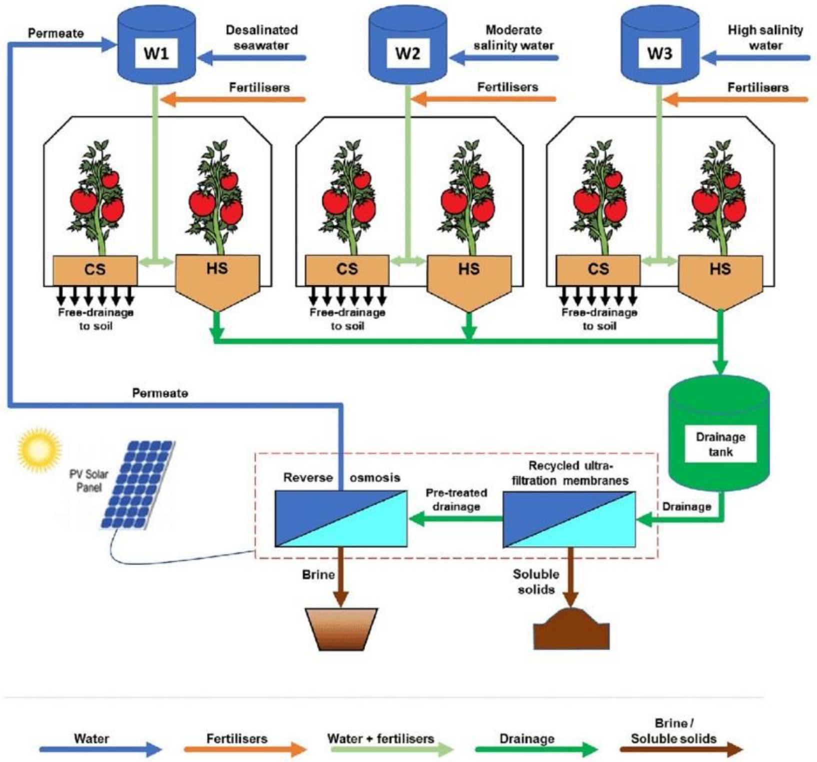

**Figure 7. Schematic diagram of a precision irrigation and fertigation system in a Dutch tomato greenhouse**.

**There are several soil moisture-based irrigation scheduling methods, including:**

- Feel and appearance method: a qualitative method that involves observing and feeling the soil texture, color, and consistency to estimate the soil moisture status and irrigation need.
- Gravimetric method: a quantitative method that involves taking soil samples, weighing them before and after drying, and calculating the soil water content as the ratio of water mass to dry soil mass.
- Soil moisture sensors: electronic devices that measure the soil water content or potential using various principles, such as resistance, capacitance, or reflectometry, and provide continuous and real-time data on the soil moisture status.

- Soil water balance models: computer programs that simulate the soil water dynamics based on inputs of climate, soil, crop, and irrigation data, and estimate the soil moisture content and irrigation requirements over time.
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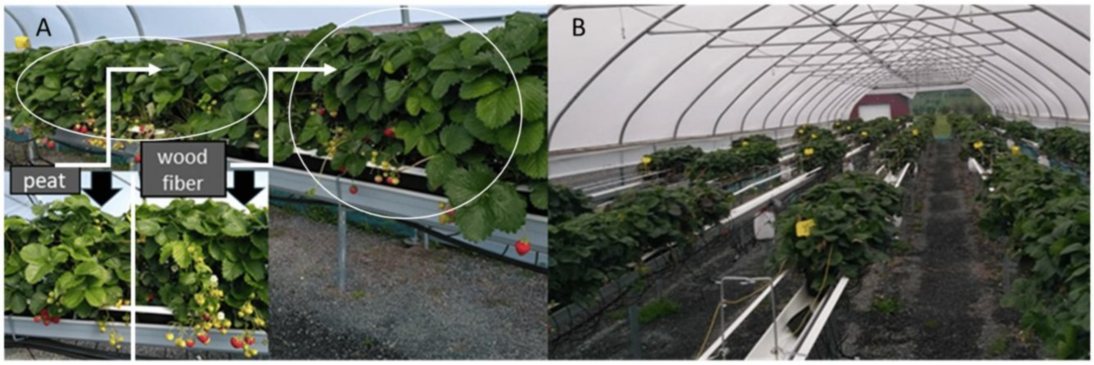

**Figure 8. Example of a precision irrigation and fertigation system in a Japanese strawberry high tunnel.**

## Conclusion

Precision irrigation is a key technology and approach for the sustainable intensification and resilience of protected cultivation systems, which can optimize the use of water, nutrients, energy, and other resources, and achieve the desired crop yield, quality, and profitability, while minimizing the environmental and social impacts. The adoption and scaling of precision irrigation in protected cultivation have been driven by the increasing population, urbanization, and income growth, the declining water and land resources, the changing climate and market conditions, and the advancing technologies and innovations.

## References

[1] Tawegoum, R., Leroy, F., Sintes, G., &Chassériaux, G. (2006). Real time climatic control of a greenhouse using tendencies. *Acta Horticulturae*, *718*, 133-140. https://doi.org/10.17660/ActaHortic.2006.718.14

[2] Montero, J. I., Stanghellini, C., & Castilla, N. (2009). Greenhouse technology for sustainable production in mild winter climate areas: Trends and needs. *Acta Horticulturae*, *807*, 33-44. https://doi.org/10.17660/ActaHortic.2009.807.2

[3] Ruiz-Garcia, L., Lunadei, L., Barreiro, P., &Robla, J. I. (2009). A review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends. *Sensors*, *9*(6), 4728-4750. https://doi.org/10.3390/s90604728

[4] MarketsandMarkets. (2020). Precision irrigation market by system type (sprinkler irrigation, drip irrigation), application (agriculture, non-agriculture), offering (hardware, software & services), and geography - Global forecast to 2025. https://www.marketsandmarkets.com/Market-Reports/precision-irrigation-market-1247.html

[5] Bauchet, J., & Baudry, J. (2010). Networking and innovation in the ornamental horticulture industry: An empirical analysis of the Veiling Holambra cooperative. *Acta Horticulturae*, *872*, 79-86. https://doi.org/10.17660/ActaHortic.2010.872.7

[6] Kumar, P., Sharma, N., & Ranjan, R. (2018). Precision horticulture: A new approach for doubling farmers' income in India. *Indian Farming*, *68*(03), 23-25. http://epubs.icar.org.in/ejournal/index.php/IFJ/article/view/87037

[7] Goel, A. K., & Kumar, P. (2020). Economic analysis of cucumber cultivation under protected conditions. *Indian Journal of Horticulture*, *77*(1), 141-145. https://doi.org/10.5958/0974-0112.2020.00028.9

[8] Nicola, S., & Fontana, E. (2014). Global horticulture: Challenges and opportunities. *Acta Horticulturae*, *1112*, 11-22. https://doi.org/10.17660/ActaHortic.2016.1112.3

[9] Chai, Q., Gan, Y., Zhao, C., Xu, H.-L., Waskom, R. M., Niu, Y., & Siddique, K. H. M. (2016). Regulated deficit irrigation for crop production under drought stress. A review. *Agronomy for Sustainable Development*, *36*(1), 3. https://doi.org/10.1007/s13593-015-0338-6

[10] Rouphael, Y., Cardarelli, M., Rea, E., & Colla, G. (2008). Grafting of cucumber as a means to minimize copper toxicity. *Environmental and Experimental Botany*, *63*(1), 49-58. https://doi.org/10.1016/j.envexpbot.2007.10.015

[11] Francescangeli, N., Sangiacomo, M. A., & Marti, H. R. (2007). Vegetative and reproductive plasticity of broccoli at three levels of incident photosynthetically active radiation. *Spanish Journal of Agricultural Research*, *5*(3), 389-401. https://doi.org/10.5424/sjar/2007053-256

[12] Stanghellini, C., Incrocci, L., Gázquez, J. C., &Dimauro, B. (2008). Carbon dioxide concentration in Mediterranean greenhouses: How much lost production? *Acta Horticulturae*, *801*, 1541-1550. https://doi.org/10.17660/ActaHortic.2008.801.188

[13] Gómez, C., & Izzo, L. G. (2018). Increasing efficiency of crop production with LEDs. *AIMS Agriculture and Food*, *3*(2), 135-153. https://doi.org/10.3934/agrfood.2018.2.135

[14] Fernández, M. D., Bonachela, S., Orgaz, F., Thompson, R., López, J. C., Granados, M. R., Gallardo, M., &Fereres, E. (2010). Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. *Irrigation Science*, *28*(6), 497-509. https://doi.org/10.1007/s00271-010-0210-z

[15] Schröder, F.-G., & Lieth, J. H. (2002). Irrigation control in hydroponics. *In: Savvas, D., Passam, H. (eds) Hydroponic Production of Vegetables and Ornamentals*, *263-298*. Embryo Publications, Athens, Greece.

[16] Pardossi, A., Tognoni, F., &Incrocci, L. (2004). Mediterranean greenhouse technology. *Chronica Horticulturae*, *44*(2), 28-34.

[17] Jones, J. Benton. (2016). Hydroponics: A practical guide for the soilless grower (2nd ed.). CRC Press. https://doi.org/10.1201/9781439872383

[18] Baille, A. (2001). Water management in soilless cultivation in relation to inside and outside climatic conditions and type of substrate. *Italus Hortus*, *8*(6), 16-22.

[19] Zegbe, J. A., Serna-Pérez, A., & Mena-Covarrubias, J. (2014). Linking flavor and aroma of fresh-cut mango (Mangifera indica L.) to harvest maturity and storage temperature. *Journal of Food Science*, *79*(4), S624-S630. https://doi.org/10.1111/1750-3841.12393

[20] Magán, J. J., López, J. C., Granados, M. R., Pérez-Alfocea, F., & Fernández, M. D. (2019). Effects of salinity on the water balance and yield of cherry tomatoes grown in closed-soilless culture systems. *Agricultural Water Management*, *223*, 105697. https://doi.org/10.1016/j.agwat.2019.06.001

[21] Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry: A review. *European Journal of Horticultural Science*, *83*(5), 280-293. https://doi.org/10.17660/eJHS.2018/83.5.2

[22] Ullah, I., Hanping, M., Chuan, Z., Javed, Q., & Azeem, A. (2017). Optimization of irrigation and nutrient concentration based on economic returns, substrate salt accumulation and water use efficiency for greenhouse cucumber in arid region. *Archives of Agronomy and Soil Science*, *63*(13), 1748-1762. https://doi.org/10.1080/03650340.2017.1311013

[23] Rouphael, Y., & Colla, G. (2020). Editorial: Biostimulants in agriculture. *Frontiers in Plant Science*, *11*. https://doi.org/10.3389/fpls.2020.00040

[24] Bar-Tal, A., Aloni, B., Karni, L., Oserovitz, J., Hazan, A., Itach, M., Gantz, S., Avidan, A., Posalski, I., Tratkovski, N., & Rosenberg, R. (2001). Nitrogen nutrition of greenhouse pepper. I. Effects of nitrogen concentration and NO3:NH4 ratio on yield, fruit shape, and the incidence of blossom-end rot in relation to plant mineral composition. *HortScience*, *36*(7), 1244-1251. https://doi.org/10.21273/HORTSCI.36.7.1244

[25] Qaryouti, M., Hamdan, H., Shibli, R., AbuRumman, S., Blan, H. A., &Muhaisen, A. (2007). Influence of substrates on yield and quality of indoor grown cucumber (*Cucumis sativus* L.). *International Journal of Vegetable Science*, *14*(1), 33-45. https://doi.org/10.1300/J512v14n01_04

[26] Jensen, M. H. (2002). Controlled environment agriculture in deserts, tropics and temperate regions: A world review. *Acta Horticulturae*, *578*, 19-25. https://doi.org/10.17660/ActaHortic.2002.578.1

[27] Van Kooten, O., Heuvelink, E., &Stanghellini, C. (2008). New developments in greenhouse technology can mitigate the water shortage problem of the 21st century. *Acta Horticulturae*, *767*, 45-52. https://doi.org/10.17660/ActaHortic.2008.767.2

[28] Stafford, J. V. (2000). Implementing precision agriculture in the 21st century. *Journal of Agricultural Engineering Research*, *76*(3), 267-275. https://doi.org/10.1006/jaer.2000.0577

[29] Pathak, M., Chourasia, A., Bhardwaj, B., Chourasia, M. K., & Sah, D. (2018). Applications of precision farming in horticulture. *Biomolecule Reports*, *2*(2), 1-5.

[30] FAO. (2013). Good Agricultural Practices for greenhouse vegetable crops: Principles for Mediterranean climate areas. *FAO Plant Production and Protection Paper*, *230*, 1-640. http://www.fao.org/3/a-i3284e.pdf

[31] Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment

agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*, *11*(1), 1-22. https://doi.org/10.25165/j.ijabe.20181101.3210

[32] Sánchez-Molina, J. A., Rodríguez, F., Guzmán, J. L., Ramírez-Arias, J. A., &Arahal, M. R. (2014). Virtual sensors for designing irrigation controllers in greenhouses. *Sensors*, *14*(8), 15159-15178. https://doi.org/10.3390/s140815159

[33] Costa, J. M., &Heuvelink, E. (2005). The tomato crop and industry. *In: Heuvelink, E. (ed) Tomatoes, 1-19*. CABI Publishing, Wallingford, UK. https://doi.org/10.1079/9780851993966.0001

[34] Calvin, L., & Cook, R. (2005). Greenhouse tomatoes change the dynamics of the North American fresh tomato industry. *Economic Research Report*, *2*, 1-87. https://doi.org/10.22004/ag.econ.59282

[35] Pardossi, A., Carmassi, G., Diara, C., Incrocci, L., Maggini, R., & Massa, D. (2011). Fertigation and substrate management in closed soilless culture. Dipartimento Di Scienze Delle ProduzioniVegetali, Del Suolo e Dell'AmbienteAgroforestale, *University of Florence*, *1-63*. http://edepot.wur.nl/175432

[36] Peet, M., & Welles, G. (2005). Greenhouse tomato production. *In: Heuvelink, E. (ed) Tomatoes, 257-304*. CABI Publishing, Wallingford, UK. https://doi.org/10.1079/9780851993966.0257

[37] Treftz, C., & Omaye, S. T. (2015). Nutrient analysis of soil and soilless strawberries and raspberries grown in a greenhouse. *Food and Nutrition Sciences*, *6*(9), 805-815. https://doi.org/10.4236/fns.2015.69084

[38] Putra, P. A., &Yuliando, H. (2015). Soilless culture system to support water use efficiency and product quality: A review. *Agriculture and Agricultural Science Procedia*, *3*, 283-288. https://doi.org/10.1016/j.aaspro.2015.01.054

[39] Liang, Y., Gao, W., Luo, C., Tang, J., Yin, Z., & Han, P. (2021). Soil water and salt dynamics and okra production as affected by soil surface mulching and drip irrigation in saline soils. *Agricultural Water Management*, *256*, 107061. https://doi.org/10.1016/j.agwat.2021.107061

[40] Hanson, B., Schwankl, L., Grattan, S., & Pritchard, T. (1993). Drip irrigation for row crops. Division of Agriculture and Natural Resources, *University of California*, *1-13*. https://doi.org/10.3733/ucanr.93-05

[41] Burt, C., & Styles, S. (2007). Drip and micro irrigation design and management (3rd ed.). Irrigation Training and Research Center, California Polytechnic State University. https://www.irrigation.org/IA/FileUploads/IA/Resources/TechnicalPapers/IA-2007-Burt1.pdf

[42] Lamm, F. R., Bordovsky, J. P., & Schwankl, L. J. (2012). Subsurface drip irrigation: Status of the technology in 2010. *Transactions of the ASABE*, *55*(2), 483-491. https://doi.org/10.13031/2013.41387

[43] Enciso, J., Jifon, J., Anciso, J., & Ribera, L. (2015). Productivity of onions using subsurface drip irrigation versus furrow irrigation systems with an internet based irrigation scheduling program. *International Journal of Agronomy*, *2015*, 1-6. https://doi.org/10.1155/2015/178180

[44] Arbat, G., Puig-Bargués, J., Duran-Ros, M., Barragán, J., Ramírez de Cartagena, F., & Lamm, F. R. (2013). Subsurface drip irrigation versus center-pivot sprinkler for applying reclaimed water to turf grass. *Agricultural Water Management*, *122*, 1-7. https://doi.org/10.1016/j.agwat.2013.02.004

[45] Singh, A. (2014). Conjunctive use of water resources for sustainable irrigated agriculture. *Journal of Hydrology*, *519*, 1688-1697. https://doi.org/10.1016/j.jhydrol.2014.09.049

[46] Sarma, A., & Upadhyay, A. (2019). Sustainable micro-irrigation management for orchards. *ICAR-Central Institute for Subtropical Horticulture, Technical Bulletin, 1-48.* http://www.cish.res.in/ebook/Technical_Bulletin_No._54.pdf

[47] Shani, U., Tsur, Y., Zemel, A., & Zilberman, D. (2009). Irrigation production functions with water-capital substitution. *Agricultural Economics*, *40*(1), 55-66. https://doi.org/10.1111/j.1574-0862.2008.00359.x

[48] Darouich, H. M., Pedras, C. M. G., Gonçalves, J. M., & Pereira, L. S. (2014). Drip vs. surface irrigation: A comparison focussing on water saving and economic returns using multicriteria analysis applied to cotton. *Biosystems Engineering*, *122*, 74-90. https://doi.org/10.1016/j.biosystemseng.2014.03.010

[49] Shock, C. C., & Wang, F.-X. (2011). Soil water tension, a powerful measurement for productivity and stewardship. *HortScience*, *46*(2), 178-185. https://doi.org/10.21273/HORTSCI.46.2.178

[50] Pardossi, A., &Incrocci, L. (2011). Traditional and new approaches to irrigation scheduling in vegetable crops. *HortTechnology*, *21*(3), 309-313. https://doi.org/10.21273/HORTTECH.21.3.309

[51] Kang, Y., Wang, R., Wan, S., Hu, W., Jiang, S., & Liu, S. (2012). Effects of different water levels on cotton growth and water use through drip irrigation in an arid region with saline ground water of Northwest China. *Agricultural Water Management*, *109*, 117-126. https://doi.org/10.1016/j.agwat.2012.02.013

[52] Favati, F., Lovelli, S., Galgano, F., Miccolis, V., Di Tommaso, T., & Candido, V. (2009). Processing tomato quality as affected by irrigation scheduling. *Scientia Horticulturae*, *122*(4), 562-571. https://doi.org/10.1016/j.scienta.2009.06.026

[53] Harmanto, Salokhe, V. M., Babel, M. S., &Tantau, H. J. (2005). Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. *Agricultural Water Management*, *71*(3), 225-242. https://doi.org/10.1016/j.agwat.2004.09.003

[54] Cahn, M., & Johnson, L. (2017). New approaches to irrigation scheduling of vegetables. *Horticulturae*, *3*(2), 28. https://doi.org/10.3390/horticulturae3020028

[55] Camp, C. R. (1998). Subsurface drip irrigation: A review. *Transactions of the ASAE*, *41*(5), 1353-1367. https://doi.org/10.13031/2013.17309

[56] Thompson, T. L., Pang, H., & Li, Y. (2009). The potential contribution of subsurface drip irrigation to water-saving agriculture in the western USA. *Agricultural Sciences in China*, *8*(7), 850-854. https://doi.org/10.1016/S1671-2927(08)60287-4

[57] Ayars, J. E., Fulton, A., & Taylor, B. (2015). Subsurface drip irrigation in California: Here to stay? *Agricultural Water Management*, *157*, 39-47. https://doi.org/10.1016/j.agwat.2015.01.001

[58] Hanson, B., & May, D. (2004). Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. *Agricultural Water Management*, *68*(1), 1-17. https://doi.org/10.1016/j.agwat.2004.03.003

[59] Ayars, J. E., Phene, C. J., Hutmacher, R. B., Davis, K. R., Schoneman, R. A., Vail, S. S., & Mead, R. M. (1999). Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. *Agricultural Water Management*, *42*(1), 1-27. https://doi.org/10.1016/S0378-3774(99)00025-6

[60] Lamm, F. R., Ayars, J. E., & Nakayama, F. S. (Eds.). (2007). Microirrigation for crop production: Design, operation, and management (Vol. 13). Elsevier.

[61] Badr, M. A., Abou Hussein, S. D., & El-Tohamy, W. A. (2016). Tomato yield, nitrogen uptake and water use efficiency as affected by planting geometry and level of nitrogen in an arid region. *Agricultural Water Management*, *169*, 90-97. https://doi.org/10.1016/j.agwat.2016.02.012

[62] Hanson, B., Schwankl, L., & Fulton, A. (2004). Scheduling irrigations: When and how much water to apply. Division of Agriculture and Natural Resources, *University of California*, *3396*, 1-202. https://doi.org/10.3733/ucanr.3396

[63] Dabach, S., Shani, U., &Lazarovitch, N. (2015). Optimal tensiometer placement for high-frequency subsurface drip irrigation management in heterogeneous soils. *Agricultural Water Management*, *152*, 91-98. https://doi.org/10.1016/j.agwat.2015.01.003

[64] Gonçalves, I. Z., Mekonnen, M. M., Neale, C. M. U., Campos, I., & Neale, M. R. (2020). Temporal and spatial variations of irrigation water use for commercial corn fields in Central Nebraska. *Agricultural Water Management*, *228*, 105924. https://doi.org/10.1016/j.agwat.2019.105924

[65] Grabow, G. L., Huffman, R. L., Evans, R. O., Jordan, D. L., & Nuti, R. C. (2006). Water distribution from a subsurface drip irrigation system and dripline spacing effect on cotton yield and water use efficiency in a coastal plain soil. *Transactions of the ASABE*, *49*(6), 1823-1835. https://doi.org/10.13031/2013.22291

[66] Lamm, F. R., Harmoney, K. R., Aboukheira, A. A., & Johnson, S. K. (2012). Alfalfa production with subsurface drip irrigation in the Central Great Plains. *Transactions of the ASABE*, *55*(4), 1203-1212. https://doi.org/10.13031/2013.42258

[67] Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management*, *80*(1), 5-22. https://doi.org/10.1016/j.agwat.2005.07.001

[68] Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, *97*(4), 528-535. https://doi.org/10.1016/j.agwat.2009.03.023

[69] Fereres, E., Orgaz, F., & Gonzalez-Dugo, V. (2011). Reflections on food security under water scarcity. *Journal of Experimental Botany*, *62*(12), 4079-4086. https://doi.org/10.1093/jxb/err165

[70] Surendran, U., Sushanth, C. M., Mammen, G., & Joseph, E. J. (2015). Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: A case study in Palakkad district of humid tropical Kerala, India. *Aquatic Procedia*, *4*, 1211-1219. https://doi.org/10.1016/j.aqpro.2015.02.154

[71] Pereira, L. S., Allen, R. G., Smith, M., & Raes, D. (2015). Crop evapotranspiration estimation with FAO56: Past and future. *Agricultural Water Management*, *147*, 4-20. https://doi.org/10.1016/j.agwat.2014.07.031

[72] Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper*, *56*, 1-326. http://www.fao.org/3/X0490E/x0490e00.htm

[73] Hargreaves, G. H., & Samani, Z. A. (1985). Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, *1*(2), 96-99. https://doi.org/10.13031/2013.26773

[74] Steduto, P., Hsiao, T. C., Fereres, E., & Raes, D. (2012). Crop yield response to water. *FAO Irrigation and Drainage Paper*, *66*, 1-505. http://www.fao.org/3/i2800e/i2800e.pdf

[75] Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, *58*(2), 147-159. https://doi.org/10.1093/jxb/erl165

[76] Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, *96*(9), 1275-1284. https://doi.org/10.1016/j.agwat.2009.04.009

[77] Kang, S., Shi, W., & Zhang, J. (2000). An improved water-use efficiency for maize grown under regulated deficit irrigation. *Field Crops Research*, *67*(3), 207-214. https://doi.org/10.1016/S0378-4290(00)00095-2

[78] Costa, J. M., Ortuño, M. F., & Chaves, M. M. (2007). Deficit irrigation as a strategy to save water: Physiology and potential application to horticulture. *Journal of Integrative Plant Biology*, *49*(10), 1421-1434. https://doi.org/10.1111/j.1672-9072.2007.00556.x

[79] Chai, Q., Gan, Y., Turner, N. C., Zhang, R.-Z., Yang, C., Niu, Y., & Siddique, K. H. M. (2014). Water-saving innovations in Chinese agriculture. *Advances in Agronomy*, *126*, 149-201. https://doi.org/10.1016/B978-0-12-800132-5.00002-X

[80] Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, *93*(2), 281-289. https://doi.org/10.2134/agronj2001.932281x

[81] Lovelli, S., Perniola, M., Ferrara, A., & Di Tommaso, T. (2007). Yield response factor to water (Ky) and water use efficiency of *Carthamus tinctorius* L. and *Solanum melongena* L. *Agricultural Water Management*, *92*(1-2), 73-80. https://doi.org/10.1016/j.agwat.2007.05.005

[82] Nagaz, K., Masmoudi, M. M., & Ben Mechlia, N. (2012). Yield response of drip-irrigated onion under full and deficit irrigation with saline water in arid regions of Tunisia. *ISRN Agronomy*, *2012*, 1-8. https://doi.org/10.5402/2012/562315

[83] Saleh, A. A. H., & Ibrahim, M. M. (2016). Effect of deficit irrigation on onion yield, nutrient content and water use efficiency in sandy soils. *Egyptian Journal of Horticulture*, *43*(2), 385-400. https://doi.org/10.21608/ejoh.2016.3115

[84] El-Noemani, A. A., El-Zeiny, H. A., El-Gindy, A. M., El-Sahhar, E. A., & El-Shawadfy, M. A. (2010). Performance of some bean (*Phaseolus vulgaris* L.) varieties under different irrigation systems and regimes. *Australian Journal of Basic and Applied Sciences*, *4*(12), 6185-6196. https://www.researchgate.net/publication/266886198

[85] Yenesew, M., & Tilahun, K. (2009). Yield and water use efficiency of deficit-irrigated maize in a semi-arid region of Ethiopia. *African Journal of Food, Agriculture, Nutrition and Development*, *9*(8), 1635-1651. https://doi.org/10.4314/ajfand.v9i8.48402

[86] Kebe, H. M., & Guttieri, M. J. (2020). Deficit irrigation effects on yield and quality of Quinoa. *Agronomy*, *10*(11), 1748. https://doi.org/10.3390/agronomy10111748

[87] Fathi, A., & Tari, D. B. (2016). Effect of drought stress and its mechanism in plants. *International Journal of Life Sciences*, *10*(1), 1-6. https://doi.org/10.3126/ijls.v10i1.14509

[88] Rai, N., Yadav, D. S., Patel, K. K., Yadav, R. K., Yadav, B. S., & Rai, A. B. (2005). Effect of water management on yield, quality and water-use efficiency in onion (*Allium cepa* L.). *Indian Journal of Agricultural Sciences*, *75*(11), 747-749.

[89] Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2009). Plant drought stress: effects, mechanisms and management. *Agronomy for Sustainable Development*, *29*(1), 185-212. https://doi.org/10.1051/agro:2008021

[90] Sleper, D. A., & Poehlman, J. M. (2006). *Breeding field crops* (5th ed.). Blackwell Publishing.

[91] Dodd, I. C. (2009). Rhizosphere manipulations to maximize 'crop per drop' during deficit irrigation. *Journal of Experimental Botany*, *60*(9), 2454-2459. https://doi.org/10.1093/jxb/erp192

[92] Hoddy, E. T. (2019). Critical information literacy and critical service learning in a food justice project. *portal: Libraries and the Academy*, *19*(2), 229-245. https://doi.org/10.1353/pla.2019.0013

[93] Mupambi, G., Anthony, B. M., Layne, D. R., Musacchi, S., Serra, S., Schmidt, T., &Kalcsits, L. A. (2018). The influence of protective netting on tree physiology and fruit quality of apple: A review. *Scientia Horticulturae*, *236*, 60-72. https://doi.org/10.1016/j.scienta.2018.03.014

[94] Möller, M., & Assouline, S. (2007).Effects of a shading screen on microclimate and crop water requirements. *Irrigation Science*, *25*(3), 171-181. https://doi.org/10.1007/s00271-006-0045-9

[95] Castellano, S., ScarasciaMugnozza, G., Russo, G., Briassoulis, D., Mistriotis, A., Hemming, S., &Waaijenberg, D. (2008). Plastic nets in agriculture: a general review of types and applications. *Applied Engineering in Agriculture*, *24*(6), 799-808. https://doi.org/10.13031/2013.25368

[96] Gogo, E. O., Saidi, M., Itulya, F. M., Martin, T., &Ngouajio, M. (2012). Microclimate modification using eco-friendly nets for high-quality tomato transplant production by small-scale farmers in East Africa. *HortTechnology*, *22*(3), 292-298. https://doi.org/10.21273/HORTTECH.22.3.292

[97] Ilić, Z. S., Milenković, L., Šunić, L., &Fallik, E. (2015). Effect of coloured shade-nets on plant leaf parameters and tomato fruit quality. *Journal of the Science of Food and Agriculture*, *95*(13), 2660-2667. https://doi.org/10.1002/jsfa.7000

[98] Briassoulis, D., Mistriotis, A., &Eleftherakis, D. (2007). Mechanical behaviour and properties of agricultural nets. Part II: Analysis of the performance of the main categories of agricultural nets. *Polymer Testing*, *26*(8), 970-984. https://doi.org/10.1016/j.polymertesting.2007.06.010

[99] Castellano, S., Hemming, S., & Russo, G. (2008). The influence of color on radiometric performances of agricultural nets. *Acta Horticulturae*, *801*, 227-236. https://doi.org/10.17660/ActaHortic.2008.801.21

[100] Al-Helal, I. M., & Abdel-Ghany, A. M. (2010). Responses of plastic shading nets to global and diffuse PAR transfer: Optical properties and evaluation. *NJAS - Wageningen Journal of Life Sciences*, *57*(2), 125-132. https://doi.org/10.1016/j.njas.2010.02.002

[101] Kittas, C., Rigakis, N., Katsoulas, N., &Bartzanas, T. (2009). Influence of shading screens on microclimate, growth and productivity of tomato. *Acta Horticulturae*, *807*, 97-102. https://doi.org/10.17660/ActaHortic.2009.807.10

[102] Shahak, Y. (2014). Photoselective netting: An overview of the concept, R&D and practical implementation in agriculture. *Acta Horticulturae*, *1015*, 155-162. https://doi.org/10.17660/ActaHortic.2014.1015.17

[103] Kong, Y., Avraham, L., Ratner, K., &Shahak, Y. (2012). Response of photosynthetic parameters of sweet pepper leaves to light quality manipulation by photoselective shade nets. *Acta Horticulturae*, *956*, 501-506. https://doi.org/10.17660/ActaHortic.2012.956.60

[104] Shahak, Y., Gussakovsky, E. E., Gal, E., &Ganelevin, R. (2004). ColorNets: Crop protection and light-quality manipulation in one technology. *Acta Horticulturae*, *659*, 143-151. https://doi.org/10.17660/ActaHortic.2004.659.17

[105] Meena, R. K., Vashisth, A., Singh, R., Singh, B., &Manjaih, K. M. (2014). Study on change in microenvironment under different colour shade nets and its impact on yield of spinach (*Spinacia oleracea* L.). *Journal of Agrometeorology*, *16*(1), 104-111.

[106] Tinyane, P. P., Sivakumar, D., & Soundy, P. (2013). Influence of photo-selective netting on fruit quality parameters and bioactive compounds in selected tomato cultivars. *Scientia Horticulturae*, *161*, 340-349. https://doi.org/10.1016/j.scienta.2013.06.024

[107] Selahle, M. K., Sivakumar, D., Jifon, J., & Soundy, P. (2015). Postharvest responses of red and yellow sweet peppers grown under photo-selective nets. *Food Chemistry*, *173*, 951-956. https://doi.org/10.1016/j.foodchem.2014.10.034

[108] Ilić, Z. S., &Fallik, E. (2017). Light quality manipulation improves vegetable quality at harvest and postharvest: A review. *Environmental and Experimental Botany*, *139*, 79-90. https://doi.org/10.1016/j.envexpbot.2017.04.006

[109] Shahak, Y. (2008). Photo-selective netting for improved performance of horticultural crops. A review of ornamental and vegetable studies carried out in Israel. *Acta Horticulturae*, *770*, 161-168. https://doi.org/10.17660/ActaHortic.2008.770.18

[110] Stamps, R. H. (2009). Use of colored shade netting in horticulture. *HortScience*, *44*(2), 239-241. https://doi.org/10.21273/HORTSCI.44.2.239

[111] Ilić, Z. S., Milenković, L., Šunić, L., Barać, S., Mastilović, J., Kevrešan, Ž., &Fallik, E. (2017). Effect of shading by coloured nets on yield and fruit quality of sweet pepper. *Zemdirbyste-Agriculture*, *104*(1), 53-62. https://doi.org/10.13080/z-a.2017.104.008

[112] Mashabela, M. N., Selahle, K. M., Soundy, P., Crosby, K. M., & Sivakumar, D. (2015). Bioactive compounds and fruit quality of green sweet pepper grown under different colored shade netting during postharvest storage. *Journal of Food Science*, *80*(11), H2612-H2618. https://doi.org/10.1111/1750-3841.13103

[113] Kong, Y., Avraham, L., Perzelan, Y., Alkalai-Tuvia, S., Ratner, K., Shahak, Y., &Fallik, E. (2013). Pearl netting affects postharvest fruit quality in 'Vergasa' sweet pepper via light environment manipulation. *Scientia Horticulturae*, *150*, 290-298. https://doi.org/10.1016/j.scienta.2012.11.029

[114] Alkalai-Tuvia, S., Yishay, M., Rein, A., Goren, A., Perzelan, Y., Weinberg, T., Rodov, V., &Fallik, E. (2014). Photoselective netting improves postharvest quality of 'Or' and 'Odem' peach cultivars. *Israel Journal of Plant Sciences*, *61*(1-2), 27-35. https://doi.org/10.1080/07929978.2014.897568

[115] Shahak, Y., Ratner, K., Zur, N., Offir, Y., Matan, E., Yehezkel, H., Rosenberg, R., Kennepohl, E., Messika, Y., Gal, E., &Gabizon, B. (2009). Photoselective netting: An emerging approach in protected agriculture. *Acta Horticulturae*, *807*, 79-84. https://doi.org/10.17660/ActaHortic.2009.807.7

[116] Shehata, S. A., Saad, M. A., El-Helaly, M. A., & Ibrahim, W. A. (2019). Effect of photoselective netting colors on the performance of bell pepper grown under greenhouse conditions. *Acta Horticulturae*, *1256*, 159-166. https://doi.org/10.17660/ActaHortic.2019.1256.24

[117] Sivakumar, D., Jifon, J., & Soundy, P. (2018). Spectral quality of photo-selective shade nettings improves antioxidants and overall quality in selected fresh produce after postharvest storage. *Journal of Food Science and Technology*, *55*(9), 3425-3438. https://doi.org/10.1007/s13197-018-3255-2

[118] Mahmood, A., Hu, Y., Tanny, J., & Asante, E. A. (2018). Effects of shading and insect-proof screens on crop microclimate and production: A review of recent advances. *Scientia Horticulturae*, *241*, 241-251. https://doi.org/10.1016/j.scienta.2018.06.078

[119] Kim, K., Yoon, T., Jang, H., Shin, K., Sung, N., Chun, C., & Kang, H. (2008). Effects of stabilized ground covers on soil physical properties in a greenhouse. *Korean Journal of Environmental Agriculture*, *27*(2), 150-157. https://doi.org/10.5338/KJEA.2008.27.2.150

[120] Wang, X., & Xing, Y. (2017). Evaluation of the effects of irrigation and fertilization on tomato fruit yield and quality: A principal component analysis. *Scientific Reports*, *7*, 1-13. https://doi.org/10.1038/s41598-017-00373-8

[121] Padmavathy, A., & Poyyamoli, G. (2011). Effects of conventional and organic fertilizers on soil fertility and productivity of mulberry: A review. *Agricultural Reviews*, *32*(3), 177-187.

[122] Savvas, D., & Lenz, F. (1996). Influence of NaCl concentration in the nutrient solution on mineral composition of eggplants grown in sand culture. *AngewandteBotanik*, *70*(3-4), 124-127.

[123] Magán, J. J., Gallardo, M., Thompson, R. B., & Lorenzo, P. (2008). Effects of salinity on fruit yield and quality of tomato grown in soil-less culture in greenhouses in Mediterranean climatic conditions. *Agricultural Water Management*, *95*(9), 1041-1055. https://doi.org/10.1016/j.agwat.2008.03.011

[124] Wan, S., Kang, Y., Wang, D., & Liu, S. P. (2010). Effect of saline water on cucumber (Cucumis sativus L.) yield and water use under drip irrigation in North China. *Agricultural Water Management*, *98*(1), 105-113. https://doi.org/10.1016/j.agwat.2010.08.003

[125] Colla, G., Rouphael, Y., Leonardi, C., &Bie, Z. (2010). Role of grafting in vegetable crops grown under saline conditions. *Scientia Horticulturae*, *127*(2), 147-155. https://doi.org/10.1016/j.scienta.2010.08.004

[126] Savvas, D. (2002). Automated replenishment of recycled greenhouse effluents with individual nutrients in hydroponics by means of two alternative models. *Biosystems Engineering*, *83*(2), 225-236. https://doi.org/10.1006/bioe.2002.0112

[127] Rouphael, Y., Cardarelli, M., Rea, E., Battistelli, A., & Colla, G. (2006). Comparison of the subirrigation and drip-irrigation systems for greenhouse zucchini squash production using saline and non-saline nutrient solutions. *Agricultural Water Management*, *82*(1-2), 99-117. https://doi.org/10.1016/j.agwat.2005.07.018

[128] Serio, F., Elia, A., Signore, A., & Santamaria, P. (2004). Influence of nitrogen form on yield and nitrate content of subirrigated early potato. *Journal of the Science of Food and Agriculture*, *84*(11), 1428-1432. https://doi.org/10.1002/jsfa.1824

[129] Komosa, A., Piróg, J., Weber, Z., & Markiewicz, B. (2011). Comparison of yield, nutrient solution changes and nutritional status of greenhouse tomato grown in recirculating and non-recirculating nutrient solution systems. *Journal of Plant Nutrition*, *34*(10), 1473-1488. https://doi.org/10.1080/01904167.2011.585204

[130] Wortman, S. E. (2015). Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. *Scientia Horticulturae*, *194*, 34-42. https://doi.org/10.1016/j.scienta.2015.07.045

[131] Schwarz, D., Franken, P., Krumbein, A., Kläring, H. P., & Bar-Yosef, B. (2009). Nutrient management in soilless culture. *In Soilless Culture: Theory and Practice* (pp. 571-607). Elsevier. https://doi.org/10.1016/B978-044452975-6.50015-2

[132] Carmassi, G., Incrocci, L., Maggini, R., Malorgio, F., Tognoni, F., & Pardossi, A. (2005). Modeling salinity build-up in recirculating nutrient solution culture. *Journal of Plant Nutrition*, *28*(3), 431-445. https://doi.org/10.1081/PLN-200049163

[133] Saavoss, M., Majsztrik, J., Belayneh, B., Lea-Cox, J., & Lichtenberg, E. (2016). Yield, quality and profitability of sensor-controlled irrigation: A case study of snapdragon (*Antirrhinum majus* L.) production. *Irrigation Science*, *34*(5), 409-420. https://doi.org/10.1007/s00271-016-0511-y

[134] Baille, M., Baille, A., & Delmon, D. (1994). Microclimate and transpiration of greenhouse rose crops. *Agricultural and Forest Meteorology*, *71*(1-2), 83-97. https://doi.org/10.1016/0168-1923(94)90101-5

[135] Jones, J. W., Dayan, E., Allen, L. H., Van Keulen, H., & Challa, H. (1991). A dynamic tomato growth and yield model (TOMGRO). *Transactions of the ASAE*, *34*(2), 663-0672. https://doi.org/10.13031/2013.31715

[136] Gallardo, M., Thompson, R. B., & Fernández, M. D. (2013). Water requirements and irrigation management in Mediterranean greenhouses: The case of the southeast coast of Spain. In: Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate Areas, *Food and Agriculture Organization of the United Nations (FAO), 109-136*. http://www.fao.org/3/a-i3284e/i3284e06.pdf

[137] Stanghellini, C., Van't Ooster, B., &Heuvelink, E. (2019). *Greenhouse horticulture: technology for optimal crop production*. Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-879-7

[138] Nikolaou, G., Neocleous, D., Katsoulas, N., &Kittas, C. (2019). Irrigation of greenhouse crops. *Horticulturae*, *5*(1), 7. https://doi.org/10.3390/horticulturae5010007

[139] Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, *17*(4), 364-371. https://doi.org/10.5958/2455-7145.2018.00056.5

[140] Liang, J. (2018). Monitoring system for smart greenhouse agriculture. *IEEE International Conference on Electro/Information Technology (EIT), 0465-0469*. https://doi.org/10.1109/EIT.2018.8500294

[141] Ammad-Uddin, M., Ayaz, M., Mansour, E. H., Aggoune, E. H. M., & Sajjad, A. (2019). Wireless sensor network: A complete solution for poultry farming. *IEEE 2nd International Conference on Telecommunication and Networks (TEL-NET), 1-6*. https://doi.org/10.1109/TEL-NET.2019.8901496

[142] Moon, T., Hong, S., Choi, H. Y., Jung, D. H., Chang, S. H., Son, J. E., & Kim, H. K. (2014). Interpolation of greenhouse environment data using multilayer perceptron. *Computers and Electronics in Agriculture*, *108*, 183-190. https://doi.org/10.1016/j.compag.2014.08.004

[143] Rodríguez, F., Berenguel, M., Guzmán, J. L., & Ramírez-Arias, A. (2015). *Modeling and control of greenhouse crop growth*. Springer International Publishing. https://doi.org/10.1007/978-3-319-11134-6

[144] Xu, G., Zhang, F., Shah, S. G., Ye, Y., & Mao, H. (2011). Use of leaf color images to identify nitrogen and potassium deficient tomatoes. *Pattern Recognition Letters*, *32*(11), 1584-1590. https://doi.org/10.1016/j.patrec.2011.04.020

[145] Story, D., &Kacira, M. (2015). Design and implementation of a computer vision-guided greenhouse crop diagnostics system. *Machine Vision and Applications*, *26*(4), 495-506. https://doi.org/10.1007/s00138-015-0670-5

[146] Wang, H., Sanchez-Molina, J. A., Li, M., Berenguel, M., Yang, X. T., & Bienvenido, J. F. (2017). Leaf area index estimation for a greenhouse transpiration model using external climate conditions based on genetics algorithms, back-propagation neural networks and nonlinear autoregressive exogenous models. *Agricultural Water Management*, *183*, 107-115. https://doi.org/10.1016/j.agwat.2016.11.021

[147] Baille, A., González-Real, M. M., & Gutiérrez Colomer, R. P. (2006). Integrated control of greenhouse crop transpiration. In: Dayan, E., Presnov, E., Fuchs, M. (eds) *ISHS Acta Horticulturae 718: III International Symposium on Models for Plant Growth, Environmental Control and Farm*

*Management in Protected Cultivation (HortiModel 2006), 93-100.* https://doi.org/10.17660/ActaHortic.2006.718.9

[148] Katsoulas, N., Sapounas, A., De Zwart, F., Dieleman, J. A., & Stanghellini, C. (2015). Reducing ventilation requirements in semi-closed greenhouses increases water use efficiency. *Agricultural Water Management*, *156*, 90-99. https://doi.org/10.1016/j.agwat.2015.04.003

[149] Nicolás-Cañas, F. J., Galdeano-Gómez, E., & Molina-Morales, Á. (2021). Environmental sustainability in the agrifood sector: The role of water footprint and carbon footprint on Almería's greenhouse vegetable production. *Sustainability*, *13*(15), 8223. https://doi.org/10.3390/su13158223

[150] Pardossi, A., Malorgio, F., Incrocci, L., Carmassi, G., Maggini, R., Massa, D., &Tognoni, F. (2006). Simplified models for the water relations of soilless cultures: What they do or suggest for sustainable water use in intensive horticulture. *Acta Horticulturae*, *718*, 425-434. https://doi.org/10.17660/ActaHortic.2006.718.52

[151] Incrocci, L., Massa, D., & Pardossi, A. (2017). New trends in the fertigation management of irrigated vegetable crops. *Horticulturae*, *3*(2), 37. https://doi.org/10.3390/horticulturae3020037

[152] Montesano, F. F., Serio, F., Mininni, C., Signore, A., Parente, A., & Santamaria, P. (2015). Tensiometer-based irrigation management of subirrigated soilless tomato: Effects of substrate matric potential control on crop performance. *Frontiers in Plant Science*, *6*, 1150. https://doi.org/10.3389/fpls.2015.01150

[153] Gallardo, M., Thompson, R. B., & Fernandez, M. D. (2013). Water requirements and irrigation management in Mediterranean greenhouses: The case of the southeast coast of Spain. *Good Agricultural Practices for Greenhouse Vegetable Crops, FAO, 109-136.* http://www.fao.org/3/i3284e/i3284e.pdf

[154] Abdel-Razzak, H. S., Wahb-Allah, M. A., Ibrahim, M. E., Alenazi, M., &Alsadon, A. (2016). Response of cherry tomato to irrigation levels and fruit pruning under greenhouse conditions. *Journal of Agricultural Science and Technology*, *18*(4), 1091-1103. http://jast.modares.ac.ir/article-23-4987-en.html

[155] Sánchez-Molina, J. A., Reinoso, J. V., Acién, F. G., Rodríguez, F., & López, J. C. (2019). Development of a biomass-based system for nocturnal temperature and diurnal CO2 concentration control in greenhouses. *Biomass and Bioenergy*, *124*, 142-154. https://doi.org/10.1016/j.biombioe.2019.03.013

[156] Bueno-Delgado, M. V., Molina-Martínez, J. M., Correoso-Campillo, R., &Pavón-Mariño, P. (2016). Ecofert: An Android application for the optimization of fertilizer cost in fertigation. *Computers and Electronics in Agriculture*, *121*, 32-42. https://doi.org/10.1016/j.compag.2015.11.006

[157] Gallardo, M., Thompson, R. B., Valdez, L. C., & Fernández, M. D. (2006). Use of stem diameter variations to detect plant water stress in tomato. *Irrigation Science*, *24*(4), 241-255. https://doi.org/10.1007/s00271-005-0027-3

[158] Fernández, M. D., González, A. M., Carreño, J., Pérez, C., &Bonachela, S. (2007). Analysis of on-farm irrigation performance in Mediterranean greenhouses. *Agricultural Water Management*, *89*(3), 251-260. https://doi.org/10.1016/j.agwat.2007.02.001