

Chapter 10

Precision Irrigation for Sustainable Agricultural Productivity

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ABSTRACT

Precision irrigation is a water management strategy that applies water to crops based on their specific needs. It is a sustainable practice that can help to increase crop yields, reduce water use, improve fertilizer use efficiency, and reduce environmental impact. This chapter offers a detailed overview of precision irrigation for sustainable agricultural productivity. It defines precision irrigation and discusses its benefits, types, components, design, implementation, management, applications, and economic and environmental benefits. The chapter also discusses the role of precision irrigation in sustainable agriculture, challenges and opportunities for adoption, and the future of precision irrigation. It is intended to be a valuable resource for farmers, researchers, policymakers, and other stakeholders interested in learning more about precision irrigation's role in sustainable agriculture.

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Precision Irrigation for Sustainable Agricultural Productivity

1. INTRODUCTION TO PRECISION IRRIGATION

1.1. What Is Precision Irrigation?

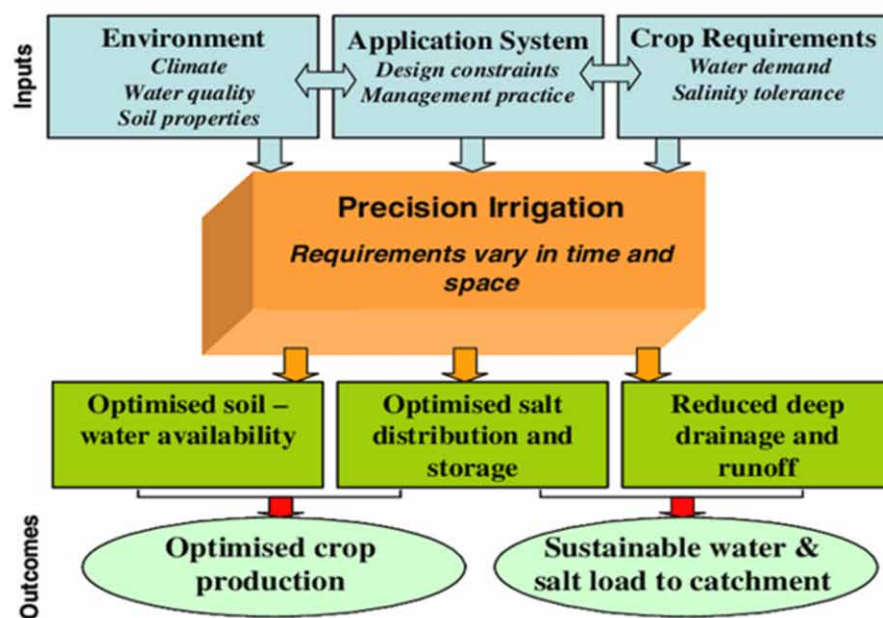
Precision irrigation is an advanced water management strategy that involves carefully distributing water resources to crops according to their individual needs (Abioye, *et al.*, 2020). This advanced and meticulously calibrated irrigation system represents a departure from traditional irrigation techniques like flood irrigation. Instead, it relies on a wealth of data to optimize the irrigation process, enhancing its overall efficiency and sustainability. This technique transcends traditional methods of irrigation by employing cutting-edge technology and data-driven approaches to optimize water usage.

The primary focus of precision irrigation is to deliver the right amount of water, at the right time, and in the right place to maximize crop productivity while minimizing water wastage and environmental impacts (Zhang, *et al.*, 2021). Figure 1 illustrates the implementation of precision irrigation techniques in contemporary agriculture, showcasing efficient water management for optimized crop growth and resource utilization. This rigorous method makes it possible to apply water precisely, ensuring that crops receive the ideal level of moisture needed for the best possible growth and development.

1.2. Benefits of Precision Irrigation for Sustainable Agricultural Productivity

- Precision irrigation is an essential practice in contemporary agriculture owing to its manifold advantages, encompassing economic, environmental, and agronomic dimensions. The system enhances water efficiency by precisely delivering an appropriate quantity of water directly to the root

Figure 1. Precision irrigation



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zone of crops, thereby mitigating water loss and promoting the preservation of water resources (Smith and Baillie, 2009).

- Precision irrigation has the potential to greatly improve crop yields by customizing irrigation practices to meet the individual needs of different crops. Precision irrigation systems have the capability to incorporate nutrient management measures, hence mitigating nutrient leaching and minimizing environmental damage. Through the use of nutrient delivery control, farmers have the ability to mitigate the quantity of fertilizers utilized, resulting in financial savings and a reduction in environmental repercussions. Energy-efficient components, such as drip irrigation and micro-irrigation systems, have been found to effectively decrease operational expenses.
- Precision irrigation is an effective technique that mitigates the occurrence of surface runoff, a phenomenon that has the potential to induce soil erosion, particularly in areas characterized by susceptible topsoil conditions. This technology enables farmers to customize irrigation schedules according to certain growth stages, so providing optimal water supply throughout crucial developmental times for plants. Additionally, there are remote monitoring and control capabilities that may be utilized, which prove particularly advantageous for expansive or geographically scattered fields.
- Precision irrigation plays a significant role in disease and pest management through its ability to prevent excessive wetness and maintain a consistent level of soil moisture. The implementation of precision irrigation techniques by farmers leads to enhanced profitability through the augmentation of crop yields, reduction in operational expenses, and optimization of resource utilization. The responsible and efficient utilization of water and nutrients is of paramount importance in fostering sustainable agriculture, as it contributes significantly to the preservation of the environment and the long-term security of food production.

1.3. Overview of Precision Irrigation Technologies

Precision irrigation systems employ advanced sensors, controls, and actuators to accurately administer water to crops, hence maintaining ideal moisture levels conducive to their best growth and development (García, *et al.*, 2020). Soil moisture sensors are utilized to quantify the moisture content in soil, thereby offering instantaneous data that can be employed for the purpose of scheduling irrigation activities. Crop water stress sensors are utilized to monitor the levels of water stress in crops, hence facilitating the making of well-informed decisions regarding irrigation. Weather stations gather data on temperature, humidity, and precipitation in order to predict the water requirements of crops. These meteorological stations offer precise meteorological data that has a significant impact on agricultural decision-making, encompassing the scheduling of irrigation, management of crops, and control of pests. Variable rate irrigation (VRI) systems enable farmers to modify water application rates according to individual requirements, thereby facilitating the efficient utilization of water resources and mitigating environmental consequences (Balafoutis, *et al.*, 2017). Automated irrigation systems provide meticulous regulation of water distribution, supplanting labor-intensive procedures with mechanized elements, so empowering farmers to maximize water utilization, enhance agricultural productivity, and save valuable resources. The utilization of these technologies plays a pivotal role in contemporary agriculture, facilitating the optimization of water resources, mitigating environmental repercussions, and augmenting agricultural productivity. In general, precision irrigation technologies play a crucial role in improving crop development, managing water resources, and conserving valuable resources.

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Figure 2. Furrow irrigation



2. TYPES OF PRECISION IRRIGATION SYSTEM

Precision irrigation systems encompass several types, each with its unique characteristics and advantages. These systems are designed to optimize water use, enhance crop productivity, and reduce environmental impact. Here's a detailed exploration of the main types of precision irrigation systems.

2.1. Surface Irrigation Systems

Surface irrigation systems are a category of agricultural irrigation methods where water is distributed and applied directly over the soil surface to supply crops with the necessary moisture. Unlike subsurface drip or sprinkler irrigation, surface irrigation systems rely on the natural flow of water across the field or through a network of canals or ditches. These systems are commonly used in agriculture and are one of the oldest and most widely practiced forms of irrigation. Several common types of surface irrigation systems include.

2.1.1. Furrow Irrigation

Furrow irrigation is a widely used agricultural practice primarily applied to row crops such as corn, cotton, and various vegetables. It involves the creation of small channels or furrows between rows of crops, which serve as conduits for water delivery. Figure 2 provides a visual representation of a furrow irrigation system, demonstrating the traditional method of watering crops through channels or furrows in the field. Gravity plays a crucial role as water is introduced at the upper end of these furrows and naturally flows down, saturating the soil around the plant roots. While furrow irrigation is popular due to its simplicity and low equipment requirements, it presents challenges related to water distribution uniformity. Furrows closest to the water source tend to receive more water than those farther away, leading to uneven moisture levels within the field (Haghnazari, *et al.*, 2015).

Excessive water runoff is a common concern, which not only contributes to water wastage but can also cause soil erosion and environmental issues, such as nutrient leaching. To address these challenges

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and enhance the precision and efficiency of furrow irrigation, modern technologies like automation systems and soil moisture sensors are increasingly being integrated, offering better control over water application, optimized resource usage, and reduced environmental impacts.

Furrow irrigation provides several advantages, including cost-effectiveness, suitability for row crops, simplicity, low energy requirements, and adaptability to various field sizes and configurations. It is well-suited for flat terrain, aids in soil aeration, and can be integrated with conservation practices to promote soil health. Additionally, furrow irrigation generally involves lower labor requirements and helps reduce soil compaction. However, it's essential to manage furrow irrigation effectively to address challenges related to uneven water distribution, potential water wastage, and runoff, which can be mitigated through modern technologies and improved management techniques to optimize resource usage and minimize environmental impacts.

2.1.2. Basin Irrigation

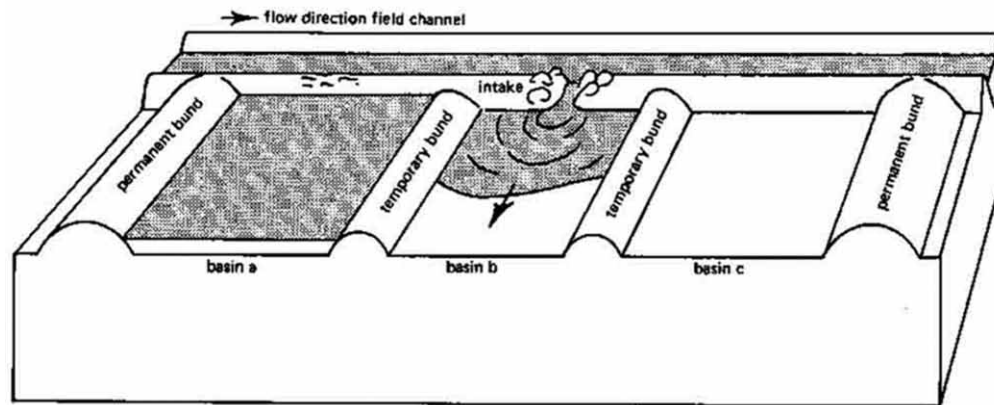
Basin irrigation, a time-tested method, proves highly effective, especially for perennial crops like fruit trees, grapevines, and even annual crops like rice. This technique offers a suite of benefits, aligning seamlessly with the precision irrigation approach. By creating enclosed basins tailored to crop needs, basin irrigation achieves water efficiency and conservation objectives central to precision irrigation, preventing water wastage and runoff while preserving this precious resource. In Figure 3, basin irrigation is depicted, showing a farming method where fields are divided into basins, allowing for controlled water application and improved moisture distribution to support crop growth. It also curbs weed proliferation and shields against soil erosion, addressing sustainability goals. Moreover, basin irrigation stands out for its simplicity, making it accessible to diverse farmer profiles. Its adaptability to sloped terrain further underscores its value, particularly in hilly landscapes. Nonetheless, its performance hinges on factors like soil type and crop variety, necessitating meticulous planning and diligent upkeep to avert waterlogging in poorly drained soils, demonstrating the precision irrigation ethos that underlines effective and sustainable water management.

2.1.3. Contour Farming

Contour farming is an agricultural method designed to combat soil erosion, especially in hilly or sloping terrain. By creating terraces or contour rows that follow the natural contours of the land, it effectively reduces the risk of soil loss during heavy rainfall. Figure 4 portrays contour farming, an agricultural technique that follows the natural contours of the land, helping to reduce soil erosion and conserve water resources while promoting sustainable crop cultivation. This approach not only prevents topsoil erosion but also allows water to infiltrate the soil, aiding in water conservation and groundwater recharge. Contour farming is particularly suitable for regions with rolling topography and is environmentally sustainable, as it safeguards water quality and aquatic habitats (Jin, *et al.*, 2011). While it requires initial effort and resources for construction and maintenance, the benefits in terms of soil conservation and erosion control make it a valuable practice. Contour farming can also be integrated with other conservation methods, such as cover cropping and reduced tillage, to further enhance soil health and agricultural sustainability.

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Figure 3. Basin irrigation



2.2. Drip Irrigation

Drip irrigation is a highly efficient and precise method of delivering water and nutrients directly to the root zone of plants, ensuring they receive the moisture and nutrients needed for optimal growth. This irrigation system has been widely adopted in agriculture due to its water-saving and productivity-enhancing capabilities.

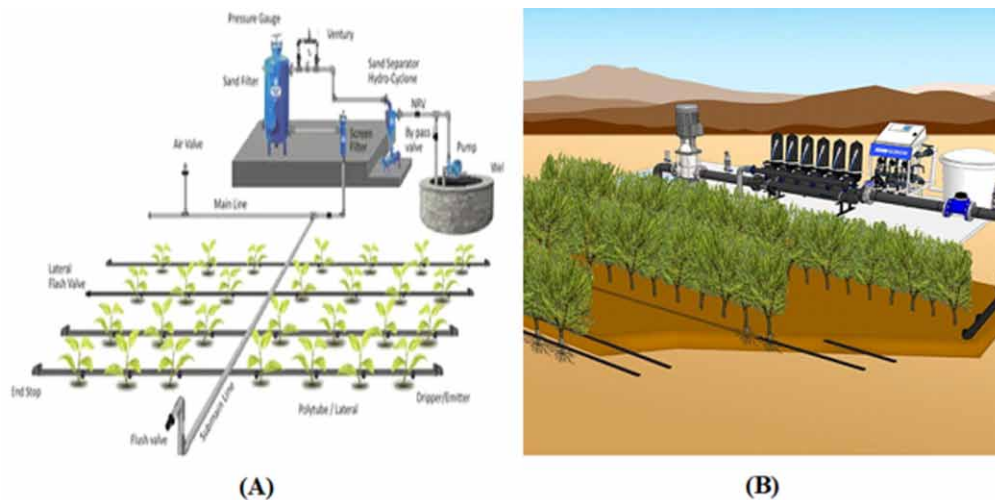
2.2.1. Types of Drip Irrigation

Surface Drip Irrigation

Surface drip irrigation is an agricultural irrigation method where water is delivered directly to the soil surface through a network of pipes and emitters as shown in figure 5 (A). Unlike subsurface drip ir-

Figure 4. Contour farming



Precision Irrigation for Sustainable Agricultural Productivity*Figure 5. Surface drip irrigation*

rigation, it does not involve burying the pipes, and the emitters are visible on the ground. Surface drip irrigation is valued for its efficiency and precision in delivering water and nutrients to crops, promoting healthier plant growth and conserving water resources. It is widely used in various agricultural applications, including row crops, orchards, vineyards, and gardens, and is adaptable to a range of crop types and soil conditions.

Subsurface Drip Irrigation

Subsurface drip irrigation (SDI) is an efficient agricultural irrigation method involving buried pipes with emitters that deliver water and nutrients directly to the root zone of crops as shown in figure 5 (B). It minimizes water wastage, reduces evaporation and runoff, and allows for precise control of water and nutrient delivery, resulting in improved crop health and yield. SDI can also help control weeds and reduce the risk of certain crop diseases, though it requires initial investment and suitability assessment for optimal performance in specific agricultural settings.

2.2.2. Components of Drip Irrigation System

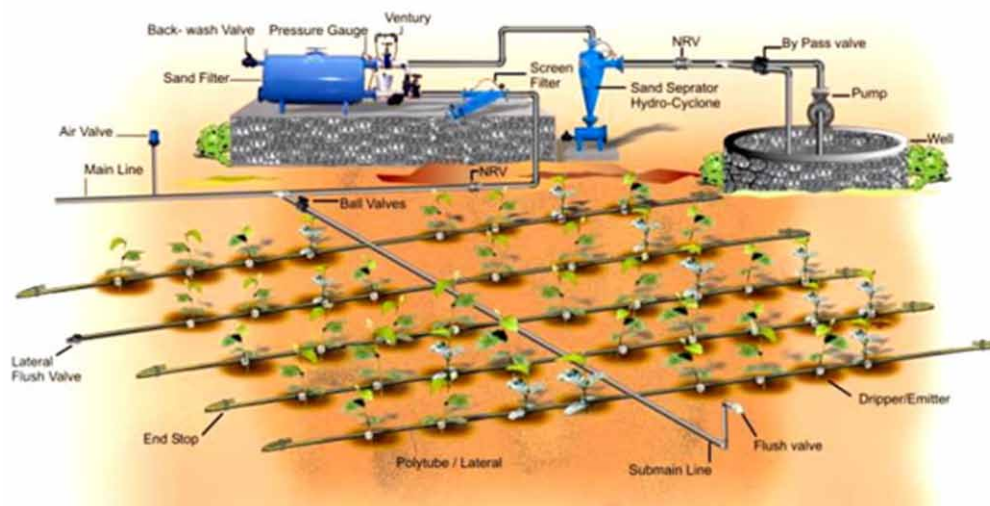
Figure 6 illustrates the constituent elements of a drip irrigation system, showcasing the sophisticated apparatus and tubing employed to administer accurate quantities of water straight to the roots of plants, hence augmenting water efficiency in agricultural practices.

Drippers (Emitters)

Drippers are small devices that release water in a controlled and uniform manner. They are typically attached to tubing and placed near the base of each plant. Drippers are designed to deliver a specific flow rate, which can be adjusted to meet the water requirements of different crops.

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Figure 6. Elements of a drip irrigation system



Water Delivery System

The central element of the majority of drip irrigation systems consists of a water delivery pathway, which is typically constructed using either PVC pipes for underground delivery or polyethylene tubing for above-ground applications. This water delivery system is composed of various components that serve the purpose of conveying water from the water source to the plants. It encompasses a network of mainlines, pipelines, and drip lines, all interconnected using couplings.

Water Filters

Water filters play a vital role in every irrigation system, serving as a crucial component to block silt and other debris from entering the system and ensure the delivery of clean water to plants. Drip irrigation system providers offer a range of in-line filter options to accommodate diverse setups, including media, screen, and disk filters, along with sand separators. These filters are each designed for use with various water sources, helping to maintain the quality of the irrigation water and safeguard the system's components from clogging and damage, thus contributing to the efficient and consistent supply of water to the plants.

Sand filters are commonly employed in water treatment processes to eliminate suspended particles and sediments. This is normally accomplished by utilizing a tank that contains a carefully selected grade of sand. Impurities are effectively captured by the system, resulting in the accumulation of pure water in the lower portion, which is subsequently directed towards the irrigation system. Screen filters employ a mesh or screen structure to effectively separate particles and detritus, therefore eliminating a diverse spectrum of particle sizes. Pre-filtration mechanisms are frequently employed as an initial barrier to impurities in order to safeguard the irrigation system from potential pipe and nozzle blockages. Hydro-cyclone filters employ the principle of centrifugal force to effectuate the segregation of solid particles from water (Tian, *et al.*, 2018). This process engenders a spiral flow pattern, which facilitates the outward displacement of denser particles towards the periphery, ultimately leading to their sedimentation at the

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bottom. These devices demonstrate high efficiency in the removal of larger particles, however their effectiveness in the removal of finer sediments may be limited. Disk filters consist of a series of stacked disks that possess grooves or tiny mesh, effectively capturing particles on their surfaces. These filtration systems demonstrate efficacy in the removal of particles of varying sizes and are commonly employed in scenarios where the preservation of water quality is a priority (Wen-Yong *et al.*, 2015).

Water Pressure Regulators

Water pressure regulators, also known as pressure-reducing valves (PRVs), are essential plumbing devices designed to control and regulate water pressure within a building's plumbing system. Installed at the point where the municipal water supply enters the structure, they serve to reduce high-pressure water to a safe and manageable level, ensuring the protection of pipes, fixtures, and appliances from damage due to excessive pressure. These valves are set to different pressure levels, which are 25, 50, and 100 kPa (kilopascals), or equivalently, 0.25, 0.5, and 1 bar. These pressure levels are typically measured to ensure that the fluid (in this case, likely water) flows through the submain at the desired pressure (Sokol *et al.*, 2019).

Valves and Gauges

Valves and gauges play vital roles in maintaining efficient and effective water delivery to plants. Valves serve as the control points for flow management, allowing users to adjust the volume of water to meet specific plant requirements and create irrigation zones, ensuring that water is distributed precisely where and when needed. They also facilitate shut-off for maintenance or repairs without disrupting the entire system, thus conserving water. On the other hand, gauges provide critical monitoring and feedback. Pressure gauges help maintain uniform water distribution by monitoring system pressure, while flow gauges measure and monitor actual flow rates to optimize water usage and scheduling.

Chemical Injectors

Chemical injectors serve the essential purpose of introducing specific chemicals, including fertilizers, pH adjusters, water treatment agents, pesticides, and herbicides, into the irrigation water (Evans *et al.*, 2007). This controlled injection of chemicals is crucial for optimizing plant health and crop yields by providing precise and consistent nutrient delivery, maintaining appropriate pH levels, and enabling water treatment and pest control. By automating the introduction of chemicals, chemical injectors ensure that plants receive the correct amounts of substances at the right times, promoting efficient resource utilization, reducing the risk of overuse, and contributing to the overall success of drip irrigation in terms of crop health and productivity.

System Controller

Controllers are responsible for regulating the duration and timing of water delivery to the fields through the distribution lines. They come in different types, including manual ones that operate based on pre-programmed schedules, activating and deactivating the system at specified times.

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2.2.3. Working Principle

Drip irrigation systems are designed to distribute water with precision to the root zones of plants, effectively minimizing water loss due to evaporation, runoff, or deep percolation. Water is applied in a gradual and constant manner, so assuring a continual supply of moisture. Drip irrigation systems employ strategically placed drippers to ensure consistent water distribution, hence facilitating uniform crop development and mitigating the occurrence of arid patches. Drip irrigation is a highly advantageous irrigation technique that enables accurate delivery of water to the specific root zones of individual plants. This precision makes it particularly advantageous for cultivating row crops, fruit trees, and garden vegetables.

2.2.4. Advantages

- Drip irrigation is highly efficient, reducing water usage compared to other irrigation methods. It minimizes water waste, making it ideal for regions with water scarcity.
- The consistent supply of water and nutrients directly to the root zone promotes optimal plant growth and higher yields.
- By delivering water only to the crop's root area, drip irrigation minimizes moisture availability to weeds, reducing weed growth.
- Drip irrigation limits the wetting of plant foliage, which can help reduce the spread of certain plant diseases.
- Drip irrigation systems can be combined with nutrient management strategies, ensuring that fertilizers are applied precisely where needed.
- Drip irrigation systems are often automated, reducing the need for manual labor in irrigation management.

2.2.5. Challenges

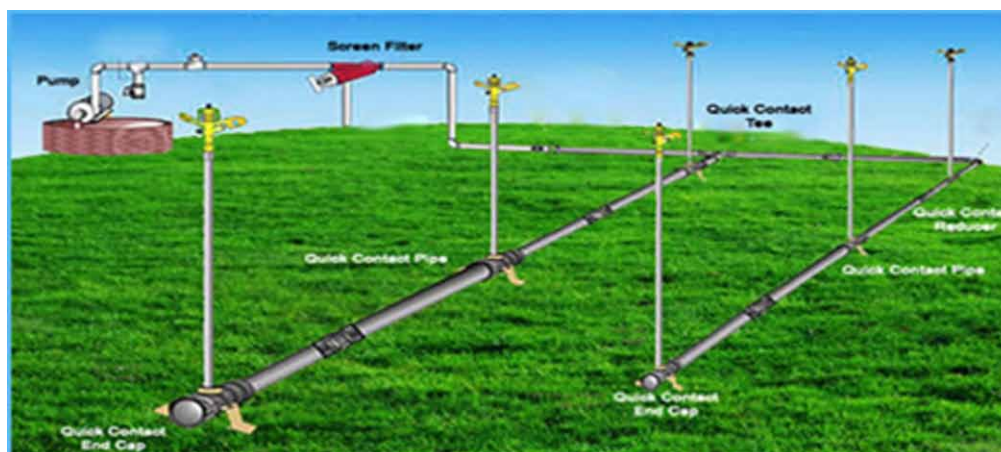
- Installing a drip irrigation system can be costly, primarily due to the need for equipment such as filters, pressure regulators, and tubing.
- Regular maintenance, including cleaning filters and checking for clogs or damage to emitters, is essential to ensure the system's efficiency.
- Drippers are prone to clogging from sediments and mineral deposits in the water. Effective filtration and regular maintenance are critical to prevent clogs.

2.3. Sprinkler irrigation

Sprinkler irrigation is a versatile method of applying water to crops by simulating natural rainfall. It is widely used in agriculture to efficiently distribute water to fields, orchards, and gardens. Sprinkler systems come in various configurations, each designed to meet specific needs. Figure 7 depicts a sprinkler irrigation system, a modern and efficient method of irrigating agricultural areas by evenly dispersing water over the crops.

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Figure 7. Sprinkler irrigation system



2.3.1. Key Components

Sprinkler Heads

Sprinkler heads are the devices responsible for distributing water over the crops. They come in various types, including impact, rotary, and fixed spray heads, each with specific characteristics suited to different applications.

Piping and Tubing

A network of pipes or tubing carries water from the water source (such as a well or pump) to the sprinkler heads. The pipes are typically made of materials like PVC or aluminum.

Pumps

In some cases, pumps are required to pressurize the water and supply it to the sprinkler system. The choice of pump depends on factors like field size, water source, and topography.

Filters

Filters are essential components to remove debris and impurities from the water, preventing clogs and damage to the sprinkler heads.

Pressure Regulators

Pressure regulators maintain a consistent pressure within the system, ensuring that sprinklers operate at the desired flow rate.

Control System

Some modern sprinkler systems are equipped with controllers that allow for automation, scheduling, and remote operation. These controllers enable precise control over when and how long the system runs.

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2.3.2. Working Principle

The principal purpose of sprinkler systems is to distribute water evenly across crops in a manner that emulates natural rainfall. This objective is accomplished by means of the sprinkler heads, which dispense water in a regulated and consistent manner. Certain types of sprinkler heads, such as rotary or oscillating variants, exhibit movement in order to effectively cover a designated area. The rotation or oscillation pattern employed in this process guarantees the uniform distribution of water. The flow rate and pressure of the water can be modified in order to fulfill the particular demands of the crop and the land.

2.3.3. Types of Sprinkler Irrigation Systems

Center Pivot Irrigation Systems

Center pivot systems consist of a series of towers with wheeled sprinkler lines that rotate around a central pivot point as shown in Figure 8 (A). These systems are typically used in large, circular fields. The central pivot point remains fixed, while the sprinkler lines move in a circular pattern, irrigating the field as they rotate. It is suitable for large, open, and circular fields, such as those used for large-scale agriculture.

Lateral Move Irrigation Systems

Lateral move systems are similar to center pivots but move linearly, irrigating rectangular fields as shown in Figure 8 (B). The sprinklers move along towers running parallel to the field's length. The entire system moves laterally, covering rectangular or square fields, and irrigating as it goes. It is suitable for rectangular or square fields, especially when circular patterns are not ideal.

Fixed Sprinkler Systems

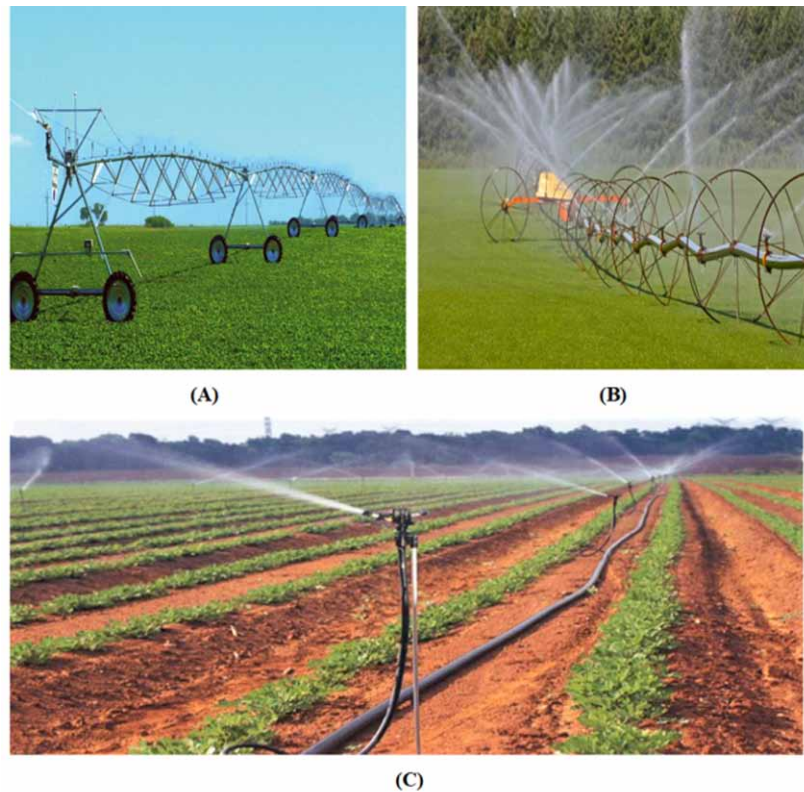
Fixed systems are stationary and do not move during operation. They can be configured with various types of sprinkler heads, including impact and spray heads as shown in Figure 8 (C). The sprinklers in a fixed system are placed strategically to cover the target area. Water is supplied through a network of pipes, and the sprinklers distribute it to the crops or garden without moving. It is suitable for smaller fields, gardens, and areas with irregular shapes where mobility is not necessary.

2.3.4. Applications

Sprinkler irrigation is commonly used for field crops like wheat, corn, and soybeans. It can efficiently cover large areas with water, especially when coupled with automated systems. Sprinkler systems are employed to protect fruit and grape crops from frost and to supply consistent moisture for growth. Small-scale sprinkler systems are ideal for vegetable gardens, providing uniform water distribution and efficient water use. Sprinkler systems are widely used for residential and commercial lawns and golf courses to maintain lush, green landscapes.

2.3.5. Advantages

- Sprinkler systems provide even coverage across the field, promoting consistent crop growth.
- Sprinklers can be used to protect crops from frost damage by providing a protective ice layer.

Precision Irrigation for Sustainable Agricultural Productivity*Figure 8. Types of sprinkler irrigation systems*

- Sprinklers can be used to apply fertilizers, pesticides, and herbicides evenly.
- Sprinkler systems can be adapted to various field sizes and crop types.

2.3.6. Challenges

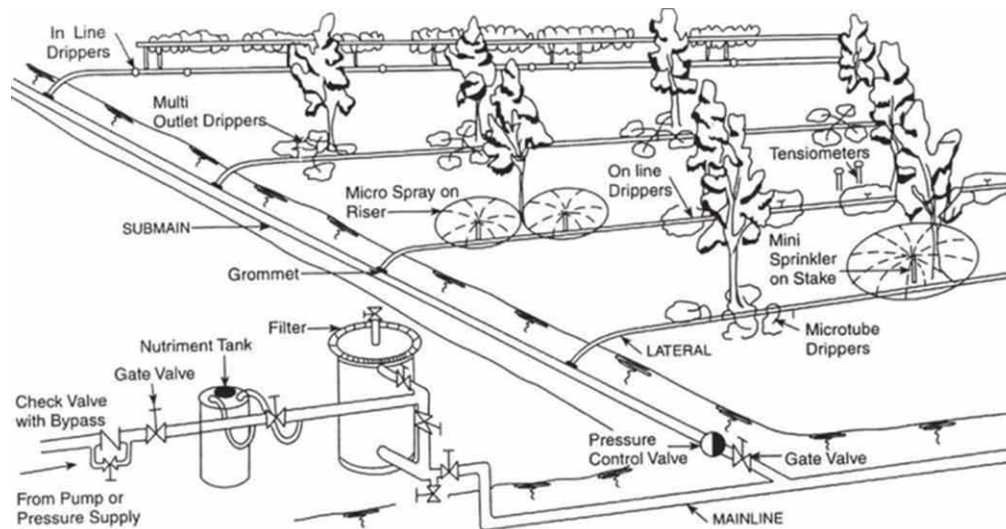
- Evaporation and wind drift can lead to water loss in sprinkler irrigation systems.
- Operating pumps and maintaining pressure can result in higher energy costs.
- Filters and sprinkler heads require regular cleaning and maintenance to prevent clogs.

2.4. Micro-Irrigation Systems

Micro-irrigation systems, commonly known as drip irrigation or trickle irrigation, represent a revolutionary approach to efficiently provide water and essential nutrients directly to a plant's root zone. They have become a cornerstone of modern agriculture, landscaping, and horticulture due to their remarkable ability to conserve water resources and optimize crop productivity. Unlike traditional irrigation methods, micro-irrigation systems ensure that water is applied with unparalleled precision, a feature that has transformed the way we nurture and cultivate various plant species. These systems are celebrated for their contribution to sustainable agriculture and environmental stewardship. Figure 9 showcases a

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Figure 9. Micro-irrigation system



micro-irrigation system and its various components, highlighting the precision and efficiency of this method for delivering water directly to plants, optimizing water use in agriculture.

2.4.1. Components of Micro-Irrigation Systems

Emitters

Emitters used in micro-irrigation systems, including drip emitters and micro-sprinklers, play a pivotal role in delivering water and nutrients with precision and control directly to the root zone of plants. Grouping multiple emitters together as a unit in an irrigation system means connecting them in a cluster or manifold. This configuration allows for more consistent water distribution and helps reduce variability in water flow among the emitters (Barragan *et al.*, 2006).

Tubing and Pipes

These convey water from the source to the emitters. Tubes and pipes are typically made of materials like PVC, polyethylene, or drip tape.

Filters

Filters remove debris and particles from the water to prevent clogging of emitters. Common filter types include screen filters and disc filters.

Pressure Regulators

Pressure regulators maintain a consistent pressure in the system, ensuring uniform water distribution to all emitters.

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Valves and Control Systems

Valves are used to control the flow of water, and control systems can be manual or automated to manage irrigation schedules and duration.

2.4.2. Benefits of Micro-Irrigation Systems

Micro-irrigation is a highly efficient and precise water management method that delivers water directly to the plant's root zone, reducing water wastage and runoff. With water use efficiencies of over 90%, micro-irrigation is one of the most water-efficient irrigation methods available, contributing significantly to water resource conservation. Micro-irrigation, when integrated with precision irrigation scheduling, offers a tailored approach to watering crops based on their specific water needs (Jamroen, *et al.*, 2020). This method takes into account various factors, including real-time weather data, soil conditions, and the rate at which a crop loses water through evapotranspiration. It also ensures consistent moisture delivery, reducing water stress during dry periods and enhancing overall water use efficiency. Micro-irrigation also plays a crucial role in weed control, as it delivers water directly to the plant root zones, reducing water availability for weed growth in non-irrigated areas. This not only conserves resources but also contributes to a healthier and weed-free plant environment.

Micro-irrigation also maintains plant health by keeping foliage dry, minimizing the risk of foliar diseases and reducing the need for chemical treatments. This sustainable and eco-friendly nature promotes both agricultural productivity and environmental stewardship. Micro-irrigation systems also offer environmental benefits, such as water conservation by minimizing water wastage and runoff, preventing soil erosion, and reducing energy consumption. Operating at lower pressure requirements than traditional irrigation methods, these systems are more energy-efficient, leading to reduced energy consumption and operational costs, making them an economically and ecologically sound choice for water resource management. Overall, micro-irrigation is a sustainable and eco-friendly approach to water resource conservation and sustainability.

3. COMPONENTS OF PRECISION IRRIGATION SYSTEMS

3.1. Sensors

Sensor is a specialized device or instrument used to detect and measure specific environmental factors relevant to the management of water resources in agriculture and horticulture. These sensors are designed to monitor variables such as soil moisture, weather conditions, soil temperature, leaf wetness, and water quality. The data collected by these sensors provides critical information for irrigation management, helping farmers and growers make informed decisions about when, where, and how much water to apply to crops. These sensors play a crucial role in optimizing water usage, enhancing crop health, and ensuring efficient and sustainable irrigation practices in agriculture.

Here is a visual representation of various agricultural sensors used in water management as shown in Figure 10. Each sensor is designed to provide critical information for efficient irrigation and crop management in agriculture and horticulture.

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Figure 10. Micro-irrigation system components



3.1.1. Soil Moisture Sensors

Soil moisture sensors are essential for efficient irrigation management, providing data on water content in the root zone. Common types include volumetric soil moisture sensors, which measure soil volumetric water content, tensiometers, which measure soil water tension, Time Domain Reflectometry (TDR) sensors, which analyze electromagnetic pulses, capacitance sensors, and dielectric sensors.

Volumetric soil moisture sensors measure water content in a percentage, providing precise data on water availability. Tensiometers measure soil water tension, indicating water holding strength in the soil (Bhatt *et al.*, 2016). TDR sensors are used in fields like soil science, telecommunications, geophysics, and environmental monitoring, accurately measuring soil moisture content for efficient irrigation. Capacitance sensors estimate moisture content using changes in soil capacitance, used in precision irrigation systems. Dielectric sensors measure changes in soil dielectric properties due to moisture content, known for their accuracy and suitability for various soil types.

3.1.2. Weather Sensors

Weather sensors are essential tools for adjusting irrigation schedules based on environmental conditions. They collect data on temperature, humidity, wind speed, and solar radiation, which are crucial for understanding plant growth and water requirements. Temperature sensors measure air temperature, which affects irrigation needs. Relative humidity sensors measure moisture in the air, allowing for better understanding of plant transpiration and evaporation. Wind speed and direction sensors provide data on air movement, influencing irrigation scheduling. Rain gauges measure precipitation amounts, helping determine irrigation delays. Solar radiation sensors estimate sunlight reaching crops, estimating evapotranspiration rates and plant water requirements. Barometric pressure sensors track atmospheric pressure

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changes, indicating approaching weather systems and forecasting irrigation needs. Overall, these sensors are essential for ensuring optimal irrigation management.

3.1.3. Soil Temperature Sensors

Soil temperature sensors are crucial for understanding plant growth and water requirements. Types include resistive sensors, thermocouples, and resistors. Resistive sensors measure temperature by monitoring changes in electrical resistance, known for accuracy and reliability. Thermocouples, made of two metals, work by changing voltage with temperature, often used in rugged environments. Thermistors, temperature-sensitive resistors, have significant electrical resistance changes with temperature, allowing for precise temperature measurements.

3.1.4. Leaf Wetness Sensors

Leaf wetness sensors detect the presence of moisture on plant leaves, which can be an important indicator of disease risk and the need for irrigation. These sensors are specialized instruments used in agriculture and horticulture to monitor and measure the presence of moisture on plant leaves. These sensors play a crucial role in disease management, irrigation control, and overall plant health.

3.1.5. Water Quality Sensors

Water quality sensors are essential for assessing the chemical composition of irrigation water, ensuring it meets crop health standards. pH sensors measure the water's acidity or alkalinity, determining its suitability for irrigation and nutrient management. Electrical conductivity (EC) sensors measure the water's salinity and ion content, assessing potential soil and root damage. Turbidity sensors assess water clarity by measuring suspended particles and contaminants, evaluating water quality and its impact on irrigation systems. Dissolved oxygen sensors measure the water's dissolved oxygen concentration, assessing its ability to support aquatic life and microbial activity. Nutrient sensors detect the concentration of specific nutrients, such as nitrogen and phosphorus, in the water, crucial for fertigation management.

3.2. Controllers

Controllers serve as the primary control center for precision irrigation systems, effectively leveraging data obtained from sensors to make informed decisions regarding the optimal allocation of water to plants. The individuals in question bear the responsibility of overseeing irrigation schedule, controlling the flow of water, and administering fertilizer injection. The initiation of irrigation cycles is determined by considering factors such as soil moisture levels, prevailing weather conditions, and the specific requirements of the crops. In addition, valves and actuators are employed to manage the flow of water, facilitating its distribution to designated zones. In addition to their primary functions, contemporary controllers also include the capability of remote control and monitoring. This feature enables farmers to conveniently oversee and regulate the system through mobile applications or web interfaces.

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4. DESIGN AND IMPLEMENTATION OF PRECISION IRRIGATION SYSTEMS

4.1. Design Considerations

4.1.1. Local Environmental Conditions, Crop Types, and Soil Types

Local climate conditions, such as temperature, humidity, and precipitation patterns, need to be considered to determine the irrigation needs. Different crop types have distinct water requirements. The system should be tailored to accommodate these variations. Soil types vary in their water-holding capacity and drainage properties. Understanding the specific soil conditions is essential to prevent over-irrigation or under-irrigation.

4.1.2. Proper Sensor Placement and Calibration

Sensor placement is crucial to collect accurate data. Soil moisture sensors should be positioned at various depths to monitor the entire root zone. Regular sensor calibration is essential to ensure data accuracy and to account for sensor drifting over time. Calibration involves comparing sensor readings with actual soil moisture levels.

4.1.3. Water Sources and Irrigation Methods

Identify and assess the available water sources, whether they're from wells, rivers, reservoirs, or reclaimed water. The source's quality and quantity can influence system design. Choose the appropriate irrigation method, such as drip irrigation, sprinklers, or pivot systems, based on factors like crop type, water availability, and infrastructure constraints.

4.2. Implementation Steps

4.2.1. Conduct a Comprehensive Site Assessment

A thorough site assessment involves gathering information about the specific characteristics of the land to be irrigated. This includes soil types, topography, and the presence of any physical barriers. Crop needs assessment should consider the growth stages, water requirements, and expected yield goals.

4.2.2. Select and Install Appropriate Sensors and Controllers

Based on the site assessment and crop requirements, choose the most suitable sensors (soil moisture, weather, or crop sensors) and controllers. Proper installation of sensors is essential to ensure they provide reliable data. Follow manufacturer guidelines and best practices.

4.2.3. Develop an Irrigation Schedule and Set Up Automation

Create an irrigation schedule that factors in real-time data from the sensors. This schedule should specify when and how much water to apply. Configure the automation system (controllers) to execute

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the irrigation schedule. Automation ensures that water is delivered precisely when and where needed, reducing human error.

4.2.4. Continuously Monitor and Adjust the System

Regularly monitor the sensor data to ensure that the system is functioning correctly. Use the sensor data and crop growth stage information to make necessary adjustments to the irrigation schedule. Periodically check and maintain the entire system, including sensors, controllers, and water delivery components. By adhering to these design considerations and implementing the outlined steps, a precision irrigation system can be effectively tailored to the specific needs of a given agricultural site. This, in turn, maximizes water efficiency, crop productivity, and sustainability while minimizing water wastage and environmental impact.

5. PRECISION IRRIGATION FOR SUSTAINABLE AGRICULTURE

5.1. The Role of Precision Irrigation in Sustainable Agriculture

Precision irrigation plays a significant role in promoting sustainable agriculture by improving the efficiency of water and resource use, reducing environmental impacts, and enhancing crop yield and quality. Precision irrigation technologies and practices significantly contribute to water conservation in agriculture and landscaping. These systems reduce water waste, promote efficient water use, and help mitigate the environmental and economic impacts of over-irrigation, ultimately playing a crucial role in addressing the challenges of water scarcity and sustainability. Drip and sprinkler systems deliver water directly to the root zone of plants, reducing water waste through evaporation and runoff. This efficient water use helps conserve this precious resource, especially in regions facing water scarcity and droughts. Precision irrigation minimizes the overuse of fertilizers and pesticides and delivers them straight to the root zone, which lowers water pollution, safeguards aquatic ecosystems, and contributes to safe drinking water. By doing this, runoff and leaching are less likely to damage non-target creatures and contaminate water systems. By preserving water quality, precision irrigation also helps to ensure the long-term viability of natural ecosystems and agriculture. Figure 11 showcases precision irrigation in sustainable agriculture, highlighting its effectiveness and environmental benefits. It features drip irrigation systems, efficient sprinklers, remote farmer control, and real-time soil sensors, reducing water waste and improving crop health.

Precision irrigation systems can deliver fertilizers and nutrients directly to the root zone of plants. This targeted nutrient application minimizes excess use of fertilizers, reducing the risk of nutrient runoff into water bodies and mitigating soil degradation. Precision irrigation systems often operate at lower pressure than traditional methods, reducing the energy required for water pumping. This energy efficiency contributes to cost savings and a lower carbon footprint. Maintaining consistent soil moisture levels through precision irrigation helps prevent both overwatering and underwatering. This promotes healthier plants, reduces stress, minimizes disease susceptibility, and ultimately leads to higher crop yields and quality. Precision irrigation systems rely on data from various sensors to create customized irrigation schedules based on real-time environmental conditions. This flexibility ensures that water is applied precisely when and where it is needed. Slow and even water delivery in precision irrigation

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Figure 11. Precision irrigation



systems helps prevent soil erosion caused by rapid water flow. Soil erosion can degrade soil quality and negatively impact ecosystems.

Precision irrigation systems deliver water only to the crop's root zone, reducing weed growth in between rows. This decreases the need for herbicides and manual weeding. Many precision irrigation systems offer remote monitoring and control capabilities, allowing farmers to manage their irrigation systems from a distance, which is particularly valuable for large-scale operations. Precision irrigation relies on data from various sensors and monitoring tools. This data is used to make informed decisions, leading to more efficient and sustainable irrigation practices. Precision irrigation can help agriculture adapt to changing climate conditions, such as increased droughts and unpredictable weather patterns, by providing more precise control over water resources.

5.2. Challenges for Precision Irrigation Adoption

The adoption of precision irrigation in agriculture faces several challenges that can limit its widespread implementation. Precision irrigation systems often require a significant upfront investment in technology, including sensors, controllers, and infrastructure. The adoption of certain irrigation innovations can be challenging due to their high initial costs, greater knowledge and skill requirements, and increased time commitment (Morrison, *et al.*, 2009). The cost can be a barrier for small-scale and resource-constrained farmers, making adoption more challenging. To boost the adoption of micro-irrigation technology in developing countries, there is a requirement for robust institutional support, promotional efforts, subsidies for the products, and improved access to credit. These measures can encourage and facilitate the widespread use of this efficient irrigation technology, which can significantly benefit agriculture in these regions by conserving water and enhancing crop yields (Varma, *et al.*, 2006).

Effective use of precision irrigation systems demands a good understanding of the technology, data interpretation, and system management. Farmers may require training and technical expertise to operate and maintain these systems properly. Precision irrigation systems generate large volumes of data on soil moisture, weather conditions, and plant needs. Managing and analyzing this data can be overwhelming,

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and farmers may need support in harnessing its full potential. Retrofitting existing irrigation systems with precision technology can be complex and costly. Not all farms have the necessary infrastructure for seamless integration, which can impede adoption. The accuracy and reliability of sensors, such as soil moisture sensors, are critical for making informed decisions. Faulty sensors can lead to incorrect data, undermining the efficiency of precision irrigation. While precision irrigation can save water, it may increase energy consumption, particularly when water needs to be pumped over long distances or when energy-intensive sensors and controls are used.

Precision irrigation systems are not universally applicable and may need customization to suit the specific needs and conditions of each farm. This requirement can add complexity to adoption. Ongoing maintenance, sensor calibration, and software updates are crucial for the proper functioning of precision irrigation systems. Neglecting these tasks can lead to reduced system effectiveness. In some regions, water rights and regulations can restrict the use of water-saving technologies like precision irrigation. Farmers may need to navigate legal and regulatory obstacles to adopt these systems. In rural or remote areas, limited access to technology and internet connectivity can hinder the implementation of precision irrigation systems. Some farmers may be hesitant to adopt new technologies due to concerns about potential risks and uncertainties associated with changing their established irrigation practices.

6. WORLDWIDE APPLICATIONS OF PRECISION IRRIGATION SYSTEM

Precision irrigation systems have gained worldwide recognition, fundamentally transforming agricultural methods via the optimization of water use, enhancement of crop productivity, and encouragement of sustainable farming practices. The implementation of these technologies differs across different places, since it is impacted by elements like as climate, water availability, and economic circumstances. North America, Israel, India, and China have all adopted precision irrigation systems, with more than half of the irrigated land in the United States using these methods. Precision irrigation is of utmost importance in the wine business as it enables grape production to achieve a notable decrease of 20-30% in water consumption, all the while ensuring the maintenance or even enhancement of grape quality. Precision irrigation has been widely used in cotton farming, resulting in improved yields and fiber quality in precision-irrigated cotton fields.

Precision irrigation offers significant economic advantages, leading to higher farm profitability and sustainability. According to research conducted by the World Bank, farmers that use precision irrigation technology see a notable 20-50% rise in their net income as a result of enhanced crop yields and more efficient utilization of resources (Adeyemi *et al.*, 2017). The use of precision irrigation is in accordance with the objectives of sustainable agriculture, as emphasized by the International Food Policy Research Institute (IFPRI).

According to a survey, the worldwide precision irrigation market is expected to develop significantly, reaching a market value of USD 14.95 billion by 2028 (Jolly *et al.*, 2023), report also forecasts a compound annual growth rate (CAGR) of 13.1% from 2021 to 2028. The use of this data-centric method is swiftly revolutionizing agricultural practices worldwide, addressing the issue of water shortages, enhancing crop production, and protecting the environment. Precision irrigation is a fast advancing technology that is revolutionizing farms worldwide. It addresses the issue of water shortage, enhances crop productivity, and protects the environment. Precision irrigation has several benefits that go beyond

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water saving, including higher agricultural yields, improved crop quality, less environmental footprint, and better profitability.

Precision irrigation is being used in many settings, ranging from dry areas to productive valleys, on several continents. Israel, known for its innovative approaches to addressing water constraint, has successfully implemented precision irrigation techniques, leading to significant improvements in water efficiency and agricultural productivity. Spain has acute drought conditions, but India is actively assisting farmers in enhancing the efficiency of rice and wheat cultivation, hence enhancing food security and improving the lives of farmers. With the continuous progress of technology, precision irrigation is expected to have a significant influence. Advancements like artificial intelligence, automation, and remote monitoring provide the potential for enhanced optimization and immediate control, resulting in more effective water management. By adopting this intelligent strategy, we may foster a more environmentally friendly future in which every unit of water is valued, providing sustenance not just to crops but also to the populations who rely on them.

Precision irrigation offers many long-term advantages, including water conservation, higher crop yields, and less fertilizer runoff. Governments, commercial enterprises, and farmers globally are aggressively allocating resources towards the development and use of this technology, acknowledging its significant capacity for transformation. Precision irrigation provides a clear path towards a more sustainable and secure future for agriculture as we face the challenges of a rising population and climate change.

7. CHALLENGES AND FUTURE OUTCOMES

Precision irrigation is an innovative technology that transforms water management in agriculture, although it encounters several obstacles on its journey towards a sustainable future. The factors to consider include the significant upfront expenses, specialized knowledge, dependability and connection of data, compatibility with current systems, acceptance and education among farmers, and governmental assistance and financial backing. In order to address these difficulties, a comprehensive and multifaceted strategy is required. To facilitate the general implementation of precision irrigation, we may contribute by offering financial assistance, enhancing technical expertise, promoting innovation, and highlighting successful case studies. Consequently, this may enable a future in which every unit of water not only sustains crops but also promotes a more environmentally friendly and adaptable agricultural environment.

Financial obstacles provide a substantial hurdle. Farmers face a substantial financial obstacle because to the considerable upfront cost associated with precision irrigation systems, which include sensors, controls, and specialist equipment. Restricted implementation, particularly among small-scale farmers who may encounter financial difficulties in procuring the technology, resulting in inequitable access to sustainable agricultural methodologies. Technological intricacy poses a further hurdle, since precision irrigation systems include intricate technology like as sensors, data analytics, and automation, which may be challenging for farmers to comprehend and oversee. A further obstacle is the reliance of many precision irrigation systems on constant and cost-effective energy sources for pumps and automation. However, in some places, these energy sources may be unreliable or costly. The lack of inexpensive and dependable electricity in some places might lead to higher operating expenses and decreased feasibility of using precision irrigation techniques. Water shortage and pollution pose significant challenges to precision irrigation systems since they rely on a reliable and high-quality water supply.

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Ensuring data security and privacy is an additional obstacle. Precision irrigation systems collect and retain intricate data on crop conditions, soil health, and water use, hence giving rise to issues over the security and privacy of this data. Farmers may exhibit reluctance in embracing the technology due to concerns around illegal access or improper use of their agricultural data. Potential remedies include cost mitigation tactics, streamlined user interfaces and training, energy-conserving devices, water conservation measures, and data governance and education. Collaboration among governments, NGOs, and private sector groups may facilitate the provision of financial incentives, subsidies, or financing alternatives to enhance the affordability of precision irrigation systems for farmers.

Potential future results include heightened acceptance and availability, higher efficiency in production and resource use, technical progress, enhanced water management, and a revolution in agriculture driven by data. Due to the implementation of cost reduction strategies and heightened awareness, the use of precision irrigation systems is expected to expand, hence increasing the accessibility of sustainable farming techniques to a greater number of farmers. To summarize, addressing the difficulties related to precision irrigation systems requires a comprehensive strategy that encompasses technology advancements, financial backing, and instructional programs. The potential future results provide the prospect of a more environmentally friendly and efficient agricultural environment, as long as focused endeavors are undertaken to overcome the current obstacles.

8. CONCLUSION

Precision irrigation, a sustainable water management approach tailored to crops' specific needs, offers a multitude of benefits, including enhanced crop yields, reduced water use, improved fertilizer efficiency, and minimized environmental impact. It encompasses various precision irrigation systems, like surface, sprinkler, drip, and micro-irrigation, with detailed insights into components and design considerations. Managing precision irrigation systems involves monitoring, data collection, scheduling, and maintenance.

The applications span crop irrigation, soil moisture, nutrient, and salinity management, along with frost protection. Economic and environmental advantages include increased yields, water conservation, efficient fertilizer use, and environmental sustainability. The chapter underscores precision irrigation's role in sustainable agriculture, emphasizing associated challenges and opportunities for adoption. Ultimately, precision irrigation holds promise for enhancing sustainable agricultural productivity and serves as a valuable resource for stakeholders in agriculture.

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