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

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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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 horticulturel; water use efficiency; sensors.

1. INTRODUCTION

Precision irrigation techniques have emerged as a critical tool for enhancing the productivity, efficiency, and sustainability of protected cultivation systems worldwide (Tawegoum et al., 2006; Montero et al., 2009). 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 (Ruiz-Garcia et al., 2009). 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 (Marketsand Markets, 2020). Protected cultivation, including greenhouse horticulture, is a key application segment for precision irrigation technologies, accounting for over 30% of the global market share (Bauchet & Baudry, 2010).

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 (Kumar et al., 2018). 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 (Goel & Kumar, 2020).

2. 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 (Nicola & Fontana, 2014; Chai et al., 2016; Rouphael et al., 2008; Francescangeli et al., 2007).

2.1 Scope of Precision Irrigation Technologies

- 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 (Stanghellini et al., 2007).
- **Micro-sprinklers and foggers** that provide localized irrigation and humidity control in greenhouses (Gómez & Izzo, 2018).
- **Substrate moisture sensors** that monitor the water content and availability in soilless growing media (Fernández et al., 2010).
- **Plant-based sensors** that measure indicators of crop water status, such as stem diameter variations or leaf temperature (Schröder & Lieth, 2002).
- **Automated irrigation controllers** that adjust irrigation schedules based on sensor feedback and weather data (Pardossi et al., 2004).
- **Fertigation systems** that integrate precision irrigation with nutrient management to optimize crop nutrition (Jones, 2016).
- **Data analytics and decision support tools** that help growers interpret sensor data and make informed irrigation decisions (Baille, 2001).

2.2 Benefits of Precision Irrigation

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% (Zegbe et al., 2014; Magán et al., 2019; Savvas & Gruda, 2018; Ullah et al., 2017). 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 (Rouphael & Colla, 2020; Bar-Tal et al., 2001; Qaryouti et al., 2007).

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

Region	Greenhouse Area (ha)	Precision Irrigation Adoption (%)	Main Crops
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

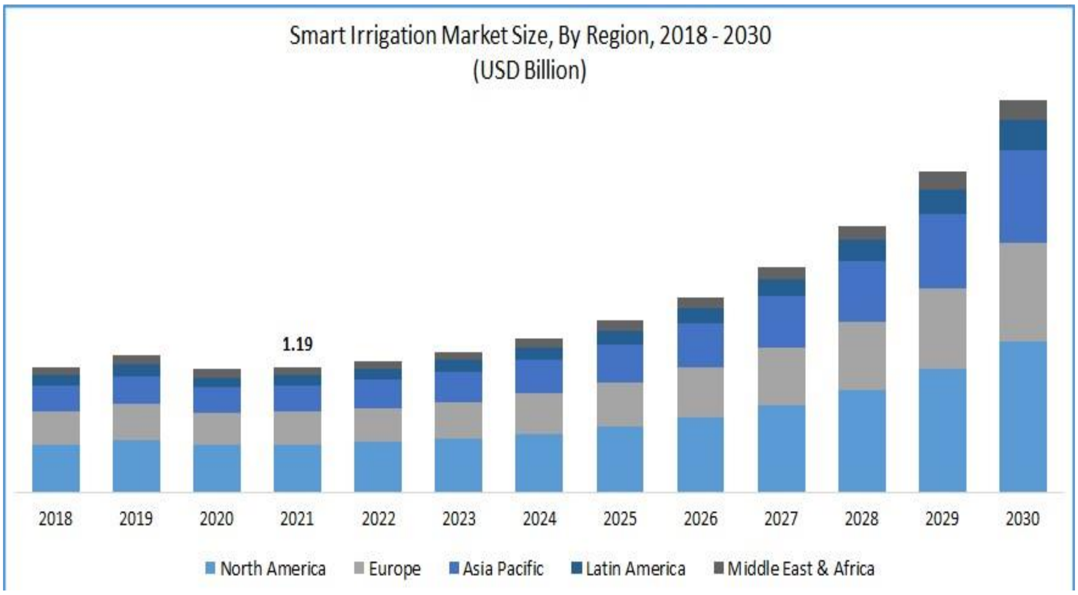

Fig. 1. Global precision irrigation market size and growth forecast by application, 2020-2026 (USD Billion)

2.3 Enablers of Precision Irrigation Adoption

Several factors are driving the adoption and scaling of precision irrigation in protected cultivation. 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 (Jensen, 2002).

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 (Van Kooten et al., 2008).

Capacity building and training programs that provide growers with the knowledge and skills needed to effectively implement and manage precision irrigation systems (Stafford, 2000).

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 (Pathak et al., 2018).

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 (FAO, 2013).

3. 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 (Putra & Yuliando, 2015; Liang et al., 2021).

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 (Hanson et al., 1993; Singh et al., 2022; Singh et al., 2023).

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 (Saikanth et al., 2023; Singh et al., 2023).

A main line that conveys the water from the source to the field, usually made of PVC or polyethylene pipes (Verma et al., 2023).

Submains and laterals that distribute the water across the field, with emitters or drippers spaced at regular intervals to match the plant spacing (Kumar et al., 2023).

Pressure regulators and valves that maintain a constant operating pressure and allow for zoning and automation of the irrigation system (Singh & Patel, 2022).

Optional components such as fertilizer injectors, water meters, and sensors that enable fertigation and monitoring of the irrigation performance (Kumar et al., 2023).

Surface drip irrigation is suitable for a wide range of protected cultivation systems, including row crops, raised beds, and potted plants (Burt & Styles, 2007; Lamm et al., 2012; Thompson et al., 2009).

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 (Camp, 1998; Singh, 2014).

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 (Enciso et al., 2015; Arbat et al., 2013).

Reduced weed growth, as the lack of surface wetting minimizes the germination and survival of weed seeds (Ayars et al., 2015).

Improved fertilizer use efficiency, as the nutrients are placed in the root zone and are less prone to leaching or runoff (Hanson & May, 2004; Ayars et al., 1999).

Enhanced crop quality, as the dry soil surface reduces the incidence of fruit rot and other diseases associated with wet foliage (Lamm et al., 2007).

Increased system longevity, as the buried emitters are protected from damage by UV radiation, pests, and cultural practices such as pruning or harvesting (Badr et al., 2016).

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 (Hanson et al., 2004; Dabach et al., 2015).

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 (Gonçalves et al., 2020; Grabow et al., 2006).

Limited suitability for shallow-rooted crops or those with high water requirements, as the emitter depth and spacing may not match the crop needs (Lamm et al., 2012; Rijsberman, 2006).

Potential for root intrusion and clogging of the emitters, especially in fine-textured soils or with poor water quality (Molden et al., 2010; Fereres et al., 2011).

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 (Surendran et al., 2015; Pereira et al., 2015).

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 (Allen et al., 1998; Hargreaves & Samani, 1985).

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 (Steduto et al., 2012; Fereres & Soriano, 2007).

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 (Geerts & Raes, 2009; Kang et al., 2000).

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 (Costa et al., 2007; Chai et al., 2014).

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 (Howell, 2001).

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 (Lovelli et al., 2007).

Scheduling the irrigation based on the crop evapotranspiration and substrate moisture, and using sensors or models to optimize the irrigation frequency and duration (Nagaz et al., 2012).

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 (Saleh & Ibrahim, 2016).

Implementing disease management strategies, such as pruning, ventilation, or fungicide applications, to reduce the risk of foliar diseases associated with micro-sprinkler irrigation (El-Noemani et al., 2010).

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

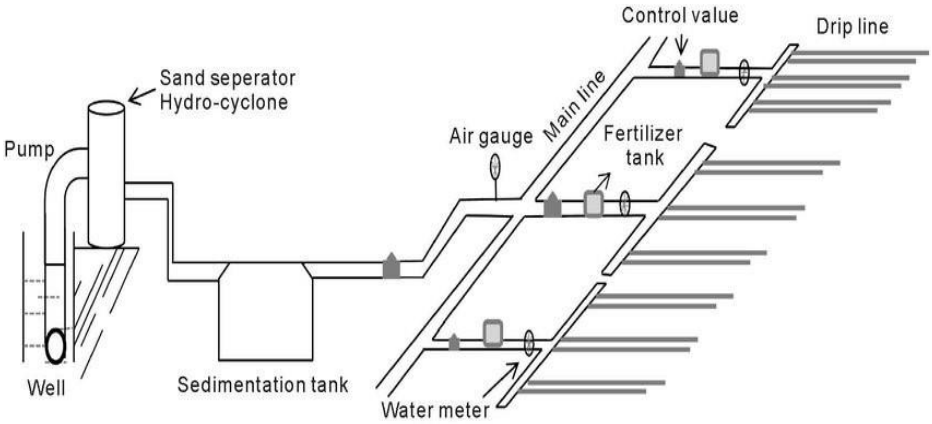

Fig. 2. Schematic diagram of a subsurface drip irrigation system in a greenhouse.
Source: (Surendran, 2015)

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

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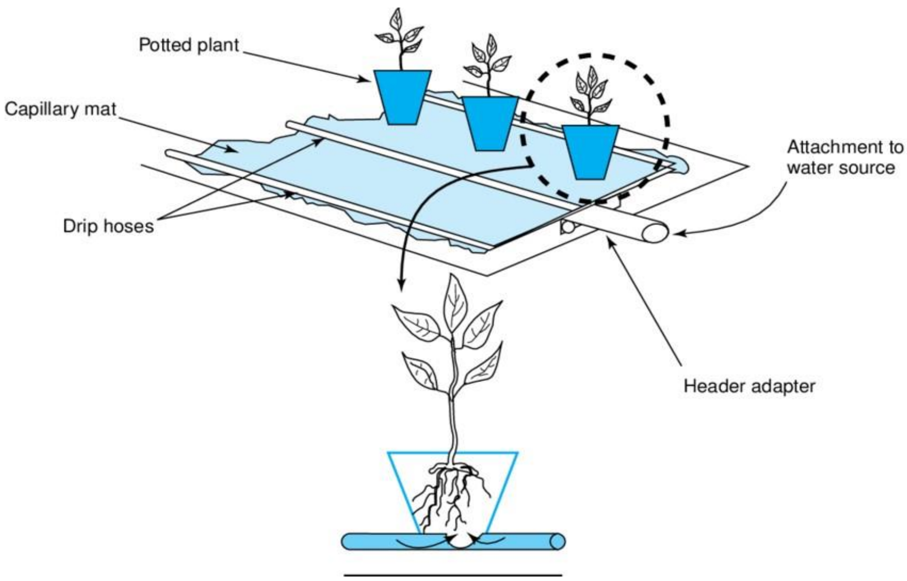

Fig. 3. Diagram of a capillary mat irrigation system for potted plants in a greenhouse

3.3 Capillary Mats and Wicks

Capillary mats and wicks are a precision irrigation technique that leverages the capillary action of water to deliver moisture directly to plant roots (Yenesew & Tilahun, 2009). These systems use thin, porous materials such as synthetic fibers or foam, which are placed under the plant containers and connected to a water reservoir (Kebe & Guttieri, 2020; Fathi & Tari, 2016; Rai et al., 2005).

Advantages of Capillary Mats and Wicks:

Capillary mats and wicks offer several benefits for protected cultivation:

1. Cost-effectiveness and simplicity: These systems require minimal equipment and can be easily installed and maintained by unskilled labor (Farooq et al., 2009).
2. Water and nutrient efficiency: The capillary action delivers water directly to the root

zone, minimizing losses from evaporation or leaching (Sleper & Poehlman, 2006).

3. Uniform moisture distribution: The porous material provides a consistent water supply to all plants, regardless of their position or size (Dodd, 2009).
4. Reduced disease risk: The absence of water on the foliage and the use of well-drained substrates minimize the growth and spread of pathogens (Hoddy, 2019).
5. Suitability for small-scale growers: Capillary mats and wicks can be used in greenhouses, grow rooms, or even indoors without the need for electricity or plumbing (Mupambi et al., 2018).

Limitations and Challenges of Capillary Mats and Wicks:

Despite their advantages, capillary mats and wicks also have some constraints:

1. Limited water holding capacity: The porous material can only store a finite amount of water and may require frequent refilling or a large reservoir for long-term use (Möller & Assouline, 2007).
2. Sensitivity to water quality: The presence of salts, algae, or other contaminants in the water can clog the pores and reduce the capillary action over time (Castellano et al., 2008).
3. Difficulty in moisture control: The capillary action depends on substrate properties and evaporative demand, which may result in over- or under-watering if not properly managed (Gogo et al., 2012).
4. Incompatibility with some growing media: Coarse or water-repellent substrates may not allow for good capillary contact or water retention (Ilić et al., 2015).

Best Practices for Optimizing Capillary Mats and Wicks:

To overcome these limitations and optimize the use of capillary mats and wicks, the following best practices are recommended:

- Select high-quality, durable, and inert materials for the mats and wicks, such as polyester, polypropylene, or fiberglass. Avoid materials that can degrade or release toxins over time (Carmassi et al., 2005).
- Use compatible and well-draining growing media, such as peat moss, coir, perlite, or vermiculite. Ensure good contact between the mat/wick and the substrate (Saavoss et al., 2016).
- Monitor the water level and quality in the reservoir regularly. Use filters, disinfectants, or nutrients as needed to maintain a clean and balanced supply (Baille et al., 1994).
- Adjust the mat/wick size and spacing according to the plant size and water needs. Use multiple mats/wicks for larger containers or higher evaporative demand (Jones et al., 1991).
- Combine 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 (Gallardo et al., 2013; Stanghellini et al., 2019).

3.4 Hydroponic Systems with Precision Irrigation

Hydroponic systems are a type of protected cultivation where plants are grown in a nutrient solution instead of soil (Nikolaou et al., 2019). The roots are either suspended directly in the solution or supported by an inert medium such as rockwool, perlite, or coconut fiber (Sharma et al., 2018).

Benefits of Hydroponic Systems:

Compared to soil-based cultivation, hydroponic systems offer several advantages:

1. Higher yields and quality: Plants have access to an optimal and balanced supply of water and nutrients, and are not limited by soil-borne pests or diseases (Liang, 2018).
2. Faster growth and shorter cycles: Plants can allocate more resources to vegetative and reproductive growth, and are not stressed by fluctuations in soil moisture or temperature (Ammad-Uddin et al., 2019).
3. Greater water and nutrient efficiency: The nutrient solution is recirculated and reused, and nutrients are precisely delivered to the roots based on crop needs (Moon et al., 2014).
4. Reduced environmental impact: Closed-loop systems minimize leaching and runoff of water and nutrients, and the absence of soil eliminates the need for fumigation or herbicides (Rodríguez et al., 2015).

Challenges and Requirements of Hydroponic Systems:

Hydroponic systems also have some challenges and requirements compared to traditional cultivation:

1. Higher initial and operational costs: The systems require specialized equipment, materials, and infrastructure, and consume more energy and labor (Xu et al., 2011).
2. Greater technical complexity: Growers need to monitor and control multiple parameters such as pH, EC, temperature, oxygen, and nutrient ratios, and respond quickly to any deviations (Story & Kacira, 2015).
3. Dependence on external inputs: The systems rely on a constant supply of water, electricity, and fertilizers, and are vulnerable to disruptions or shortages (Wang et al., 2017).
4. Limited buffer capacity: Plants are more sensitive to stresses or imbalances in the root zone, and any mistakes or failures can quickly lead to crop damage or loss (Baille et al., 2006; Katsoulas et al., 2015).

Precision Irrigation Techniques in Hydroponic Systems:

Common precision irrigation techniques used in hydroponic systems include:

- Drip irrigation: 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 crop water use and growth stage (Nicolás-Cañas et al., 2021).
- Ebb and flow irrigation: 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 substrate properties and crop requirements (Pardossi et al., 2006).
- Nutrient film technique (NFT): 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 crop uptake and environmental conditions (Incrocci et al., 2017).
- Aeroponics: Roots are suspended in air and misted with the nutrient solution at regular intervals, with the droplet size and frequency optimized based on root morphology and crop water stress (Montesano et al., 2015).

Monitoring and Control Tools for Hydroponic Systems:

To optimize the performance of hydroponic systems, various sensors and control tools can be integrated:

- pH and EC sensors: Measure the acidity and salinity of the nutrient solution, triggering the addition of acids, bases, or fertilizers to maintain optimal ranges for the crop (Gallardo et al., 2013).
- Dissolved oxygen sensors: Monitor the oxygen level in the solution and activate aeration or oxygenation systems to prevent root hypoxia or anoxia (Abdel-Razzak et al., 2016).
- Temperature sensors: Control the heating or cooling of the solution to maintain the optimal root zone temperature for crop growth and development (Sánchez-Molina et al., 2019).
- Moisture sensors: Detect the water content or matric potential in the substrate and adjust irrigation frequency or duration to prevent over- or under-watering (Bueno-Delgado et al., 2016).
- Spectral sensors: Assess crop health and nutrient status based on leaf color or reflectance, guiding fertigation and crop management decisions (Gallardo et al., 2006).
- Automated control systems: Integrate sensor data and crop models to optimize irrigation and nutrient delivery based on environmental conditions and crop growth stage (Fernández et al., 2007).

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

4. SENSORS AND MONITORING TOOLS

Sensors and monitoring tools play a crucial role in precision irrigation systems for protected cultivation. They enable real-time monitoring of key parameters related to the crop, growing medium, and environment. This data empowers growers to make informed irrigation decisions based on the crop's actual water needs rather than fixed schedules or subjective assessments (van Iersel et al., 2013; Lea-Cox, 2012). Implementing a data-driven approach to irrigation management can lead to significant benefits:

- Improved water and nutrient use efficiency
- Increased crop yield and quality
- Enhanced resource conservation
- Reduced labor and energy costs (Jones, 2004; Pardossi & Incrocci, 2011; Baille, 2001)

This section will explore some of the most common types of sensors used in precision irrigation systems.

4.1 Soil Moisture Sensors

Soil moisture sensors measure the water content or potential in the growing medium, which can be soil, soilless substrate, or hydroponic solution (Lea-Cox et al., 2018). They provide direct feedback on the moisture status of the root zone and can be used to automate irrigation events based on predefined thresholds (Chappell et al., 2013).

4.2 Types of Soil Moisture Sensors

There are several types of soil moisture sensors available, each with its own advantages and limitations. The most common types include:

4.2.1 Tensiometers

Tensiometers measure the soil water potential, which represents the force required to extract water from the soil pores (Muñoz-Carpena et al., 2005). They consist of a porous ceramic cup filled with water, connected to a pressure gauge or transducer. As the soil dries out, water is pulled out of the ceramic cup, creating a vacuum that is measured by the gauge (Marouelli & Silva, 2007).

Advantages of tensiometers:

- Simple and reliable operation
- Can be used to monitor soil moisture status and schedule irrigation based on crop- and soil-specific thresholds (Thompson et al., 2007)

Limitations of tensiometers:

- Limited measurement range (typically 0 to -85 kPa)
- Require regular maintenance and refilling to function properly (Payero & Irmak, 2006)

4.2.2 Capacitance and Time-Domain Reflectometry (TDR) Sensors

Capacitance and TDR sensors are electronic devices that measure soil water content by detecting changes in the dielectric properties of the soil (Susha Lekshmi et al., 2014). Capacitance sensors measure the capacitance between two electrodes, which is proportional to the soil water content. TDR sensors emit an electromagnetic pulse through the soil and measure the time for the pulse to reflect back, which is related to the soil water content (Robinson et al., 2003).

Advantages of capacitance and TDR sensors:

- High accuracy across a wide range of soil moisture levels
- Less affected by soil salinity or temperature compared to tensiometers
- Suitable for automated irrigation control (Fares & Polyakov, 2006)

Limitations of capacitance and TDR sensors:

- Higher cost compared to tensiometers
- Require a power source and data logger for operation (Bittelli, 2010)

The table below compares the key characteristics of tensiometers, capacitance sensors, and TDR sensors:

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: Charlesworth, 2005; Muñoz-Carpena, 2004; Leib et al., 2003

4.3 Plant Water Status Sensors

Plant water status sensors measure the water content, potential, or stress level directly in plant tissues such as leaves, stems, or fruits (Jones, 2004). They provide valuable information on the crop's actual water needs and can help optimize irrigation scheduling based on the plant's physiological responses to the environment (Fernández, 2014). Common plant water status sensors include:

4.3.1 Leaf and stem water potential sensors

Leaf and stem water potential sensors measure the negative pressure or tension in the plant xylem, which reflects the plant's water status (Hsiao, 1990). The most widely used method is the pressure chamber, where a leaf or stem sample is placed in a sealed chamber and pressurized until xylem sap appears at the cut surface. The pressure required to force the sap out is equal to the water potential of the sample (Scholander et al., 1965).

Advantages of leaf and stem water potential sensors:

- Direct measurement of plant water status
- Can be used to detect crop water stress and schedule irrigation accordingly (Shackel et al., 1997)

Limitations of leaf and stem water potential sensors:

- Destructive measurement (requires leaf or stem samples)
- Labor-intensive and time-consuming
- Not suitable for automated irrigation control (Jones, 2007)

4.3.2 Sap flow sensors

Sap flow sensors measure the rate and direction of water movement in the plant stem, which is closely related to transpiration and water uptake (Smith & Allen, 1996). They use heat as a tracer and measure the velocity of a heat pulse or the temperature difference between two probes inserted into the stem (Burgess et al., 2001).

Advantages of sap flow sensors:

- Non-destructive and continuous measurement of plant water use
- Can be used to estimate crop water requirements and optimize irrigation scheduling (Fernández et al., 2008)

Limitations of sap flow sensors:

- Indirect measurement of plant water status
- Calibration required for each plant species and growing condition
- High cost and technical complexity (Steppe et al., 2010)

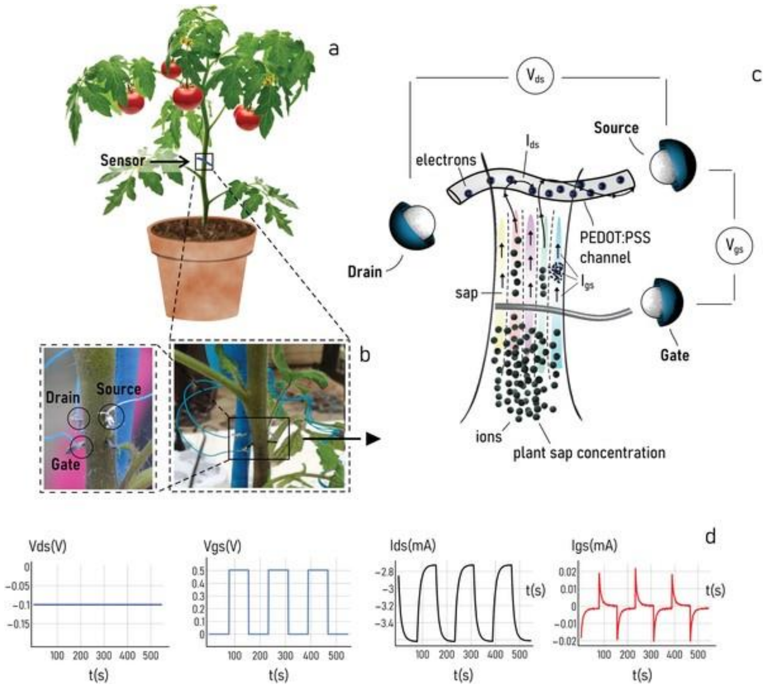

Fig. 4. Example of a sap flow sensor installed on a tomato plant stem in a greenhouse

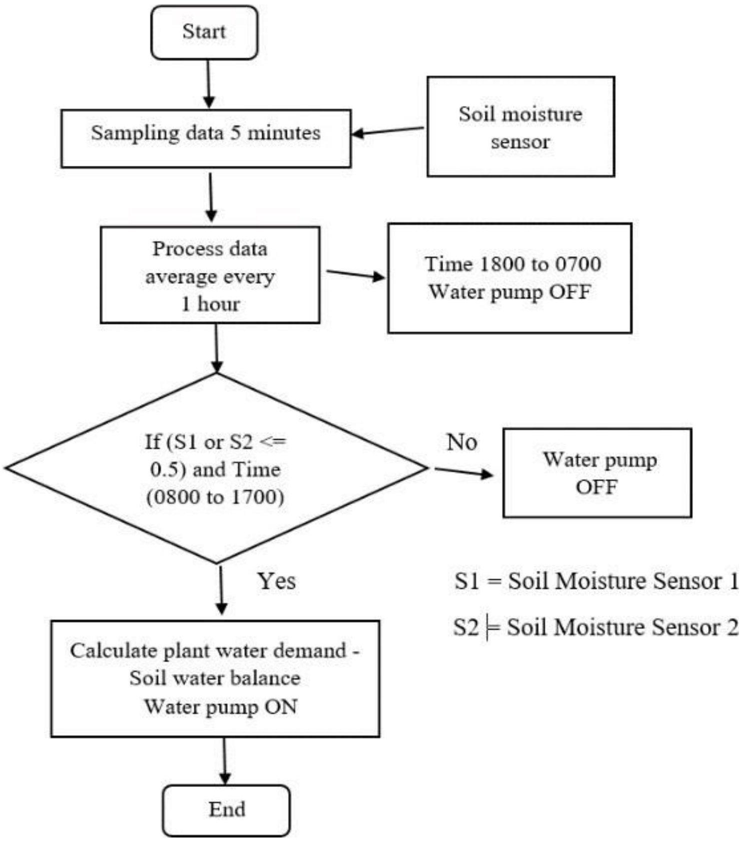

Fig. 5. Schematic diagram of a soil moisture-based irrigation control system.

4.3.3 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.

4.4 There are Several Types of Microclimate Sensors, Including:

4.4.1 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.

4.5 Evapotranspiration-based Irrigation Scheduling Methods

Evapotranspiration (ET) is the combined process of water loss from the crop and soil through evaporation and transpiration. ET-based irrigation scheduling methods estimate crop water requirements using the following key parameters:

- **Reference evapotranspiration (ETo)**: The ET rate of a reference crop (usually grass or alfalfa) under standard conditions, estimated using weather data and standardized equations such as the FAO Penman-Monteith method (Allen et al., 1998; Pereira et al., 2015).
- **Crop coefficient (Kc)**: A dimensionless factor that relates the actual crop ET to the reference ET, based on crop type, growth stage, and management practices (Doorenbos & Pruitt, 1977; Pereira et al., 2021).

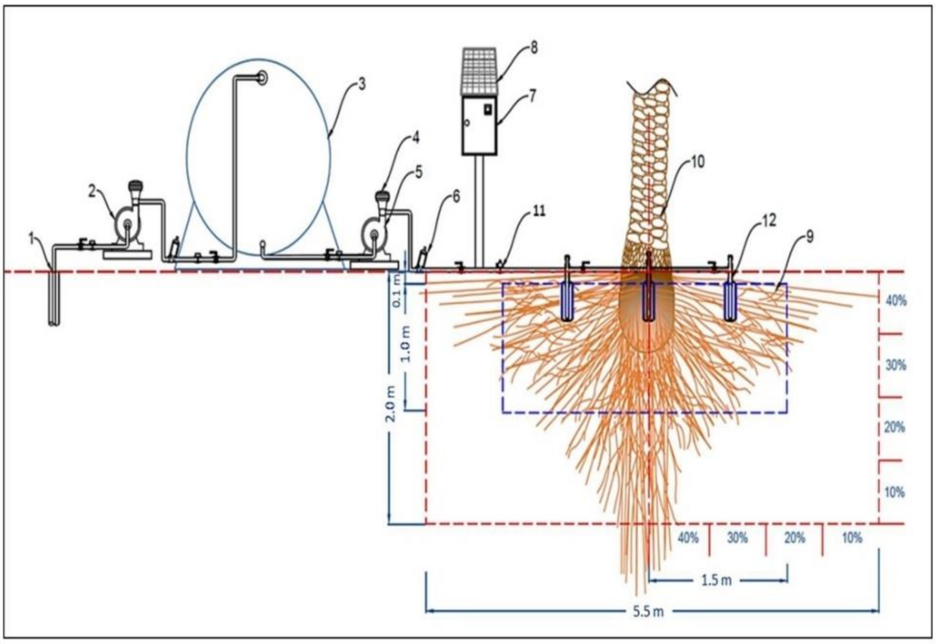

Fig. 6. Example of a sensor-based automated irrigation controller for greenhouse
Some common irrigation scheduling and control methods are described below.

- **Effective rainfall (Re)**: The portion of rainfall available for crop use after accounting for losses due to runoff, deep percolation, and canopy interception (Dastane, 1978; Patwardhan et al., 1990).
- **Irrigation efficiency (Ei)**: The ratio of water beneficially used by the crop to the water applied by the irrigation system, which depends on system design, maintenance, and operation (Burt et al., 1997; Hsiao et al., 2007).

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

IR = (5 mm/day × 1.2 - 2 mm/day) / 0.8 = 5 mm/day

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

Advantages of ET-based irrigation scheduling:

- Based on actual crop water use and climatic conditions, rather than fixed schedules or subjective judgments
- Can be adapted to different crops, growth stages, and management practices using specific crop coefficients and adjustment factors
- Can be automated using weather stations, sensors, and computer models to calculate and implement irrigation requirements in real-time (Gu et al., 2020; Mun et al., 2015)

Limitations and challenges of ET-based methods:

- Require accurate and reliable weather data, which may not be available or representative of specific site conditions
- Assume crop coefficients and other parameters are constant and uniform, which may not be true for all crops, varieties, and management practices
- Do not account for spatial variability of soil moisture and crop water status within the field, which can lead to over- or under-irrigation in some areas (Bockhold et al., 2011; Nahar et al., 2022)

The following table provides an example of typical 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

Source: Allen et al., 1998

4.6 Soil Moisture-based Irrigation Scheduling 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 (Evett & Parkin, 2005). These methods are based on the principle that crop water uptake and growth are directly related to water availability in the root zone and that maintaining soil moisture within an optimal range can maximize crop yield and quality (Thompson et al., 2007).

Several soil moisture-based irrigation scheduling methods are available, including:

1. **Feel and appearance method**: A qualitative method that involves observing and feeling soil texture, color, and consistency to estimate soil moisture status and irrigation need (USDA, 1998).
2. **Gravimetric method**: A quantitative method that involves taking soil samples, weighing them before and after drying, and calculating soil water content as the ratio of water mass to dry soil mass (Black, 1965).
3. **Soil moisture sensors**: Electronic devices that measure soil water content or potential using various principles such as resistance, capacitance, or reflectometry, providing continuous, real-time data on soil moisture status (Muñoz-Carpena et al., 2004; Pardossi et al., 2009).
4. **Soil water balance models**: Computer programs that simulate soil water dynamics based on inputs of climate, soil, crop, and irrigation data, estimating soil moisture content and irrigation requirements over time (Feddes et al., 1974; Bastiaanssen et al., 2007).

These methods allow growers to monitor soil moisture status and make informed decisions about when and how much to irrigate based on crop- and soil-specific thresholds. By maintaining optimal soil moisture levels, growers can promote crop growth and quality while minimizing water losses and environmental impacts.

Fig. 7 illustrates a precision irrigation and fertigation system in a Dutch tomato greenhouse, which integrates soil moisture sensors, weather data, and computerized control to optimize water and nutrient management based on crop requirements and environmental conditions.

4.7 Microclimate Sensors for Precision Irrigation

Microclimate sensors measure environmental conditions in the plant canopy or root zone, such as temperature, humidity, light, and CO2. These sensors provide valuable information on factors influencing crop water use and can be used to adjust irrigation and ventilation systems to optimize growing conditions. Several types of microclimate sensors are commonly used in precision irrigation systems:

4.7.1 Temperature and humidity sensors

Temperature and humidity sensors measure air or substrate temperature and relative humidity, which affect crop evapotranspiration and water demand. Temperature sensors include thermocouples, thermistors, and infrared sensors, while humidity sensors include capacitive, resistive, and dew point sensors (Castañeda-Miranda & Castaño, 2017). These sensors are widely available and relatively inexpensive but require proper placement and shielding to avoid errors due to radiation or air movement.

4.7.2 Solar radiation and PAR sensors

Solar radiation and photosynthetically active radiation (PAR) sensors 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 (Baille et al., 2001; Valiente-Banuet & Gutiérrez-Ochoa, 2016). These sensors are important for estimating crop water use and potential yield and for controlling supplemental lighting and shading systems in greenhouses. However, they are more expensive than temperature and humidity sensors and require regular calibration and maintenance to ensure accurate measurements. Integrating these sensors with irrigation scheduling and control systems can help growers optimize crop water use, yield, and quality while minimizing resource waste and environmental impact.

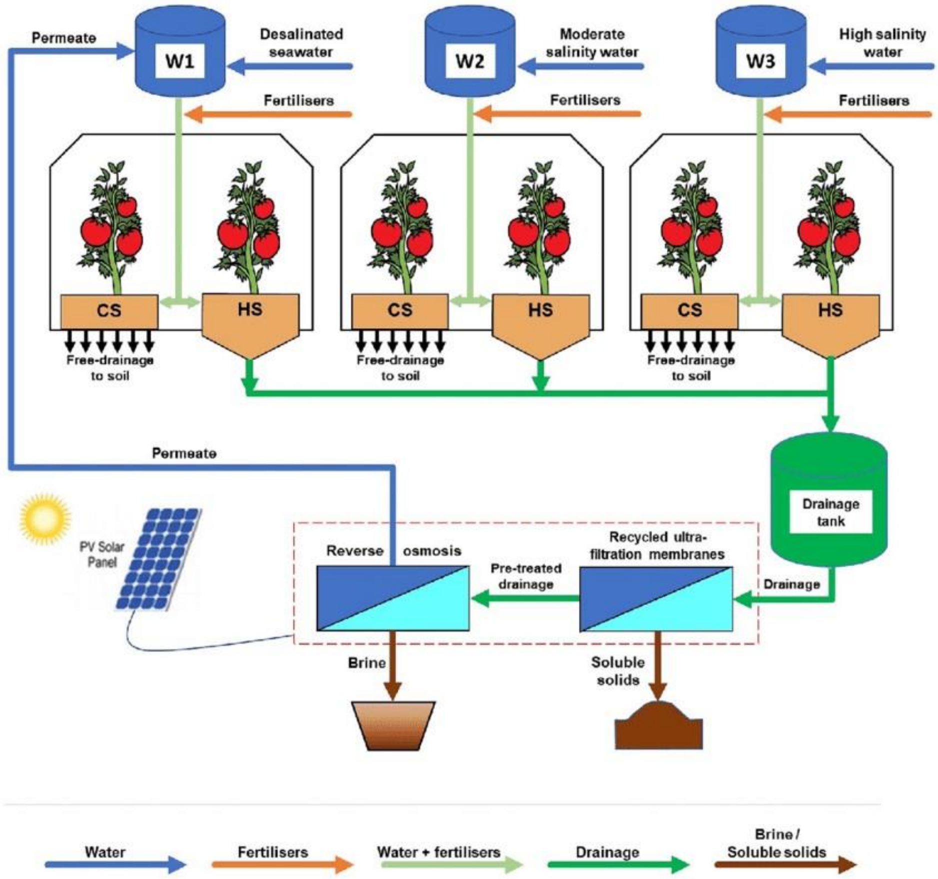

Fig. 7. Schematic diagram of a precision irrigation and fertigation system in a Dutch tomato greenhouse

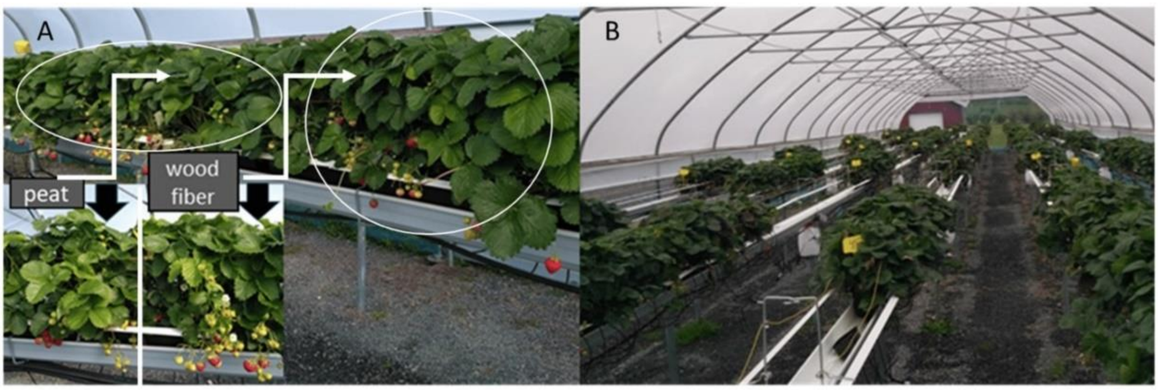

Fig. 8. Example of a precision irrigation and fertigation system in a Japanese strawberry high tunnel

5. 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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