

Potential of the Advanced Precision Irrigation Techniques for Enhanced Protected Cultivation Systems in the Developing Nations

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 to 11].

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].

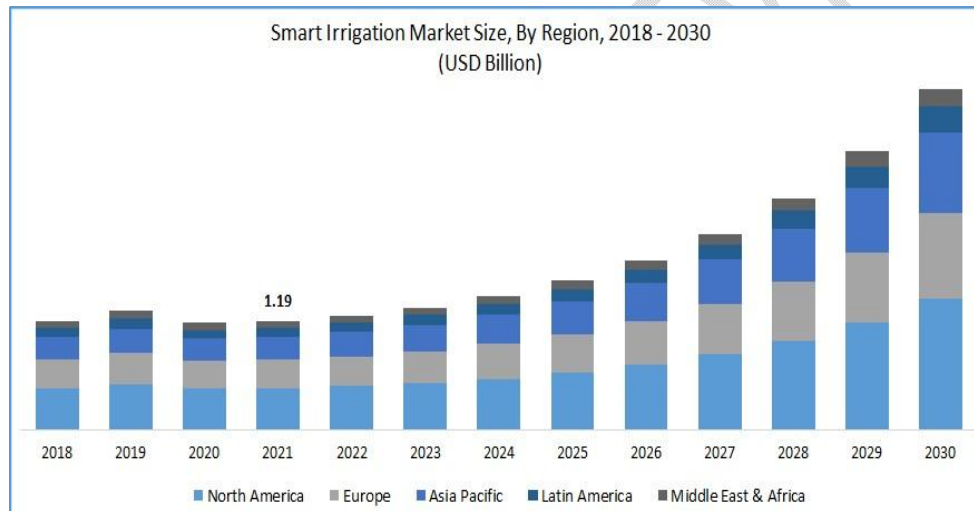
Table 1. Global adoption of precision irrigation in protected cultivation by region and crop type.

Region	Greenhouse Area	Precision Irrigation	Main Crops
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	(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/m³)
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].

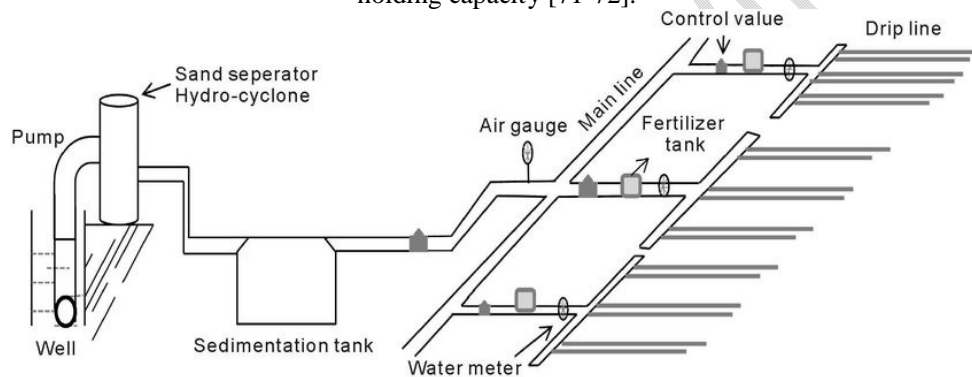


Figure 2. Schematic diagram of a subsurface drip irrigation system in a greenhouse.
Source: [70].

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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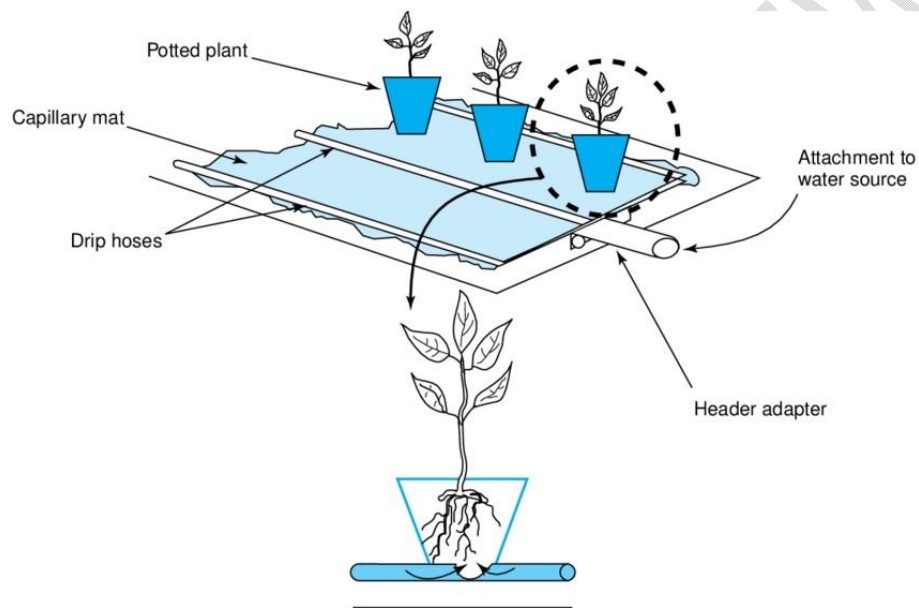


Figure 3. Diagram of a capillary mat irrigation system for potted plants in a greenhouse.

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.

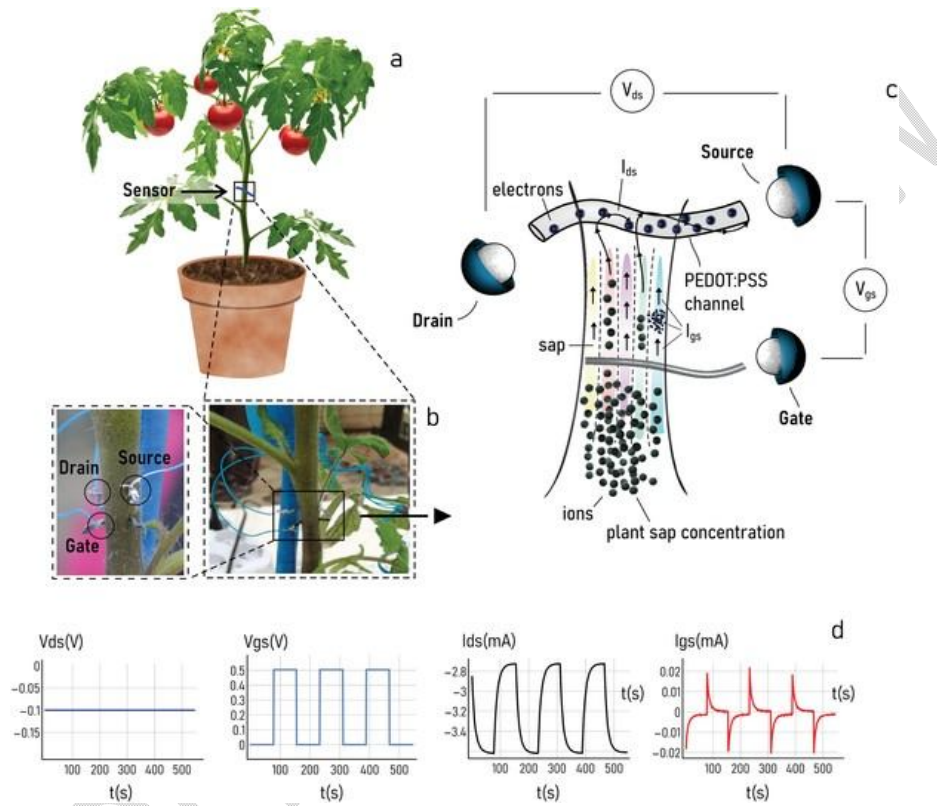


Figure 4. Example of a sap flow sensor installed on a tomato plant stem in a greenhouse

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 CO₂. 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.

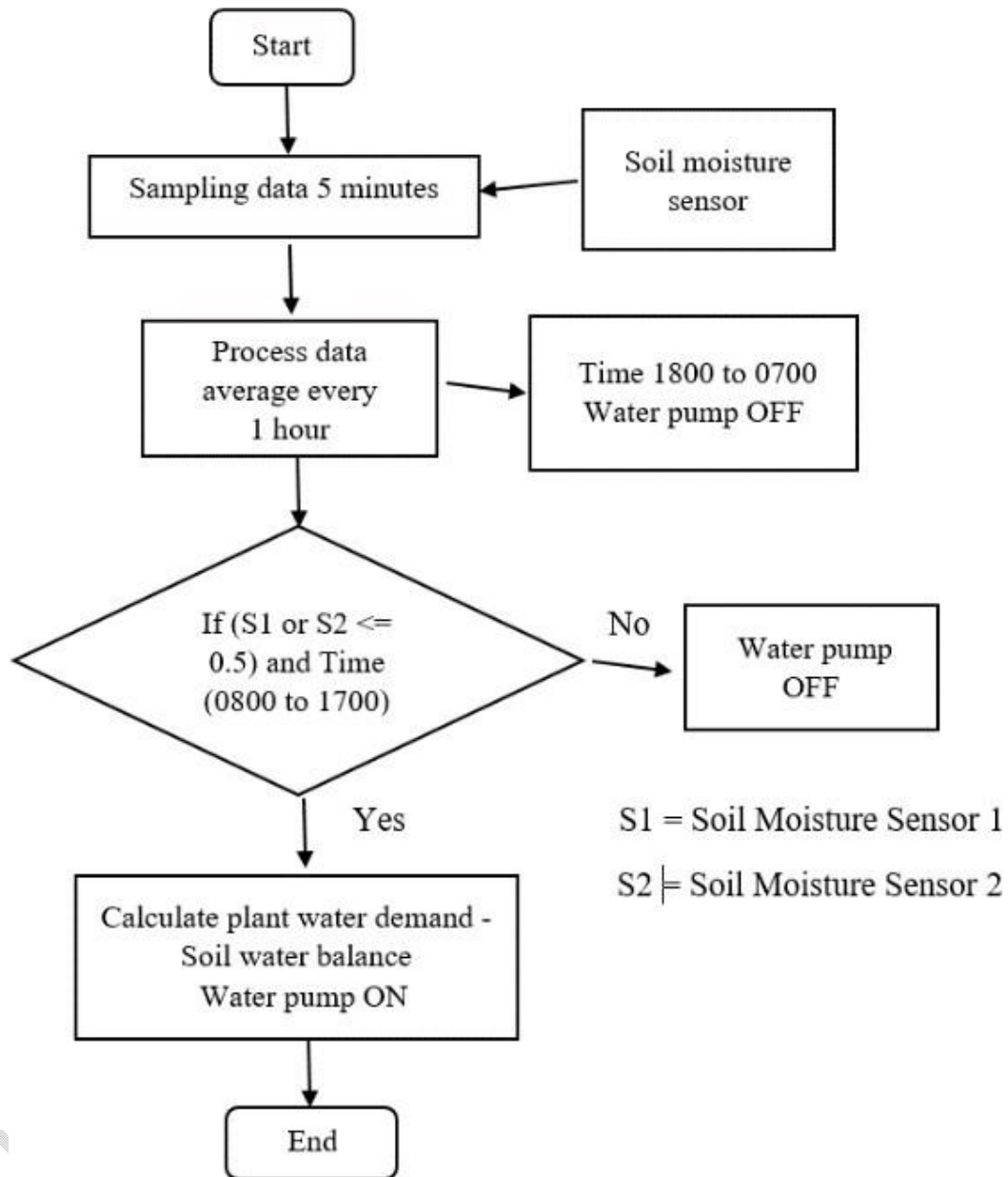


Figure 5. Schematic diagram of a soil moisture-based irrigation control system.

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	μmol/m ² /s	0 to 3000	±5

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

5. Irrigation Scheduling and Control

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.

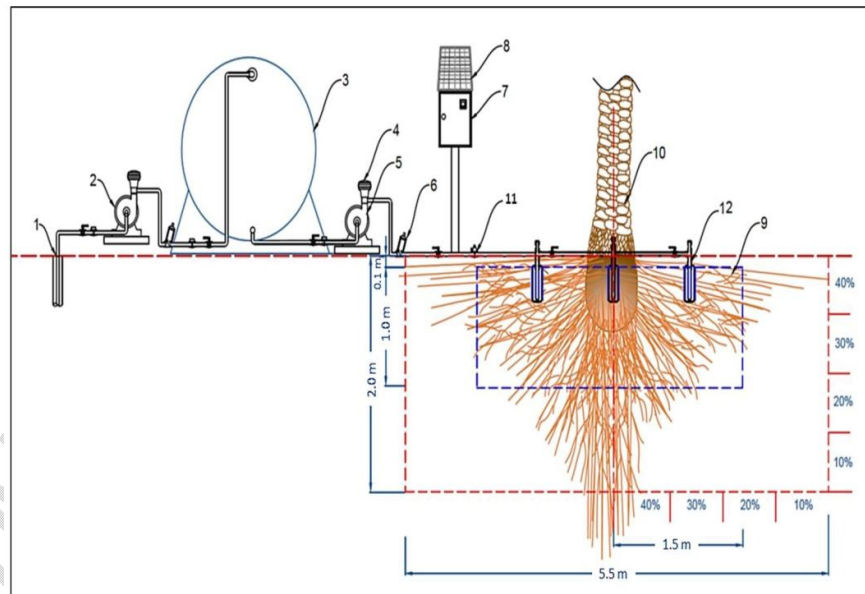


Figure 6. Example of a sensor-based automated irrigation controller for greenhouse

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 (ET_o): 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 (K_c): 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 (R_e): the portion of rainfall that is available for crop use, after accounting for losses due to runoff, deep percolation, and canopy interception
- Irrigation efficiency (E_i): 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:

$$IR = (ET_o \times K_c - R_e) / E_i$$

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 (K_c) for tomato at different growth stages.

Growth Stage	Duration (days)	K _c
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].

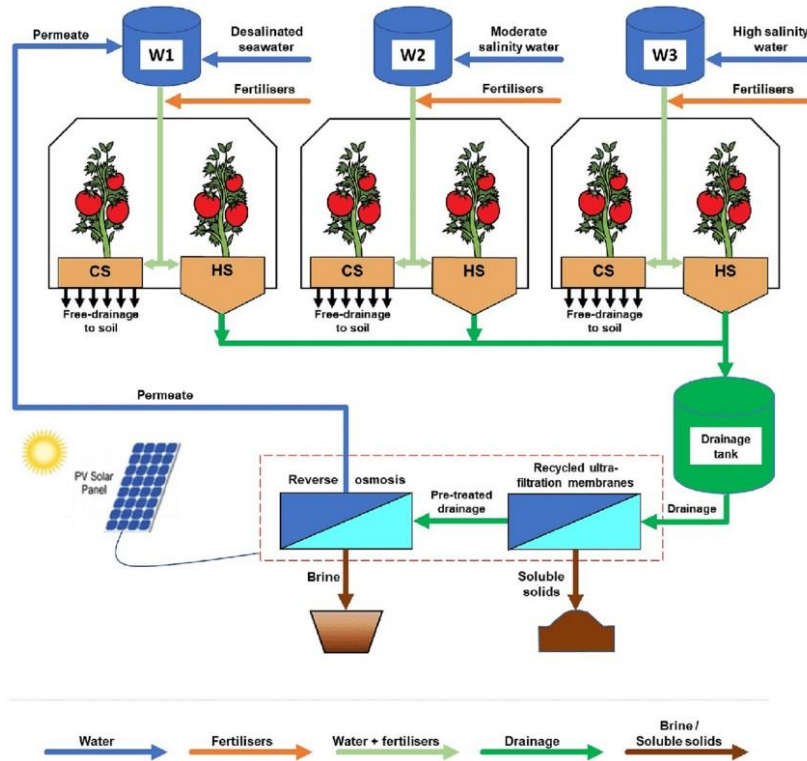


Figure 7. Schematic diagram of a precision irrigation and fertigation system in a Dutch tomato greenhouse.

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.

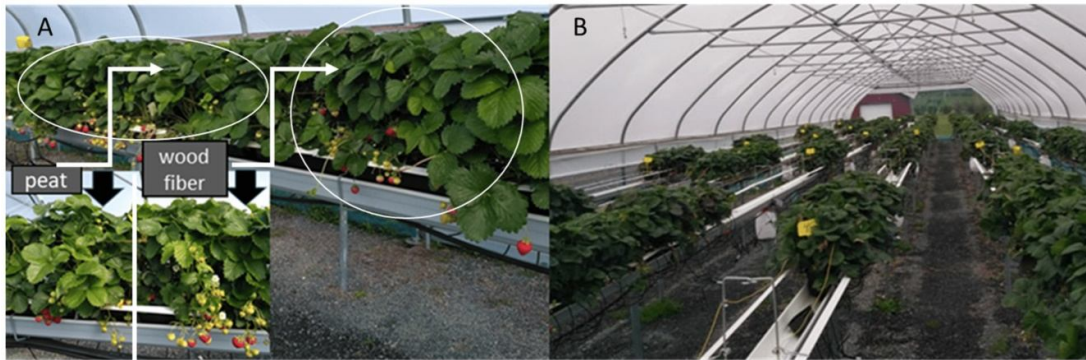


Figure 8. Example of a precision irrigation and fertigation system in a Japanese strawberry high tunnel.

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.

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