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Water-Smart Cultivation: Strategy for Sustainable Agriculture Practice

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Water scarcity and climate change have emerged as major threats to agricultural productivity and food security, contributing to the need for efficient irrigation systems that enhance crop productivity while conserving water. An integrated approach to agricultural water management is essential, incorporating innovations such as Smart irrigation technologies—drip and sprinkler irrigation, rainwater harvesting, solar-powered irrigation pumps, integrated soil and water management, and the use of Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, and sensor-based irrigation scheduling to enhance water-use efficiency while meeting the water needs of agriculture, humans, and livestock. Key innovations in modern irrigation include soil- and plant-based sensing technologies, Internet of Things (IoT)-enabled automation, satellite-guided evapotranspiration modelling, and artificial intelligence-based irrigation scheduling, all of which enhance the precision and efficiency of water management.

Keywords: water management technologies, sustainability, climate-resilient agriculture, adaptation and mitigation, climate change

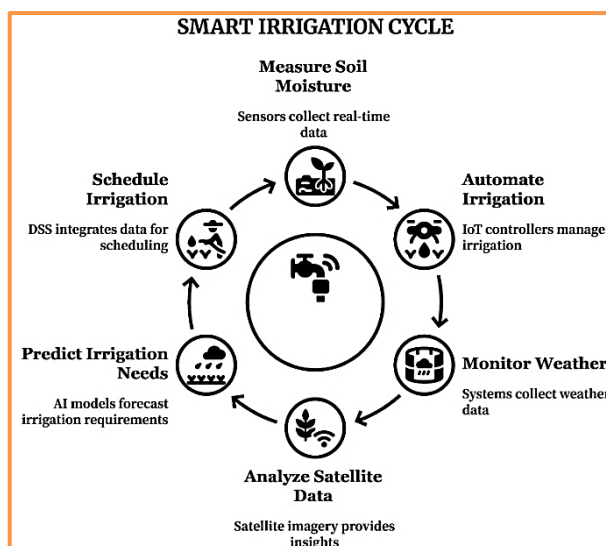
Introduction

Water is the most indispensable resource for agricultural production, accounting for more than 70% of global water withdrawals. The increasing frequency of climate variability, prolonged droughts, and intensified competition for limited water resources has created significant challenges for sustaining agricultural productivity and ensuring long-term food security. Traditional irrigation methods such as flood and furrow irrigation often dominate, leading to wastage of large quantities of water through evaporation, runoff, and deep percolation, reducing irrigation efficiency and threatening long-term agricultural sustainability. India's per capita annual water availability is projected to decline to 1,465 m³ by 2025 and further to 1,235 m³ by 2050. These challenges have made efficient water management one of the highest priorities for modern agriculture. Smart irrigation technologies have become essential tools for enhancing the precision and efficiency of water application in agricultural systems. It focuses on producing more food with less water by integrating efficient irrigation systems, soil moisture conservation, precision agriculture, climate-smart technologies, and digital farming tools. Water-smart cultivation emphasizes the right quantity of water at the right place and the right time. Smart irrigation technologies play a vital role in increasing the resilience of agricultural systems to climate change by supporting adaptive and efficient water management practices.

Current Status of Water Resources and Their Utilization in India

India has a geographical area of 329 million ha and receives approximately 4,000 billion cubic metres (BCM) of annual precipitation. The country's static freshwater groundwater reserves are estimated at 1,082 BCM, while 432 BCM is replenished annually. Of the annual groundwater recharge, 68% is contributed by rainfall and 32% by canal seepage, irrigation

return flow, tanks, ponds, and other water conservation structures. Groundwater supplies 61.6% of the irrigation water in India, whereas canals account for 24.5%. India has 12 major river basins covering a combined catchment area of 252.8 million ha, with an annual river discharge of approximately 1,869 km³. Owing to increasing population pressure, the country's per capita annual water availability declined from 1,816 m³ in 2001 to 1,544 m³ in 2011. Globally, although only 20% of cropland is irrigated, it produces 45% of the world's food, with irrigated agriculture yielding 2.2 times more than rain-fed farming. Furthermore, global food production must meet the needs of an additional 90 million people each year over the next 25 years, highlighting the increasing demand for efficient water resource management. In India, total water demand is expected to increase from 813 BCM in 2010 to 1,447 BCM by 2050, with irrigation demand alone rising from 688 BCM to 1,072 BCM, highlighting the urgent need for efficient irrigation technologies.



Challenges in traditional irrigation systems

While traditional irrigation systems have contributed significantly to agricultural production, they are often constrained by inefficient water use, which can negatively affect crop health and contribute to environmental degradation.

- Over- and Under-Irrigation: Causes of Poor Crop Health and Waterlogging
- Lack of Real-Time Monitoring of Soil Moisture and Climatic Conditions.
- Uniform Water Application Despite Variations in Soil and Crop Requirements.
- Manual Irrigation Scheduling Without the Use of Predictive Data.

Water-smart cultivation

Water-smart cultivation is a sustainable farming strategy that optimizes water resource utilization to improve water-use efficiency, enhance crop productivity and resilience, and promote long-term environmental conservation. Within this framework, several key elements play a crucial role. The primary objective of water-smart cultivation is to optimize the use of irrigation water while improving water productivity, crop yield, and farmers' income. It also aims to conserve groundwater resources, enhance resilience to drought and climate change, and promote sustainable agricultural production through efficient water management practices.

Technologies

Smart Irrigation Systems

Artificial intelligence-enabled irrigation scheduling systems integrate advanced machine learning techniques to accurately predict the optimal timing, frequency, and quantity of irrigation by processing a wide range of environmental, soil, weather, and crop-related inputs. Smart irrigation systems integrate: Soil moisture sensors, Weather stations, Remote sensing, Satellite observations, Automated valves, Internet of Things (IoT) and Artificial Intelligence (AI).

Key Inputs for AI Irrigation Scheduling: Soil Moisture rate, Evapotranspiration (ET) Rates, Crop Type and Growth Stage, and Weather Forecasts. Machine learning-based predictive models analyze historical weather records, soil conditions, and crop performance to estimate future water requirements several days or weeks in advance.

The integration of sensors with Internet of Things (IoT) technologies enables continuous real-time monitoring of soil moisture and environmental conditions. Key Sensors Used are Soil Moisture Sensors, Temperature Probes, and flow meters.

Image-Based AI Monitoring: The combination of satellite or drone imagery with artificial intelligence (AI) and deep learning models offers an advanced tool for continuous monitoring of crop health, early identification of water stress, and precision irrigation management. Image-Based AI Works by identifying Vegetation Indices and Water Stress, integrating them to create a Spatial Data Analysis for optimising irrigation distribution.

Smart Controllers and Actuators: Smart controllers and actuators facilitate automated irrigation by interacting with valves, pumps, and sprinklers to deliver water efficiently according to real-time field conditions and system requirements.

Applications: NetBeat™ by Netafim, CropX, IBM Watson Decision Platform for Agriculture, Karnataka State, India by Microsoft Azure.

Drip and Sprinkler Irrigation

Micro-irrigation methods such as drip and sprinkler irrigation have revolutionised water management. Drip irrigation applies water to the root zone at a low flow rate (2–20 L h⁻¹) through a pressurized system, achieving over 90% on-farm irrigation efficiency. Drip irrigation minimises conventional losses such as deep percolation, runoff and evaporation. Sprinkler irrigation provides uniform water distribution across the field, is suitable for uneven terrain, reduces surface runoff, and improves overall irrigation efficiency. Pressure irrigation comprises a range of irrigation techniques, including sprinkler systems, centre pivot and LEPA irrigation, micro-jets, drip (micro/trickle) irrigation, and both surface and subsurface irrigation methods. The overall efficiency is above 80%. India has an estimated micro-irrigation potential of approximately 69.5 million hectares (Mha), yet only about 7.7 Mha has been brought under micro-irrigation, indicating a significant gap in its adoption. Drip irrigation accounted for 3.37 million hectares (Mha), while sprinkler irrigation covered 4.36 Mha.

Soil Moisture Conservation

Healthy soils store more water and make it available to crops for longer periods. Water-smart cultivation therefore emphasizes soil management alongside irrigation. Important soil moisture conservation practices include mulching, minimum tillage, the application of organic manure, compost incorporation, crop residue retention, and deep tillage in compacted soils to improve soil structure, moisture retention, and overall soil health. In China, a meta-analysis showed that plastic film mulching increased the yield of maize, wheat, potato, and cotton by 24.32% and improved water-use efficiency by 27.63% Gao et al., (2019).

Rainwater Harvesting

Rainwater harvesting captures rainfall for future irrigation instead of allowing it to escape as runoff. It is achieved through structures including farm ponds, check dams, percolation tanks, contour bunds, and water harvesting pits, which enhance water conservation, storage, and groundwater recharge. Rainwater harvesting is a sustainable adaptation strategy for regions experiencing high rainfall variability. It also enhances groundwater recharge and reduces flood risks. The collection of rainwater from rooftops in urban and rural households, along with sloped roofs of low-cost and high-tech polyhouses, is emerging as an important water conservation practice, particularly in the northeastern hill states of India. Effective rainwater harvesting on arable land at the farm level can be accomplished using agronomic measures such as contour cultivation, mulching, trench planting, furrow irrigation, deep tillage, raised-bed cultivation, and ridge systems. Engineering approaches to rainwater harvesting include contour bunds, graded bunds, bench terraces, contour trenches, conservation ditches, and broad bed and furrow (BBF) systems.

Floating Agriculture

Floating agriculture is an indigenous farming system in which crops are grown on floating rafts without the use of conventional soil, offering a sustainable cultivation method in waterlogged and flood-prone areas. Traditionally, these floating rafts were constructed from

composted organic materials such as water hyacinth, algae, straw, and herbs. In Bangladesh, water hyacinth, an aquatic weed, is widely used to construct floating cultivation beds for growing vegetables and spices. These nutrient-rich beds contain sufficient nitrogen, phosphorus, and potassium, minimizing the need for chemical fertilizers. The aquatic environment around floating beds naturally limits weed infestation, thereby reducing the need for pesticides. Moreover, floating vegetable cultivation can achieve productivity levels up to ten times greater than those of land-based agriculture on a comparable area.

Laser land levelling

Laser land levelling is an effective on-farm agricultural practice that minimizes irrigation water demand, reduces irrigation duration, and enhances water-use efficiency. A smooth, levelled field minimizes the use of seeds, fertilizers, chemicals, and fuel, improving overall farm efficiency. It alters the field of uniform slope of 0-0.2%. Laser levelling could save 20–25% of irrigation water and improve yield by 5- 15%.

Cloud Seeding

Cloud seeding is used in water-deficient agricultural regions to increase rainfall and support crop production. It is a weather modification method used to produce artificial rainfall from clouds. In its early stages, cloud seeding involved the release of silver iodide from ground-based incinerators to promote precipitation. Advancements in cloud seeding technology have led to the use of specialized aircraft for dispersing seeding agents, including brine, to enhance precipitation. Cloud seeding is also employed as a hail suppression technique to reduce the occurrence of hailstorms and protect agricultural crops from extensive damage.

Retaining stubble / low till technique

The retention of crop stubble after harvest, coupled with low-tillage practices, enhances soil moisture conservation by reducing evaporation, leading to improved water-use efficiency and higher crop yields than conventional agronomic practices.

Deficit irrigation

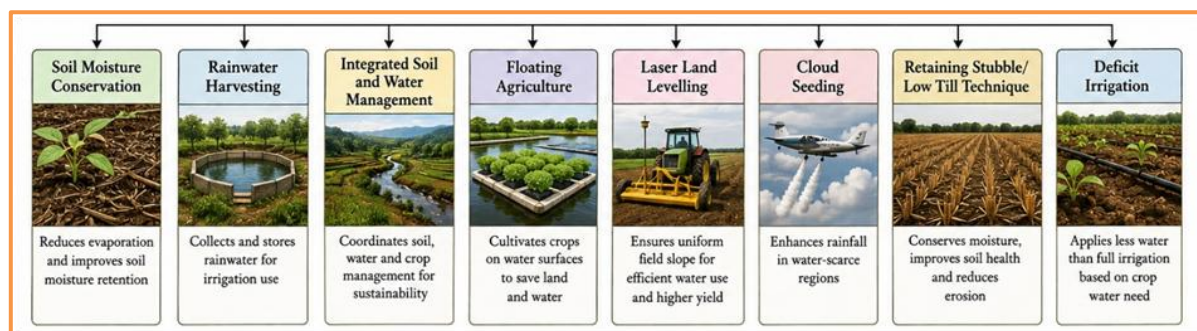
Partial root drying (PRD) involves the alternate wetting and drying of different sections of the root zone, utilizing the plant's physiological and biochemical responses to improve water-use efficiency. It involves practices like scheduling irrigation and agronomic practices for higher WUE. Partial root drying (PRD) is a novel irrigation strategy that optimizes water-use efficiency while sustaining crop yields with negligible yield loss. It aims to maximize water-use efficiency by producing higher crop yields with less water, following the principle of "more crop per drop."

Floating solar power plants

Floating solar power plants represent a rapidly growing renewable energy technology in which photovoltaic panels are attached to buoyant platforms that float on the surface of water bodies such as reservoirs, lakes, and wastewater treatment ponds. The surrounding water naturally cools floating solar panels, reducing their operating temperature and enabling higher efficiency than rooftop solar panels. Floating solar panels generate clean, renewable electricity while helping to reduce greenhouse gas emissions. Floating solar power plants protect aquatic ecosystems and reduce water evaporation by nearly 70%. The adoption of floating solar power plants is expanding rapidly across countries such as the United States, China, Japan, the United Kingdom, India, and many other parts of the world.

Challenges

While smart irrigation technologies have great potential to improve agricultural water management, their broader adoption depends on addressing several technical, economic, and operational challenges. Major challenges include High installation costs and limited digital literacy, Fragmented landholdings, and maintenance concerns in rural areas. Furthermore, the effectiveness of sensors and predictive models depends on region-specific calibration, as inaccurate calibration can result in unreliable irrigation recommendations.



Conclusion

Smart irrigation technologies offer a sustainable solution to the growing challenges of water scarcity, climate variability, and rising agricultural water demand. By integrating soil, plant, and weather-based monitoring with automation, remote sensing, and artificial intelligence, these systems enable precise irrigation scheduling, improving water-use efficiency while maintaining or enhancing crop productivity. However, their widespread adoption is constrained by high initial costs, limited technical knowledge, inadequate infrastructure, and the need for region-specific calibration. Addressing these challenges requires supportive policies, financial incentives, farmer training, and continued research to develop affordable and location-specific technologies. Future irrigation management should combine advanced monitoring, predictive analytics, and intelligent control strategies to optimize water productivity under diverse field conditions. With coordinated efforts in technology development, policy support, and farmer participation, smart irrigation can strengthen climate resilience, conserve water resources, and contribute significantly to sustainable agriculture and long-term food security.

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