PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.6601

eISSN 2348-1900

REVIEW ARTICLE

Smart water management in agroecosystems: innovations and challenges in a changing climate- A review

Gourav Sabharwal[1], K Vaiyapuri[1]*, S Selvakumar[2], M Raju[2] & R Jagadeeswaran[3]

[1]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[2]Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[3]Department of Remote-Sensing and GIS, Tamil Nadu Agricultural University, Coimbatore 641 003, India

*Correspondence email - vaiyapuri.k@tnau.ac.in

Received: 09 December 2025; Accepted: 21 April 2025; Available online: Version 1.0: 14 June 2025

Cite this article: Gourav S, Vaiyapuri K, Selvakumar S, Raju M, Jagadeeswaran R. Smart water management in agroecosystems: innovations and challenges in a changing climate-A review. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.6601

Abstract

Over the decade, rapid climatic changes threaten agroecosystem stability and food security. The rapid transition from natural vegetation to agricultural land results to alteration of surface energy balance. Numerous interactions occur within the agroecosystem among its diverse components. Properly understanding these interactions helps mitigate environmental impact through modern climate-smart technologies and sustainable crop water management based on unique needs. Smart water management paves the pathway, particularly in water crises phase through the use of numerous contemporary artificial intelligences, machine learning tools, agrometeorological models and Internet of Things based modern watering devices aid in the efficient use of resources both on and off farm to improve agricultural output and quality. The study's objective is reviewing core technologies including advanced sensors, internet of things, remote sensing and agrometeorological models. The highlights of this study to investigate SWM systems. A comparative analysis of existing technologies identifies challenges such as high cost, data privacy concerns and policy gap. To address these gaps, this study proposes an integrated approach that combines artificial intelligence, remote sensing and IoT framework as most effective approach, enabling real time monitoring, precise irrigation scheduling and adaptive response to climate variability. Advancing these technologies with suitable, cost effective solutions, and policy interventions is crucial for ensuring climate resilient, increasing the efficiency of the smart management system and sustainable agricultural water management.

Keywords: agrometeorological models; artificial intelligence; climate variability; internet of things; irrigation scheduling; remote sensing; water productivity

Introduction

After thousands of years of human development in which water has been a plentiful resource in most areas, amounting virtually to a free good, the situation is now changing abruptly to the point where, particularly in the more arid regions of the world, water scarcity has become the single greatest threat to food security, human health and natural ecosystems. Growing talks on the water problem emphasize that 1.2 billion people cannot access safe and inexpensive home water. Water shortage is a major problem in many areas, aggravated by overuse of water resources, climate change and diminishing water quality change (1). Water shortage has two separate aspects: availability and application. Availability relates to the balance between quantitative demand and resources, whereas applicability refers to the water's suitability for its intended use. This distinction is critical when comparing rural vs urban water consumption. Water is frequently lost in rural locations due to evaporation and pollution, whereas water is retained but extensively contaminated in metropolitan areas. Scarcity has a more significant impact (2).

Recent research findings emphasize the need for an intelligent irrigation system in India to tackle water scarcity and enhance water productivity. India's traditional irrigation systems, including wells, tanks and water channels, have led to groundwater depletion and are inefficient, with only 30-40 % efficiency (3). Alternate wetting and drying (AWD), the vibrant water-saving and eco-friendly option in India's rice, is a successful micro irrigation (MI) method (4). The role of the International Commission on Irrigation and Drainage (ICID) launched in 1993 is inevitable in coordinating policies to promote and recognize water-saving practices and upscaling of technologies worldwide (5).

Micro-irrigation techniques like drip irrigation and AWD have improved water productivity but remain insufficient for large-scale resilience. Smart Water Management (SWM) integrates AI, remote sensing (RS) and the internet of Things (IoT), enabling real-time monitoring, predictive analytics and automated irrigation to optimize water use. The International Commission on Irrigation and Drainage now emphasizes data-driven irrigation frameworks for sustainable water conservation. IoT-enabled precision irrigation, AI-driven forecasting and real-time soil moisture sensing are shaping the future of climate-adaptive water management in agriculture.

Smart water management (SWM) is a transformative approach to address the escalating water crisis driven by climate change and rising demand. It has been advancing since 2015, exploiting information and communication technology (ICT) to tackle water sector challenges while ensuring economic, social and environmental sustainability (6). Predictive indicate that by 2050, water scarcity can increase many times with agricultural water consumption alone about 70 % of available water (7-9).

Based on the reports of irrigation water requirements, it is the right time to explore SWM technologies for sustaining food production globally. ICT-based sensors are important tools for providing real-time monitoring of data such as pressure, water, or water quality, moisture, etc. with the capability to detect any abnormalities such as non-revenue water losses and water contamination in the water distribution system (10). The crop productivity influenced by the water as a major resource throughout agricultural revolution is depicted in (Fig. 1). The integration of innovative digital technologies transform SWM driven advancement in urban water system, enabling real-time monitoring, enhance operational efficiency, facilitate predictive maintenance and enhance water security and climate resilience.

Climate change, not easily persuadable for management and also precisely predictable, has intensified many stresses causing factors (frequent and intense droughts) that threaten food security (11, 12). Global warming is expected to result in increased sea levels due to the spreading of oceans and melting of glaciers, affecting the flow of freshwater into the oceans causing variations in stratification, nutrient availability, salinity and turbidity, influencing tourism, agriculture and industry (13). Climate change is already known for fluctuating the earth's temperature and precipitation; often increasing in the mean seasonal temperature, resulting in reducing the crop duration and water , forcing towards enormous economic losses to agroecosystems, ultimately influencing photosynthesis, respiration and translocation declined global food production (14, 15).

Recent Conference of the Parties 26 and Conference of the Parties 27 meetings have developed major policies and focus on sustainable development (16). The Internet with weather service is valuable in developing climate-resilient agriculture services. Due to an increase in contradictory or stress -causing factors the agroecosystem got disturbed which affected crop production, including alteration of soil physicochemical properties, product quality, increase in pest attack, weed prosperity, intense fire incidents and intensive crop production methods (17, 18). Freshwater ecosystems have been disturbed in past years due to over-exploitation, which makes the region's socio-economic condition insane, putting an urgency to deal with water resources smartly (19). According to the Second United Nations World Water Development Report, there is a strong positive link between investments in irrigation, poverty alleviation and food security. Irrigation facilitates minimizing abrupt and unpredictable yield reductions that many of the world's food production areas would face due to recurring or sporadic droughts (20). Agriculture 5.0 in the first half of the 21st century has developed a revolutionized agriculture sector, which plays an essential role in the utilization of digital tools for efficient and economical management of resources (21). SWM apprehends the automatic water management system that functions on AI tools and forecasting models. The utilization of water resources observed a shift in recent times has led to the development of real-time monitoring.

Artificially withdrawing the water from the earth is fuelled with emerging climate change challenges forces to adopt SWM technologies to save water and environment. Agroecosystem, being the most prone sector to climate change leading to social and economic consequences for human

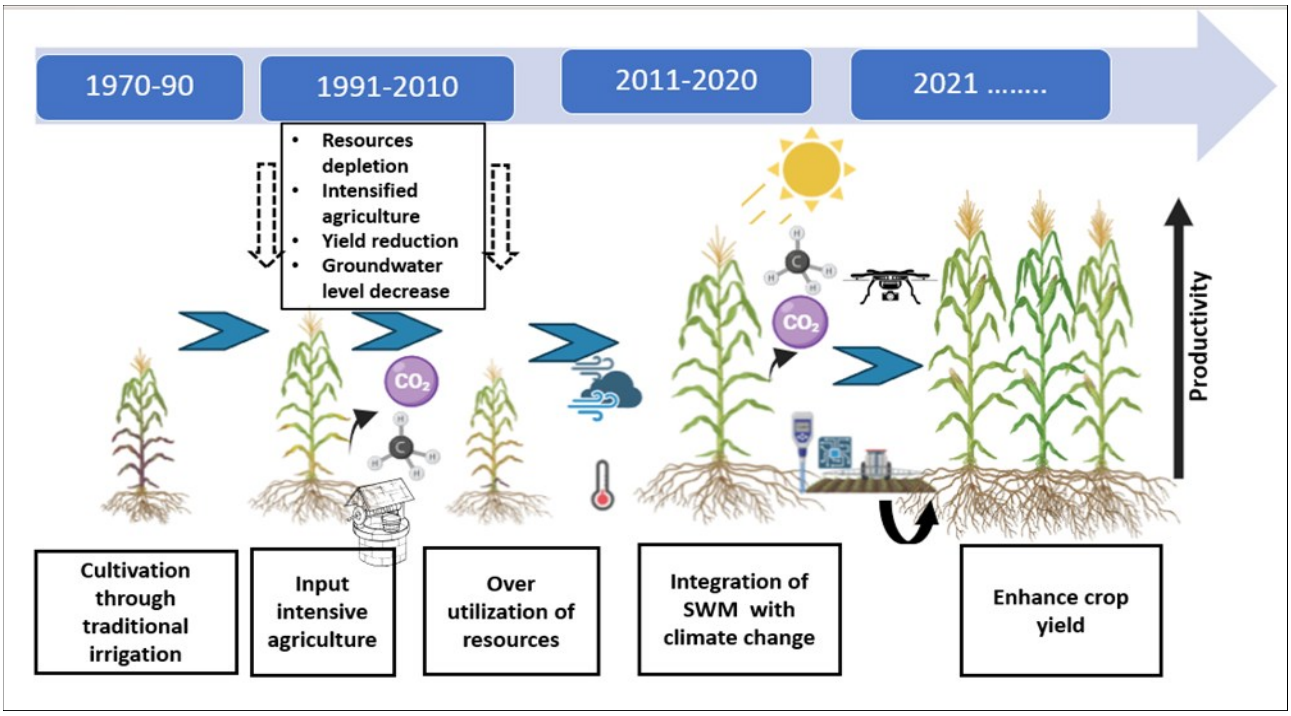


Fig. 1. Evolution of smart water management globally.

life (22), the need for development of improved technologies to fit with the new climatic scenario by duly considering cultural, social and institutional approaches (23). In a broader perspective, various digital technologies, including sensors, IoT networks, cloud computing algorithms (e.g., machine learning) and big data analytics have been employed to enhance the agricultural landscape and irrigation system (24-26). By embracing digital transformation, irrigation system improves efficiency, becomes smarter and resilient, enabling innovative cost-saving solutions for agricultural communities (27, 28). Such innovative real-time tracking and dynamic monitoring of water consumption and improve essential decision support mechanisms.

The purpose of this review is to highlight the various SWM technologies over a period of time. This brief attempt to visualize the work carried out in SWM is to project the achievements made under the following objectives.

1. A review of core technologies in SWM, including advanced sensors, IoT, RS and agrometeorological models
2. A novel SWM architecture integration of various tools like crop models, AI, IoT, etc. for real-time irrigation scheduling highlights its importance in efficient utilization of scarce water resources for agroecosystems.
3. To analyze main reasons behind the need and shortcomings of SWM technology

Materials and Methods

Using a multidisciplinary approach, a bibliometric study was performed to examine smart water management studies. Databases such as Google Scholar, the Consortium for e-Resources in Agriculture (CeRA) and Scopus were used to find the literature. More than 1200 documents were found in the first search using terms like "smart water management," "climate change," and "agriculture." The dataset was further refined to 200 papers using subject-specific selection, keyword exclusion and sophisticated filtering. The collection was further narrowed to 50 pertinent studies by additional searches, including agrometeorological models, artificial intelligence, agroecosystems, remote sensing, IoT and climate resilience. For information on managing water resources, conference papers and IPCC reports were also examined.

To guarantee the applicability and methodological soundness of chosen studies, eligibility and quality evaluation were carried out utilizing predetermined inclusion and exclusion criteria (Table 1). About 100 research publications were chosen after a thorough screening procedure. Important study features, conclusions and analytical patterns were taken out for assessment. R Studio (version 4.4.0) was used for bibliometric analysis, while Draw.io software (version 20.8.16) was used for data visualization.

A descriptive examination of the gathered literature first found 738 papers from PubMed and 1013 from Scopus. After removing irrelevant, duplicate, or non-agriculture-related studies, the final selection included 111 publications (Fig. 2). Research on smart water management has significantly increased over the last 15 years, with 64.55 % of the literature written between 2019 and 2023, according to a temporal review. Bibliometric mapping revealed China as the top contributor to publication frequency, followed by the United States and India, with variable densities reflecting strong worldwide research linkages (Fig. 3). The selected research investigated AI-based applications in agriculture, aquatic ecosystems and water resource management, including predictive analytics, smart metering, leak detection and decision-support systems. The findings highlight the growing importance of innovative water management systems for improving resource efficiency and climate resilience.

Leading peers in SWM

On proper reviewing of literature, Kamienski C. leads with more publication followed by Maia R.F., Soinen J.P as indicated in Fig. 4. projecting the major share by India and China concentrating on water saving technology.

Smart Water Management (SWM)

SWM is sustainable crop water management based on specific needs and advanced climate-smart technologies reduces water use while maintaining crop yield (29). Integrating data sources and predicts soil moisture using dynamic data processing tools like sensors and a cloud-based platform that utilizes mobile apps to adjust irrigation scheduling (30) and enabling precise water management as illustrated in Fig. 5. Artificial intelligence has innovative solutions that contribute to reducing labour demand and proficiency in the preservation of natural resources (31). Earlier reports revealed that irrigation methods from simple traditional used shaduf or shadoof followed by hand operating water lifting devices (in India, Egypt and some other countries) (32), irrigation through constructed of lakes (33), dams, water control systems for small scale/ community system (34).

Water resources are decreasing day by day due to changing climates and the demand rate is increasing at a critical rate. Hence innovative ways like MI to enhance efficiency and conserve water were first setup in Israel during the 1960s and have spread to many other parts of the world, especially in the USA, which holds good even in present condition (35). Innovative approaches to water management along with artificial learning (AL), machine learning (ML), deep learning (DL), IoT and sensors enhance water-use efficiency. Climate resilient smart water management requires an understanding of plants drought resistance mechanisms that include detoxification and carbon assimilation, which aid in increasing plant tolerance against drought stress (36). A proactive approach needs to be implemented by learning from past experiences for better sustainable drought management practices

Innovative technologies

In recent years, role of different robotics and unmanned aerial vehicles (UAV) in water management in agriculture, has been sensitized in optimizing scarce resource allocation. Though ML is the initial step in water conserving technologies, much more advanced system has evolved in pace with the scientific advancement based on human needs such as Remote sensing (RS) and AI, IoT and agrometeorological model as detailed below.

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time span	2018-2024	<2018
Document type	Article	Conference papers, Book chapters, review, Editorial
Languages	English	Non-English
Source type	Journal	Trade journal
Publication stage	Final	Press
Keywords	"smart water management," "climate change," "agriculture," "remote sensing", "artificial intelligence," "machine learning." "Internet of things"	All other keywords
Open access	All open access	Restricted access
Screening		
Title and abstract	The study includes titles and abstracts that contain preset keywords.	
Full text	The papers that address the predetermined keywords are the pertinent ones incorporated into this study.	

*Few important articles from before 2018 also included

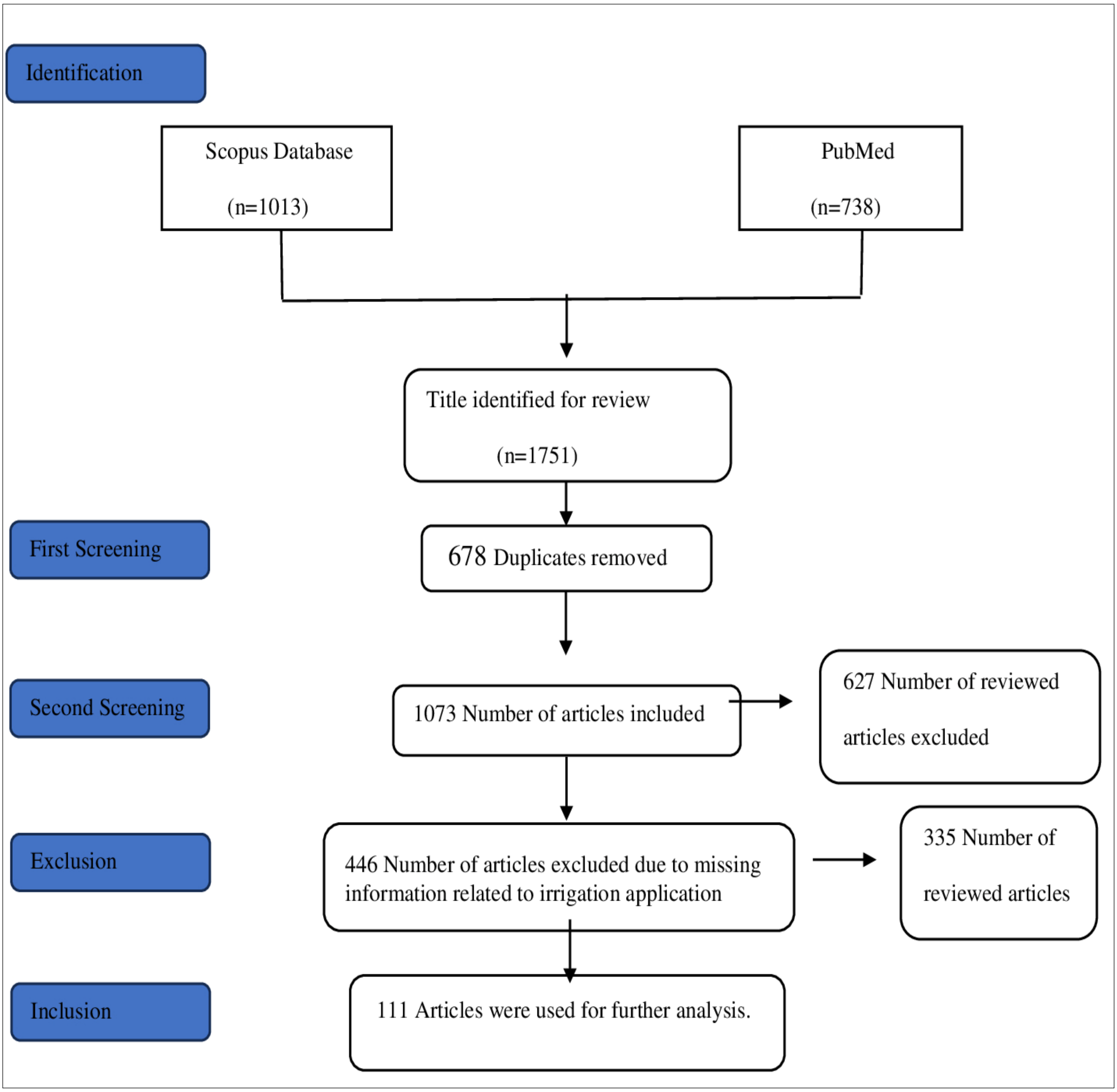
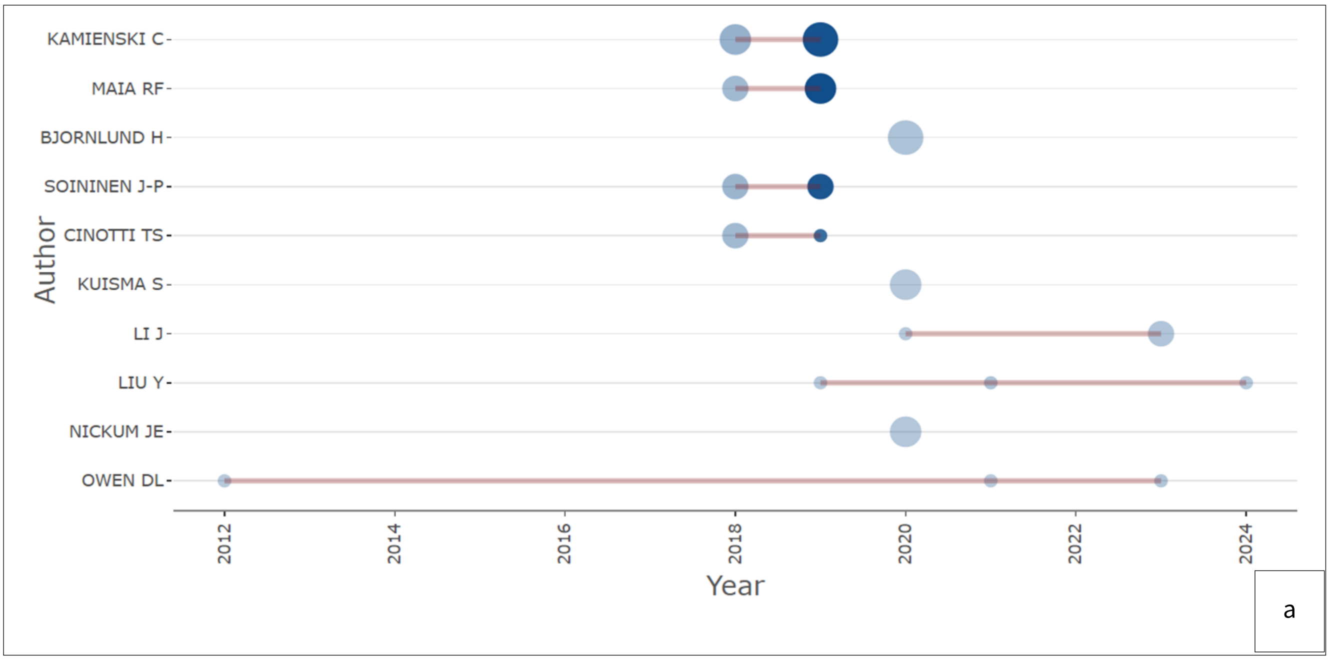


Fig. 2. Flowchart of search, selection and screening of article.

Fig. 3. Systematic overview of data-driven literature analysis on smart water management; (a) Country-wise annual scientific production; (b) Collaboration among scientists of different countries; (c) Most relevant and often used words in papers; (d) Annual publications related to topic in past 20 years.



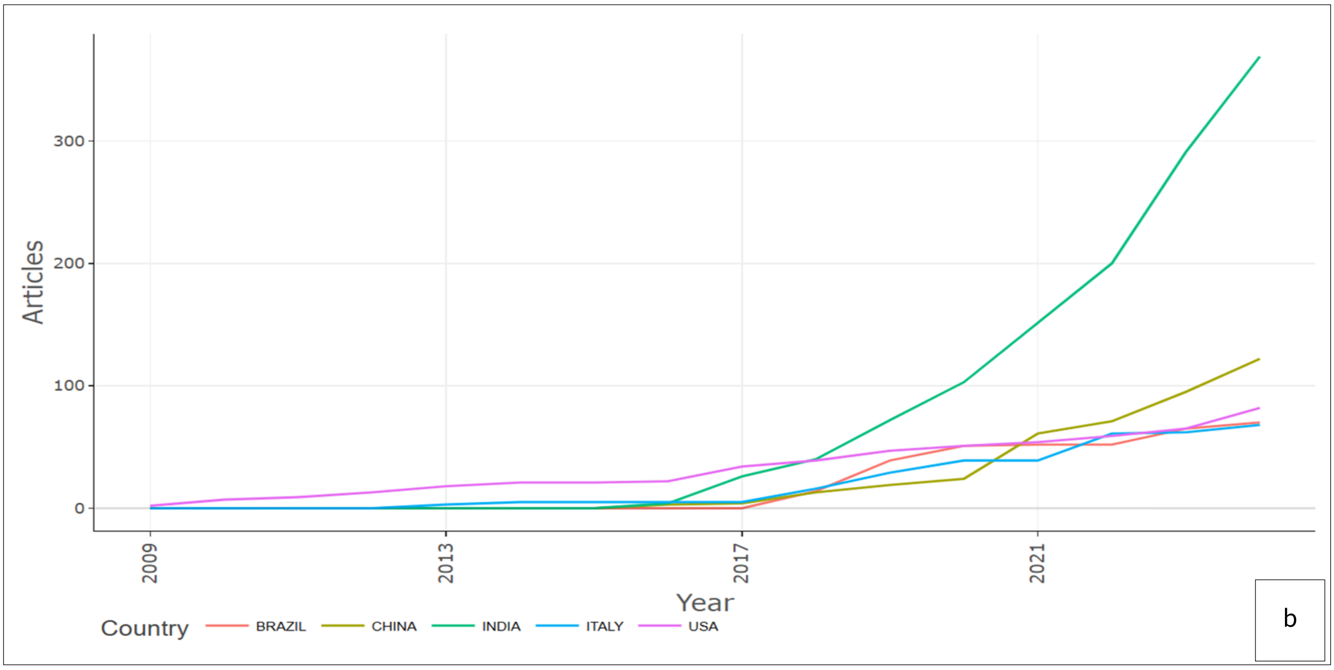


Fig. 4. Global publications; (a) Peer experts (b) Chronological.

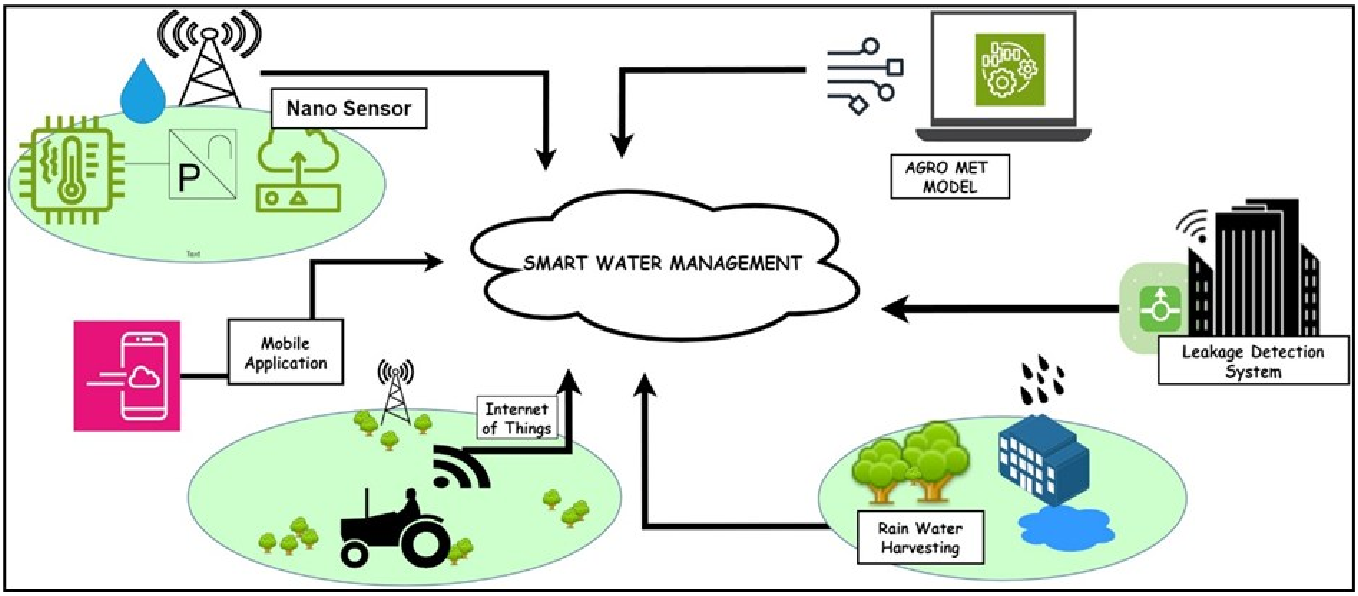


Fig. 5. Schematic diagram of associated factors for smart water management.

Remote sensing (RS) and Artificial intelligence (AI)

With the advent of satellite in the 1960s, RS technologies leverage AI revolutionizing to enable automated hydrological data processing and intelligent monitoring (37). Integration of RS and AI increase the ability to process a large amount of data and identify patterns facilitating the AI algorithms to analyze remote sensing data for crop health, soil moisture and evapotranspiration losses assessment. Further it facilitates groundwater surveillance via satellite radar, optimizing irrigation scheduling through soil moisture capacity and ET estimation. AI and deep ML technologies facilitate efficient utilization of resources both on and off-farm through various modern AI tools to improve agricultural operations, by providing recommendations to farmers for taking different farm operations (38) at right time thereby saving approximately 30 % of water.

A Drone-based spatial soil moisture survey can be done to analyze the variable water requirement of the same field (39). A successful case of Groundwater modelling done using the RS tool Earth Engine Evapotranspiration Flux (Efflux) over the Andean basin with an objective to enhance its efficiency for sustainable management and assessment of groundwater resources (40) is a monumental example. In addition to this, Moderate Resolution Imaging Spectroradiometer (MODIS) based on spatial mapping of chlorophyll-a done in Apalachicola Bay of Florida in Mexico to estimate the water quality and oyster growth in varying river flow ecosystem is another feather to the achievement (41).

Similar other advancements through effective integration of these water management technologies are listed below:

1. The Araguaia River flow assessment through Planet CubeSats via the RS constellation by effective integration of CubeSat images at CubeSat Virtual Station (CVS) for accurately estimating river flow and height variation in different time frame leading to monitoring the sub-basin scale discharge for managing water efficiently particularly in developing countries (42).
2. Monte Carlo simulation model and RS-linked eco-hydrological model facilitates to economized assessment of soil moisture by farmers, for the individual and community level, which will enable the management of water resources for efficient agricultural utilization (43).
3. Monitoring water quality of water resources in plain can be very well stored in ponds and lakes. Water quality management can be effectively done using AI-based Land Satellite (LANDSAT) imagery models and *in-situ* (44). Increasing algal blooms in freshwater, affected water quality thereby the ecosystem. AI-based image processing and sensor could be used to assess the algal mass in the water resources and find ways to utilize AI-powered real-time data collection effectively facilitate SWM techniques (45, 46).
4. AI enabled water management/hydrological models to improve water conservation efforts by strategic water allocation and cropping system optimization in hilly regions such as Uttarakhand and Tamil Nadu facing water availability fluctuation (47).
5. A remarkable transformation of African agriculture by utilizing software's like Farmer Edge in South Africa and Zenvus in Nigeria which brings more transparency empowering the farmers to use AI tech tools for sustainable agriculture by suitably in cooperating the innovative and efficient water saving method along with other crop production technologies (48).

Latest version software 5.0 the HYDRUS model evaluates irrigation strategies through refine study on soil water analysis for efficient planning (49). In contrast, sensor-based temperature vegetation dryness index (TVDI) and normalized difference water index (NDWI) offer satellite based monitoring and risk occurrence prediction (50).

The role of RS in SWM is pictorially depicted in Fig. 6 while the latest innovations and their principle and benefits are listed in (Table 2) for comprehensive understanding.

Internet of Things (IoT)

IoT is being widely applied in all scientific fields for efficient data coordination. The utility of IoT in the SWM is remarkable and the various developments witnessed are discussed here underneath. Spatial application analyses irrigated areas' size and distribution for mapping water availability and increasing cropland areas (60). Highly efficient ZR16S08 microcontrollers were identified to identify water leakage promptly, monitor water quality, supply and leakage and provide an efficient solution (61). Subsequently development of Smart and Green Iot-based framework software optimizes irrigation water-saving up to 56.4 to 90 % (62). Being IoT facilitating the connection of internet virtual infrastructure and communication technologies that collect data and transfer it for further processing (63), a IoT mobile application-based irrigation system analyses inputs (soil moisture level and chances of rain depending on water requirements) to control the motor water output remotely for saving water in highly efficient manner in comparison to manual flooding (64).

Combining the RS technology tools of digital soil mapping aids in decision-making for achieving sustainable goals. In the evolution of the IoT model with high spatial resolution and enhanced mapping, Revised Universal Soil Loss Equation (RUSEL) is fabricated for estimating rainfall-runoff erosivity, soil erodibility, land cover and management (65). Diffusion Convolutional Neural Network, a precision agriculture based accurate water requirement estimation model coordinating the different crop stages; along with moisture, various climatic parameters like temperature, humidity (66) is another milestone in the IoT integrated water management by enhancing water use efficiency, energy and management cost reduction, decrease in human interference and crop productivity enhancement.

Considering the utility of smart infrastructure, which are predominantly self-monitored, self-communicating and self-administering IoT based technologies, an integrated IoT paradigm for water supply system paves way for enhanced water management, decrease in energy usage, enhanced water utilization with minimized human intervention, thereby for the increased productivity offering high economic returns to farmers in addition to environmental sustainability. Innovation of Smart IoT lysimetric system, paved way for the development

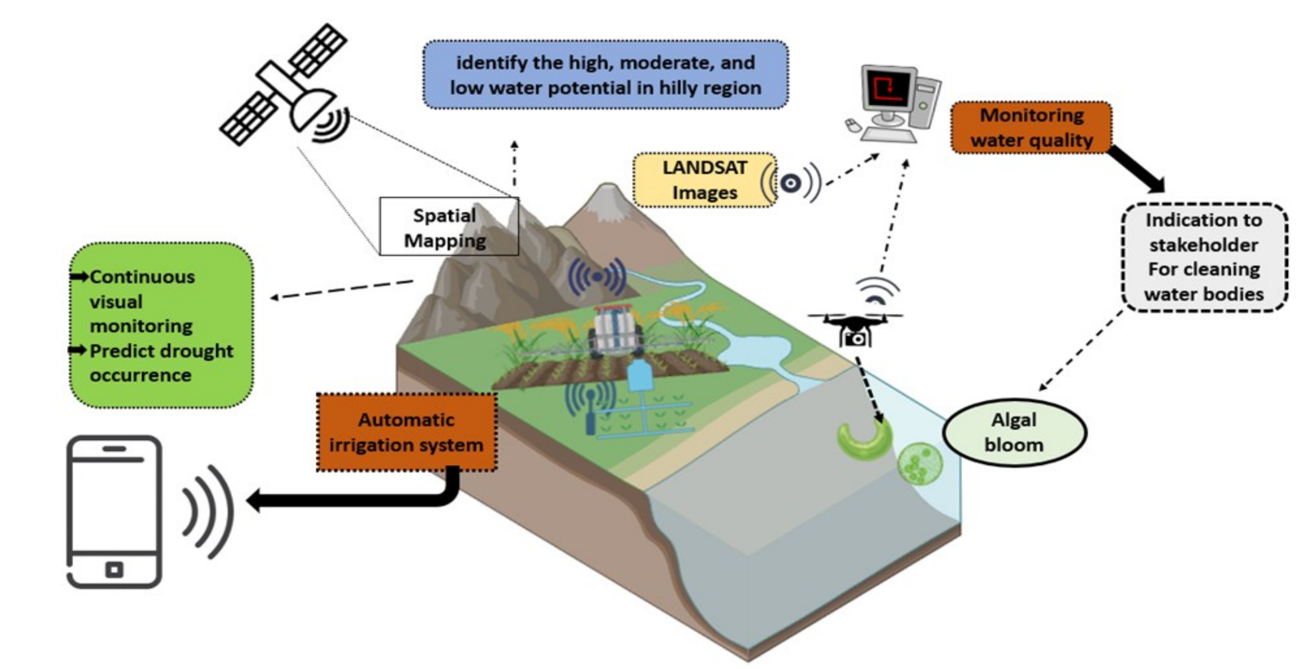


Fig. 6. Intervention of remote sensing for smart water management.

Table 2. Remote sensors with its principles and benefits

Sensor	Principle	Benefit	Reference
Cosmic ray neutron sensor (CRNS)	Volumetric soil moisture estimates by in-situ sensors or taking samples	Not expensive soil texture influence on moisture availability can be analyzed	(51)
Surface radiometric sensors	The relation between surface temperature and NDVI index value depicts the TDVI (Temperature vegetative dryness index) value, which is directly related to water stress.	Simple technology Avoid soil disturbance RS based on large-scale monitoring	(52)
WSN (Wireless Sensor Network)	Fusion of Zigbee Network and G P R S	Remotely monitoring and irrigation management	(53)
Highly sensitive Screen-printed flexible soil moisture sensor	An interdigitated electrode (IED) measures soil moisture	Soil moisture and relative humidity monitoring management	(54)
Automated irrigation prototype	system readings based on sensors and send them to the Adafruit platform IO	Real-time visualization and management of water	(55)
PSDNet	Extract plant leaves and using the Leaf Regions with CNN Features (Leaf-RCNN) module to predict water requirement	Improve accuracy Automated water system	(56)
Ardu Hydro (AH)	Ultrasonic sensor-based water monitoring device and signals through Arduino microcontroller	Significantly measure water depth in irrigating fields by spatiotemporal	(57)
REES52 Sensor	Measure real-time soil moisture data	Automated and precise water management	(58)
Hydromast	Sensor-based water flow monitoring device near the bed, current and water level	Key for water resource management decision-making	(59)

of a portable smart weighing lysimeter at CPCT, IARI, New Delhi for real-time measurement of Crop Coefficient (K_c) and water requirement of greenhouse chrysanthemum crop and bulk data storage (67). Smart IoT lysimetric system, a Wi-Fi communication interface to cloud computing services models comprising platform as a service (PaaS) and software as a service (SaaS) developed using a mechanical weighing lysimeter; sensors and actuators commanded by a digital controller based on a microcontroller platform. The smart weighing IoT is very successful for an integrated automation and control system to monitor reference evapotranspiration (ETo) (68) directly. Recently, the above lysimeter has been modified to be cost-effective in monitoring crop evapotranspiration (ET) in Central India (69). In general, those working in environmental sustainability and water technology are very concerned about developing greenhouse technologies with effective utilization of available resources and inputs with the least adverse effect. The progress in the IoT based SWM are depicted in the Table 3 for easy comprehension.

Agrometeorological models

The Agri Met system seeded in 1983, for automation weather stations to collect data for ET and resulting in water and energy saving by 15-50 % (84), predicting drought and variation in hydro-climatic conditions on different terrestrial ecosystems and their biome (85), focusing on weather forecasting at its budding initial stages and further improved by in cooperating more complex data to facilitate for agriculture decision making system (86). Efficacious noteworthy model, IABM (Irrigation Agent-Based Model) implemented in Colombia by segregating the villages based on the GIS model and Agro-met data (87), is considered a flagship achievement.

At the global Scenario, African countries are considered to have high vulnerability because of their large dependence on rainfed agriculture (88), indicating the necessity for utilizing a suitable agrometeorological model. Only a few farmers were found to adapt new practices to overcome climate change in the Indian Himalayan region, emphasizing the need for cooperative projects between local government organizations and research

Table 3. Different IoT tools for enhancing water system

IoT technology	Principle /method	Advantage	Reference
Open field condition			
Agro-industrial IoT (AI IoT) technology	Integrates ANN and FAM for automated anti-frost irrigation control via a climatological station	ANN: Forecasts greenhouse internal temperature Fuzzy Control: Predicts crop land temperature Water Pump Activation: Regulates five output levels based on predictions	(70)
Lora WAN (Long Range Wireless Area Network) IoT system	Continuous monitoring of moisture in the environment, plant and soil	Effective and economical method	(71)
Fuzzy-IoT	A fuzzy logic controller and LoRa enable real-time, long-range data monitoring for adaptive system control.	Economized irrigation and energy requirement	(72)
Zigbee Technology	Using microchips and sensors for crop growth and moisture analysis	Avoid water wastage	(73)
LysipheN prototype	Remotely (wireless connection) integrating sensors with plants and soil via a data platform	Facilitates screening the plants for ecological adaptation and WUE evaluation	(74)
SMAIoT-ferti	IoT sensors are integrated for monitoring soil, air, water and fertilizer levels.	Resource use optimization	(75)
Internet of things sensors and support vector machine integrated intelligent irrigation system	IoT-based humidity and soil sensors collect real-time soil data. The collected data is stored in a centralized cloud for further processing. The Correlation-based Feature Selection (CFS) algorithm is used to identify relevant features.	Accuracy: 98.5 % Functions: Classification, water demand prediction Impact: Optimizes irrigation, conserves freshwater	(76)
Greenhouse condition			
IT Dovetailed cloud computing resource management	Remote control of environmental needs anytime, anywhere through the web page	Controlling indoor environmental parameters and water supply	(77)
GEWA system (Green energy water-autonomous greenhouse system)	Sophisticated multidisciplinary framework Optimize water and solar energy utilization Integrated resource management	Promotes eco-friendly urban development Optimizes space and resource utilization Enhances urban aesthetics and air quality Reduces cooling and heating demands Adaptable for various urban environments	(78)
Smartphone-controlled greenhouse	Online management of greenhouse environmental parameters utilizing various sensors, GPS and robotic technology	Remotely managing moisture and temperature requirements	(79)
Adaptive neuro Neuro-Fuzzy Inference System (ANFIS) and Internet of Things (IoT)	Tracks temperature, humidity, sunlight and soil moisture via sensors Accessible through cell phone-based apps Linked with a fuzzy control system for intelligent decision-making	Easy monitoring of data by farmers and manipulation of moisture and temperature for sustainable crop production	(80)
Internet of Things (IoT) and Artificial Intelligence (AI) based smart greenhouse system	Combining the real-time sensor data with the Multivariate Decision-Making Algorithm (MDMA) along with fuzzy logic	Quick Accessibility effective greenhouse environment management	(81)
Digital twin-driven smart greenhouse technology	Real-time processing of data and machine learning for optimized decisions for enhanced productivity	Précised the timely performance of greenhouse operations	(82)
IoT platform-assisted greenhouse environment management	Sensors collect indoor and outdoor weather data and transmit it to a central sink node for processing and analys	CNNs predict inner humidity, temperature and outdoor conditions with high accuracy Regression analysis corrects faulty sensor data for reliable monitoring	(83)

projects to enhance farmers' knowledge of climate and agroecosystem (89). As per the Agrometeorological model, the sugarcane ratooning in the Semi-Arid Ago ecosystem in North India, suffering due to borer infestation could be managed with improved irrigation and potassium fertilizer supplementation (90). Multivarious models developed in recent time based on crop data are tabulated in Table 4. Understanding the various developments by integration of agroclimatic factors for SWM efficiently are portraited in the Fig. 7.

Comparative analysis of innovative technologies for SWM

Agriculture can be made more sustainable by making better use of data in decision making. Indeed, SWM is advancing through seamless fusion of AI, RS, IoT and different models enhancing water conservation, operational efficiency and precision irrigation (98). A comparative assessment reveals these technologies' distinct yet interconnected contributions (Table 5). Precision agriculture undergoing transformation collectively by innovative technology system. Broad scale observation into vegetation, soil moisture and climatic conditions providing large scale indirect monitoring and cost effective. Its effectiveness relies on satellite imagery constrained by cloud cover interference, resolution limitations and the need for expert interpretation. AI improves predictive analytics by analyzing extensive datasets for climate scale assessment. However it is large datasets

Table 4. List of models enhancing water resource management

Models	Principle	Advantages	References
Soil Flex model	Soil compaction serves as an indicator of moisture stress, aiding in precision water management	Ensures efficient water allocation while minimizing wastage Prevents soil degradation, preserving fertility and sustainability	(91)
Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model	Satellite-Sentinel-based estimation of NDVI-based ET	Enhance water resource usage. Protects water quality and the environment	(92)
Aqua Bamboo	Water requirement prediction using IT sensors and analytic models	Optimizes water supply and bamboo crop productivity	(93)
Solar ET Model	Measuring ET using multiple sensor data and solar energy data	Accurate and efficient system of irrigation scheduling	(94)
OAA-Enhanced MobileNetV2-TC model	Deep-learning models combining various sensor data	Identifying different wastewaters by processing images	(95)
Integrated multi-sensor indicators and ensemble learning (EL) model algorithms	EL-based algorithms (UAV and ground multi-sensors) for soil moisture estimation	Accurate moisture concentration estimation	(96)
LSTM (Long Short-Term Memory) Model	Uses a combination of soil, weather and satellite-based plant vegetation data for scheduling irrigation	Prediction of soil moisture reduction and irrigation scheduling	(97)

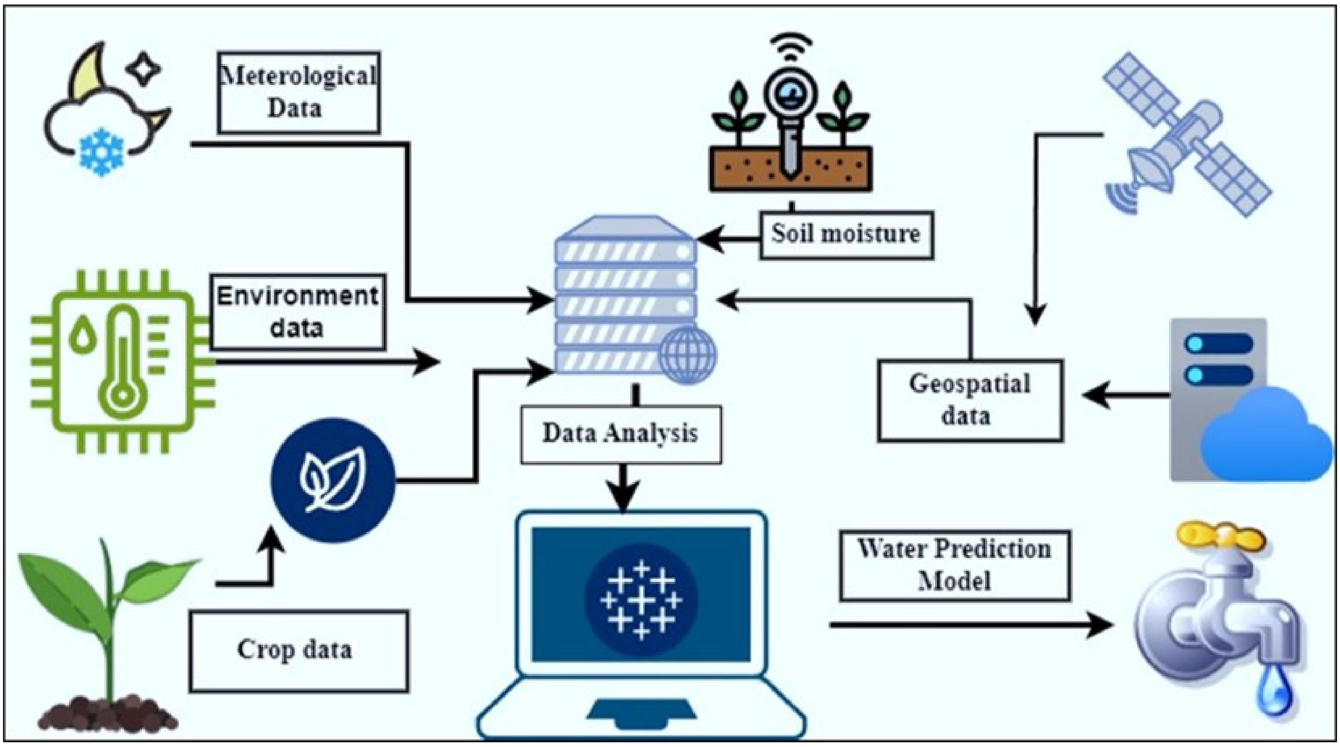


Fig. 7. Diagrammatical representation of the agrometeorological model.

Table 5. Comparative analysis of different SWM technologies

Technology	Data Source	Spatial Coverage	Temporal resolution	Accuracy	WUE	Cost	Applicability
RS & AI based system (99, 100)	Weather, soil, crop data Satelite	Field and regional to global	Moderate to High	Moderate to High	Upto 50 %	Moderate - High	Predictive analytics for WUE Large scale assessment
IoT based system (101, 102)	Sensors	Localized sensor specific	Continuous	High	40 %	Variable	Real-time monitoring & automation
Agrometeorological models (103)	Meteorological stations, soil and crop parameters	Regional to national	Moderate to High	High	-	Low to moderate	Irrigation scheduling & crop modeling

intensives, requires, substantial computational resources and often lacks interpretability. Agrometeorological models aid in predicting evapotranspiration, crop water demand and drought risks, aiding long tern agricultural planning. Although resolution limitations and the need for expert interpretation. IoT systems enable real-time monitoring of field conditions, improving irrigation efficiency and overall resource management. Yet, high initial investment costs, network connectivity limitations and cybersecurity risks must be considered. RS delivers large-scale monitoring but lacks real-time adaptability, which IoT efficiently addresses at a localized level. AI surpasses traditional Agrometeorological frameworks in forecasting precision, while real-time IoT-derived insights refine AI-powered decision-making.

Furthermore, RS-derived climate variables strengthen its predictions. While AI and IoT enhance localized automation, remote sensing provides large-scale insights and blockchain reinforces data integrity and trust in water management. The evolution of intelligent water systems depends on the synergy of these technologies, reinforced by quantum computing and decentralized networks, enabling anticipatory, adaptive and climate-resilient water management. This integrated framework is vital for fostering sustainable water utilization in agriculture, urban planning and environmental conservation, addressing urgent global water security issues.

Need of SWM in Agroecosystem

Shortage of labour in agriculture is the challenge for agriculture professionals, farmers and government's food security policy of India due to multi-dimensional, socio-economic, environmental and agricultural marketing infrastructure, are not mutually exclusive and not static in nature (104). Though the expenditure for irrigation is 8.2 % the labour cost accounted for the highest proportion of 51.3 % (105) and the availability of labour force is expected to decline due to changed socio economic conditions so forcing the land owners to take the responsibility of at least irrigation with automation facilities so that the expenditure to be incurred for labour cost for irrigation could be saved (105).

SWM is expected to handle the extreme event attribution aiming to elucidate the link between global climate change, extreme weather events and the harms experienced on the ground by people, property and nature by overcoming the limitations in attribution science, including the capacity for studying different types of events, as well as the geographical heterogeneity of both climate and impact data availability (106) thereby saving the ecosystems, wildlife and humans. By suitably quantifying drought risk situations in the long term, SWM extends a helping hand to sustain agricultural production.

Prospects and challenges

A large gap is prevailing between access and availability of all complex satellite data that can improve a decision-making process at national and regional level. SWM is a futuristic approach to utilizing water resources to enhance its credibility for future generations. To combat increasing population water demand. AI-based water management provides a unique solution for harvesting and precisely utilizing water. Precision agriculture has made agriculture smart, but traditional practices and knowledge are getting lost with the modernization of all farming practices. The potential challenges of discrimination in AI technology are driven by regional dominance over labour and knowledge (107). Additionally, there is a lack of a proper categorization framework for AI applications which makes comparisons of different applications and selects the best method. Satellite remote sensing avail real-time information of water cycle, howbeit with constrains related to accuracy, viability and utility.

Challenges and adoption barriers in SWM implementation

High cost

Being in the initial stage of SWM, the components and their installation are beyond the power of marginal and small farmers who occupy a major portion of the farming community in developing and underdeveloped countries (108).

Complexity and Data privacy

Smart devices collect and analyze huge data related to farm which can be utilized by various stakeholders like farmers, technology provider, commercial agencies, etc. where the data privacy of farmers leads to biggest concern (109).

Expertise Technical knowledge

Intensive training on the installation operation and maintenance of tools interoperability with industry for establishing common national and international standards and protocols to ensure safety.

Unavailability of precise real time data

Time Lag in the availability of precise meteorological data for the specific region of interest.

Institutional and policy barriers

Complexed administrative procedure not matching with the literacy level of major portion of the farming community for getting the access on SWM. Weak national and international cooperation for developing region or area specific SWM.

The integration of smart water management technologies in agriculture has the potential to transform our approach to water conservation and adaptation to climate change. However, several limitations and considerations must be addressed to enable successful adoption of these technologies. A primary limitation is the generalizability of findings from current studies. The success of smart water management innovations can vary significantly based on local conditions, including climate, soil types, crop varieties and socio-economic contexts. Consequently, results from one region may not apply to others, which restricts the ability to make broad generalizations. Another critical challenge is adopting these technologies among various stakeholders, particularly farmers. For successful implementation, farmers who may encounter obstacles such as financial limitations, lack of technological knowledge, or cultural resistance to new practices must actively participate. Therefore, it is vital to prioritize community empowerment and ensure that the decision-making processes concerning water management incorporate the views and needs of all stakeholders, including farmers, researchers and policymakers (110).

The study can empower community researchers and stakeholders by involving all research stakeholders and considering insights about community-specific water need and challenges. Enhancing understanding of water management issues of community and equips them with knowledge for effective community led initiatives aims at improving water supply and quality. SWM is an approach that provides a prominent solution for optimizing the utilization of scarce water resources (111). Utilizing these technologies will enhance water use efficiency and accessibility for all. These advancements will provide farmers with accurate predictions of monsoon so that crop planning can be done according to it, saving farmers from economic loss and enhancing productivity. As the timely adoption of new advanced technologies is better for global development, these tools provide prominent solutions to the problems that arose due to climate change. Indicatively, the utilization of modern innovative technologies has been catalyzing SWM. Future research should be focused on making technologies affordable for farmers. The Policy Framework needs to be modified to support and encourage smart water management and its integration with modern agriculture practices to enhance climate resilience.

Policy recommendation

A Policy Framework for Innovative Smart Water Management to guarantee food security through effective water management by suitably identifying the region-specific lacuna so far. Accordingly, the present review foreshows the deficiencies and appropriate policy interventions are suggested in Table 6.

Conclusion

Incredible development witnessed in SWM technologies pave way for effective utilization of water for sustainable agriculture. It has different prospects for making agroecosystems more sustainable, adaptive, addressing an integrated approach by utilizing innovation and resource conservation farming to increase water use efficiency. Climate change has affected various river basins worldwide, leading to variability in water availability. Simulation model for different river basins integrated with sensors, AI and different satellite data for efficiently managing water resources. IoT-based automation irrigation operations via monitoring the water quality, leakage and supply in the agricultural sectors. The major setback is that with the advanced AI technologies which are not properly adopted and gained by the stakeholders. these integrated approaches are needed to address the emerging problems related to smart-water technologies and agroecosystems to enhance sustainability and climate resilience in the eco-system.

Acknowledgements

The authors sincerely thank the Vice Chancellor, TNAU, Dean SPGS and the Faculty of the Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, for their guidance, feedback and support.

Table 6. Institutional policies to overcome lacunae in implementing SWM

Lacunae identified	Expected resolutions
High cost	Promote development of low-cost technology Initiate for providing subsidies
Complexity and Data privacy	Utilizing AI assisted online platform Easy accessible, friendly administration framework
Expertise Technical knowledge	Training and awareness through online and doorstep solutions Improved water distribution and storage systems Fair allocation and democratic water governance
Unavailability of precise real-time data	Strengthening the infrastructure of public meteorological centres and with effective and timely communication
Institutional and policy barriers	Water for the future should be established at the international and national levels who can coordinate among themselves Who can guide the economized usage of irrigation water for enhancing Physical and economic water productivity.
Cyberattack threats	Separate unit for cybersecurity they should intervene periodically to protect end users
Lack of standard protocol	Establishment of a government body for framing protocols for maintaining the quality of SWM devices
Lack of global initiative	Requesting World Water Council to have special bodies to monitor the utilization of last drop of water effectively with the use of advance technology

Authors' contributions

GS contributed in for writing the original draft, reviewing and editing it, conceptualizing it, utilizing methodology and visualization and using software to prepare figures. KV contributed to writing, review and editing, conceptualization, methodology, visualization, data curation, supervision and formal analysis. SS contributed to writing, reviewing, editing and investigating. MR contributed to writing, reviewing, editing and analyzing. RJ contributed to the conceptualization and data curation and guided the use of the software. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare there is no conflict of interest

Ethical issues: None

References

1. Belhassan K. Water scarcity management. In: Smith J, Brown K, editors. Water safety, security and sustainability: Threat detection and mitigation. New York: Springer; 2021. p. 443–62. https://doi.org/10.1007/978-3-030-76008-3_19
2. Akhtar N, Syakir Ishak MI, Bhawani SA, Umar K. Various natural and anthropogenic factors responsible for water quality degradation: A review. Water. 2021;13(19):2660. https://doi.org/10.3390/w13192660
3. Kumar S, Yadav A, Kumar A, Hasanain M, Shankar K, Karan S, et al. Climate-smart irrigation practices for improving water productivity in India: a comprehensive review. Int J Environ Clim Change. 2023;13(12):333–48. https://doi.org/10.9734/ijecc/2023/v13i123689
4. Ishfaq M, Farooq M, Zulfiqar U, Hussain S, Akbar N, Nawaz A, et al. Alternate wetting and drying: A water-saving and eco-friendly rice production system. Agric Water Manag. 2020;241:106363. https://doi.org/10.1016/j.agwat.2020.106363
5. Kumar KA, Rajitha G. Alternate wetting and drying (AWD) irrigation-a smart water-saving technology for rice: a review. Int J Curr Microbiol Appl Sci. 2019;8(3):2561–71. https://doi.org/10.20546/ijcmas.2019.803.304
6. Davydenko L, Davydenko N, Deja A, Wiśnicki B, Dzhuguryan T. Efficient energy management for the smart sustainable city multifloor manufacturing clusters: a formalization of the water supply system operation conditions based on monitoring water consumption profiles. Energies. 2023;16(11):4519. https://doi.org/10.3390/en16114519
7. Li J, Yang X, Sitzenfrei R. Rethinking the framework of smart water system: a review. Water. 2020;12(2):412. https://doi.org/10.3390/w12020412
8. Boretti A, Rosa L. Reassessing the projections of the World Water Development Report. NPJ Clean Water. 2019;2(1):15. https://doi.org/10.1038/s41545-019-0039-9
9. Aivazidou E, Banias G, Lampridi M, Vasileiadis G, Anagnostis A, Papageorgiou E, et al. Smart technologies for sustainable water management: an urban analysis. Sustainability. 2021;13(24):13940. https://doi.org/10.3390/su132413940
10. Gupta AD, Pandey P, Feijóo A, Yaseen ZM, Bokde ND. Smart water technology for efficient water resource management: a review. Energies. 2020;13(23):6268. https://doi.org/10.3390/en13236268
11. Durodola OS. The impact of climate change-induced extreme events on agriculture and food security: a review of Nigeria. Agric Sci. 2019;10(4):538–54. https://doi.org/10.4236/as.2019.104038
12. Dasgupta S, Robinson EJ. Attributing changes in food insecurity to a changing climate. Sci Rep. 2022;12(1):4709. https://doi.org/10.1038/s41598-022-08696-x
13. Hussain S, Aslam MU, Javed M, Zahra M, Ejaz H, Mushtaq I. Impact of climatic changes and global warming on water availability. Anthropog Pollut. 2021;5(2).
14. Konapala G, Mishra AK, Wada Y, Mann ME. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. Nat Commun. 2020 ;11 (1):3044. https://doi.org/10.1038/s41467-020-16757-w
15. Rajabalinejad A, Nozari N, Badr BR. The effect of climate change on agricultural production in Iran. Braz J Biol. 2024;83:e277383. https://doi.org/10.1590/1519-6984.277383
16. Hsieh YL, Yeh SC. The trends of major issues connecting climate change and the Sustainable Development Goals. Discov Sustain. 2024;5(1):31. https://doi.org/10.1007/s43621-024-00183-9
17. Scarano A, Olivieri F, Gerardi C, Liso M, Chiesa M, Chieppa M, et al. Selection of tomato landraces with high fruit yield and nutritional quality under elevated temperatures. J Sci Food Agric. 2020;100 (6):2791–9. https://doi.org/10.1002/jsfa.10312
18. Perfecto I, Hajian-Forooshani Z, Iverson A, Irizarry AD, Lugo-Perez J, Medina N, et al. Response of coffee farms to Hurricane Maria: resistance and resilience from an extreme climatic event. Sci Rep. 2019;9(1):15668. https://doi.org/10.1038/s41598-019-51416-1
19. O'Donnell E, Kennedy M, Garrick D, Horne A, Woods R. Cultural water and Indigenous water science. Science. 2023;381(6658):619–21. https://doi.org/10.1126/science.adi0658
20. Ballestero A. The anthropology of water. Annu Rev Anthropol. 2019;48(1):405–21. https://doi.org/10.1146/annurev-anthro-102218-011428
21. Balaska V, Adamidou Z, Vryzas Z, Gasteratos A. Sustainable crop protection via robotics and artificial intelligence solutions. Machines. 2023;11(8):774. https://doi.org/10.3390/machines11080774
22. Naz N, Hameed W, Tabbassum R, Farzand A, Asif A, Mushtaq N, et al. Impact of global climate change on agricultural productivity. Int J Glob Sci. 2022;4:1–11.
23. Semeraro T, Scarano A, Leggieri A, Calisi A, De Caroli M. Impact of climate change on agroecosystems and potential adaptation strategies. Land. 2023;12(6):1117. https://doi.org/10.3390/land12061117
24. Makropoulos C, Savić DA. Urban hydroinformatics: past, present and future. Water. 2019;11:1959. https://doi.org/10.3390/w11091959
25. Rahim MS, Nguyen KA, Stewart RA, Giurco D, Blumenstein M. Machine learning and data analytic techniques in digital water metering: a review. Water. 2020;12:294. https://doi.org/10.3390/w12010294
26. Nasser N, Khan N, Karim L, ElAttar M, Saleh K. An efficient time-sensitive data scheduling approach for wireless sensor networks in smart cities. Comput Commun. 2021;175:112–22. https://doi.org/10.1016/j.comcom.2021.05.016
27. Balyan S, Jangir H, Tripathi SN, Tripathi A, Jhang T, Pandey P. Seeding a sustainable future: navigating the digital horizon of smart agriculture. Sustainability. 2024;16(2):475. https://doi.org/10.3390/su16020475
28. Hrustek L. Sustainability driven by agriculture through digital transformation. Sustainability. 2020;12(20):8596. https://doi.org/10.3390/su12208596
29. Waqas MA, Wang X, Zafar SA, Noor MA, Hussain HA, Azher Nawaz M, et al. Thermal stresses in maize: effects and management strategies. Plants. 2021;10(2):293. https://doi.org/10.3390/plants10020293

30. Reddy VS, Harivardhagini S, Sreelakshmi G. IoT and cloud-based sustainable smart irrigation system. E3S Web Conf. 2024;472:01026. https://doi.org/10.1051/e3sconf/202447201026

31. Nautiyal CT, Nautiyal P, Papnai G, Mittal H, Agrawal K, Nandini R. Importance of smart agriculture and use of artificial intelligence in shaping the future of agriculture. J Sci Res Rep. 2024;30(3):129–38. https://doi.org/10.9734/jsrr/2024/v30i31864

32. Feng Y, Ovalle M, Seale JS, Lee CK, Kim DJ, Astumian RD, et al. Molecular pumps and motors. J Am Chem Soc. 2021;143(15):5569–91. https://doi.org/10.1021/jacs.0c13240

33. Liu S, Shi X, Wong KT, Chen MT, Ye W, Zhang H, et al. Synchronous millennial surface-stratified events with AMOC and tropical dynamic changes in the northeastern Indian Ocean over the past 42 ka. Quat Sci Rev. 2022;284:107495. https://doi.org/10.1016/j.quascirev.2022.107495

34. Winstanley-Chesters R. Sustainable water management in North Korean cities. In: Pursuing sustainable urban development in North Korea. Routledge; 2025. p. 148–61. https://doi.org/10.4324/9781003372035-15

35. Patle GT, Kumar M, Khanna M. Climate-smart water technologies for sustainable agriculture: a review. J Water Clim Change. 2020;11(4):1455–66. https://doi.org/10.2166/wcc.2019.257

36. Hussain HA, Hussain S, Khaliq A, Ashraf U, Anjum SA, Men S, et al. Chilling and drought stresses in crop plants: implications, cross-talk and potential management opportunities. Front Plant Sci. 2018;9:393. https://doi.org/10.3389/fpls.2018.00393

37. Yang L, Driscoll J, Sarigai S, Wu Q, Lippitt CD, Morgan M. Towards synoptic water monitoring systems: a review of AI methods for automating water body detection and water quality monitoring using remote sensing. Sensors. 2022;22(6):2416. https://doi.org/10.3390/s22062416

38. Liakos KG, Busato P, Moshou D, Pearson S, Bochtis D. Machine learning in agriculture: a review. Sensors. 2018;18(8):2674. https://doi.org/10.3390/s18082674

39. Kerry R, Ingram B, Hammond K, Shumate SR, Gunther D, Jensen RR, et al. Spatial analysis of soil moisture and turfgrass health to determine zones for spatially variable irrigation management. Agronoy. 2023;13(5):1267. https://doi.org/10.3390/agronomy13051267

40. Blin N, Suárez F. Evaluating the contribution of satellite-derived evapotranspiration in the calibration of numerical groundwater models in remote zones using the EEFlux tool. Sci Total Environ. 2023;858:159764. https://doi.org/10.1016/j.scitotenv.2022.159764

41. Huang W, Chen S, Yang X, Johnson E. Assessment of chlorophyll-a variations in high- and low-flow seasons in Apalachicola Bay by MODIS 250-m remote sensing. Environ Monit Assess. 2014;186:8329–42. https://doi.org/10.1007/s10661-014-4007-z

42. Junqueira AM, Mao F, Mendes TS, Simões SJ, Balestieri JA, Hannah DM. Estimation of river flow using CubeSats remote sensing. Sci Total Environ. 2021;788:147762. https://doi.org/10.1016/j.scitotenv.2021.147762

43. Roy A, Murtugudde R, Narvekar P, Sahai AK, Ghosh S. Remote sensing and climate services improve irrigation water management at the farm scale in Western-Central India. Sci Total Environ. 2023;879:163003. https://doi.org/10.1016/j.scitotenv.2023.163003

44. Jakovljevic G, Álvarez-Taboada F, Govedarica M. Long-term monitoring of inland water quality parameters using Landsat time-series and back-propagated ANN: assessment and usability in a real-case scenario. Remote Sens. 2023;16(1):68. https://doi.org/10.3390/rs16010068

45. Rolim SB, Veettil BK, Vieiro AP, Kessler AB, Gonzatti C. Remote sensing for mapping algal blooms in freshwater lakes: a review. Environ Sci Pollut Res Int. 2023;30(8):19602–16. https://doi.org/10.1007/s11356-023-25230-2

46. Chukwuma U, Gebremedhin KG, Uyeh DD. Imagining AI-driven decision making for managing farming in developing and emerging economies. Comput Electron Agric. 2024;221:108946. https://doi.org/10.1016/j.compag.2024.108946

47. Thilagavathi N, Subramani T, Suresh M, Karunanidhi D. Mapping of groundwater potential zones in Salem Chalk Hills, Tamil Nadu, India, using remote sensing and GIS techniques. Environ Monit Assess. 2015;187:1–7. https://doi.org/10.1007/s10661-015-4376-y

48. Obasi SN, Aa TV, Obasi CC, Jokthan GE, Adjei EA, Keyagha ER. Harnessing artificial intelligence for sustainable agriculture: a comprehensive review of African applications in spatial analysis and precision agriculture. Big Data Agri. 2024;6(1):1–13. https://doi.org/10.26480/bda.01.2024.01.13

49. Lazarovitch N, Kisekka I, Oker TE, Brunetti G, Wöhling T, Xianyue L, et al. Modelling of irrigation and related processes with HYDRUS. Adv Agron. 2023;181:79–181. https://doi.org/10.1016/bs.agron.2023.05.002

50. Shashikant V, Mohamed Shariff AR, Wayayok A, Kamal MR, Lee YP, Takeuchi W. Utilizing TVDI and NDWI to classify severity of agricultural drought in Chuping, Malaysia. Agronom. 2021;11(6):1243. https://doi.org/10.3390/agronomy11061243

51. Flynn KD, Wyatt BM, McInnes KJ. Novel cosmic ray neutron sensor accurately captures field-scale soil moisture trends under heterogeneous soil textures. Water. 2021;13(21):3038. https://doi.org/10.3390/w13213038

52. Schirmbeck LW, Fontana DC, Schirmbeck J, Dalmago GA, Fernandes JM. Water monitoring of soybean crops using the TVDI obtained from surface radiometric sensors. Pesq. Agropec Bras. 2022;57:e02581. https://doi.org/10.1590/S1678-3921.pab2022.v57.02581

53. Li DW, Xu CY, Song JC, Tian MQ, Xing XJ. Development of a remote intelligent irrigation control system based on IoT. Water Sav Irrig. 2017;10:87–91.

54. Ullah A, Zubair M, Zulfiqar MH, Kamsong W, Karuwan C, Massoud Y, et al. Highly sensitive screen-printed soil moisture sensor array as green solutions for sustainable precision agriculture. Sens Actuators A Phys. 2024;371:115297. https://doi.org/10.1016/j.sna.2024.115297

55. Meier J, Zabel F, Mauser W. A global approach to estimate irrigated areas–a comparison between different data and statistics. Hydrol Earth Syst Sci. 2018;22(2):1119–33. https://doi.org/10.5194/hess-22-1119-2018

56. Cui K, Huang Y, Li X, Li J, Lu X, Chui TC. PSDNet: Plant status detection network utilized in an intelligent Bougainvillaea glabra sensing and watering system. IEEE Sens J. 2024;24(11):18685–98. https://doi.org/10.1109/JSEN.2024.3390681

57. Galli A, Peruzzi C, Gangi F, Masseroni D. ArduHydro: a low-cost device for water level measurement and monitoring. J Agric Eng. 2024;55(1). https://doi.org/10.4081/jae.2024.1554

58. Thote D, Lanjewar V, Sharma V, Agrawal P, Soni VK. IoT and machine learning-based smart soil irrigation farming systems. In: 2024 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS). 2024. https://doi.org/10.1109/SCEECS61402.2024.10482246

59. Egerer M, Ristolainen A, Piho L, Vihman L, Kruusmaa M. Hall effect sensor-based low-cost flow monitoring device: design and validation. IEEE Sens J. 2024. https://doi.org/10.1109/JSEN.2024.3354194

60. Borges RC, Beuter CH, Dourado VC, Bento ME. Internet of Things application in an automated irrigation prototype powered by photovoltaic energy. Energies. 2024;17(9):2219. https://doi.org/10.3390/en17092219

61. Machado MR, Júnior TR, Silva MR, Martins JB. Smart water management system using the microcontroller ZR16S08 as IoT solution. In: 2019 IEEE 10th Latin Am Symp Circuits Syst (LASCAS);

2019 Feb 24. p. 169-72. IEEE. https://doi.org/10.1109/LASCAS.2019.8667571

62. Campos GS, Rocha AR, Gondim R, Coelho da Silva TL, Gomes DG. Smart & green: An internet-of-things framework for smart irrigation. Sensors. 2020;20(1):190. https://doi.org/10.3390/s20010190
63. Ayoub I, Balakrichenan S, Khawam K, Ampeau B. DNS for IoT: a survey. Sensors. 2023;23(9):4473. https://doi.org/10.3390/s23094473
64. Krishnan RS, Julie EG, Robinson YH, Raja S, Kumar R, Thong PH. Fuzzy logic-based smart irrigation system using Internet of Things. J Clean Prod. 2020;252:119902. https://doi.org/10.3390/su142013384
65. Samarinas N, Tsakiridis NL, Kalopesa E, Zalidis GC. Soil loss estimation by water erosion in agricultural areas, introducing artificial intelligence geospatial layers into the RUSLE model. Land. 2024;13(2):174. https://doi.org/10.3390/land13020174
66. Kumar P, Udayakumar A, Anbarasa Kumar A, Senthamarai Kannan K, Krishnan N. Multiparameter optimization system with DCNN in precision agriculture for advanced irrigation planning and scheduling based on soil moisture estimation. Environ Monit Assess. 2023;195(1):13. https://doi.org/10.1007/s10661-022-10529-3
67. Sagar A, Hasan M, Singh DK, Al-Ansari N, Chakraborty D, Singh MC, et al. Development of a smart weighing lysimeter for measuring evapotranspiration and developing crop coefficient for greenhouse Chrysanthemum. Sensors. 2022;22(16):6239. https://doi.org/10.3390/s22166239
68. Junior AA, da Silva TJ, Andrade SP. Smart IoT lysimetry system by weighing with automatic cloud data storage. Smart Agric Technol. 2023;4:100177. https://doi.org/10.1016/j.atech.2023.100177
69. Gupta A, Singh R, Kumar M. Design, development and performance evaluation of Iot-enabled digital weighing-type field lysimeter. [preprint] SSRN. https://doi.org/10.2139/ssrn.4824659
70. Castañeda-Miranda A, Castaño-Meneses VM. Smart frost measurement for anti-disaster intelligent control in greenhouses via embedding IoT and hybrid AI methods. Measurement. 2020;164:108043. https://doi.org/10.1016/j.measurement.2020.108043
71. Valente A, Costa C, Pereira L, Soares B, Lima J, Soares S. A LoRaWAN IoT system for smart agriculture for vine water status determination. Agriculture. 2022;12(10):1695. https://doi.org/10.3390/agriculture12101695
72. Benzaouia M, Hajji B, Mellit A, Rabhi A. Fuzzy-IoT smart irrigation system for precision scheduling and monitoring. Comput Electron Agric. 2023;215:108407. https://doi.org/10.1016/j.compag.2023.108407
73. Zhu S, Lin F. Intelligent agricultural water and fertilizer irrigation system based on ZigBee technology and STM32. In: Proceedings of the 2023 12th International Conference on Networking and Communication Computing; 2023 Dec 15. p. 144–8. https://doi.org/10.1145/3638837.3638859
74. Pineda-Castro D, Diaz H, Soto J, Urban MO. Lysiphen: a gravimetric IoT device for near real-time high-frequency crop phenotyping: a case study on common beans. Plant Methods. 2024;20(1):39. https://doi.org/10.1186/s13007-024-01170-x
75. Jani KA, Chaubey NK. SMAIoT-ferti: a smart cropland monitoring and optimal fertigation IoT system. Int J Inf Technol. 2024;16(4):2253–61. https://doi.org/10.1007/s41870-024-01731-2
76. Kumar GK, Bangare ML, Bangare PM, Kumar CR, Raj R, Arias-Gonzáles JL, et al. Internet of Things sensors and support vector machine integrated intelligent irrigation system for the agriculture industry. Discov Sustain. 2024;5(1):6. https://doi.org/10.1007/s43621-024-00179-5
77. Vatari S, Bakshi A, Thakur T. Greenhouse by using IoT and cloud computing. In: 2016 IEEE Int Conf Recent Trends Electron Inf Commun Technol (RTEICT); 2016 May 20. p. 246–50. IEEE. https://doi.org/10.1109/RTEICT.2016.7807821
78. Hung P, Peng K. Green energy water-autonomous greenhouse system: an alternative technology approach toward sustainable smart-green vertical greening in a smart city. In: Green City Planning and Practices in Asian Cities: Sustainable Development and Smart Growth in Urban Environments. 2018. p. 315–35. https://doi.org/10.1007/978-3-319-70025-0_16
79. Saha A, Das PS, Banik BC. Smart greenhouse for controlling & monitoring temperature, soil & humidity using IoT. In: 2022 2nd International Conference on Artificial Intelligence and Signal Processing (AISP); 2022 Feb 12; Visakhapatnam, India. p. 1–4. https://doi.org/10.1109/AISP53593.2022.9760541
80. Soheli SJ, Jahan N, Hossain MB, Adhikary A, Khan AR, Wahiduzzaman M. Smart greenhouse monitoring system using internet of things and artificial intelligence. Wirel Pers Commun. 2022;124(4):3603–34. https://doi.org/10.1007/s11277-022-09528-x
81. Adiga A, Chandra Darshan J, Umesh KK. Smart greenhouse management system using IoT and multivariate fuzzy logic. In: Hassanien AE, Anand S, Jaiswal A, Kumar P, editors. Innovative Computing and Communications. ICICC 2024. Lecture Notes in Networks and Systems, vol 1043. Singapore: Springer; 2024. p. 261–71. https://doi.org/10.1007/978-981-97-4228-8_18
82. Rahman H, Shah UM, Riaz SM, Kifayat K, Moqurrab SA, Yoo J. Digital twin framework for smart greenhouse management using next-gen mobile networks and machine learning. Future Gener Comput Syst. 2024;156:285–300. https://doi.org/10.1016/j.future.2024.03.023
83. Shekarian SM, Aminian M, Fallah AM, Moghaddam VA. AI-powered sensor fault detection for cost-effective smart greenhouses. Comput Electron Agric. 2024;224:109198. https://doi.org/10.1016/j.compag.2024.109198
84. Palmer PL. AgriMet: A reclamation tool for irrigation water management. In: World Environ Water Resour Congr 2011: Bearing Knowledge for Sustainability. 2011;2682–91. https://doi.org/10.1061/41173(414)279
85. Yang Y, Guan H, Batelaan O, McVicar TR, Long D, Piao S, et al. Contrasting responses of water use efficiency to drought across global terrestrial ecosystems. Sci Rep. 2016;6(1):23284. https://doi.org/10.1038/srep23284
86. Gupta D, Gujre N, Singha S, Mitra S. Role of existing and emerging technologies in advancing climate-smart agriculture through modelling: A review. Ecol Inform. 2022;71:101805. https://doi.org/10.1016/j.ecoinf.2022.101805
87. Jiménez A-F, Cárdenas P-F, Jiménez F. Smart water management approach for resource allocation in high-scale irrigation systems. Agric Water Manag. 2021;256:107088. https://doi.org/10.1016/j.agwat.2021.107088
88. Durodola OS, Mourad KA. Modelling maize yield and water requirements under different climate change scenarios. Clim. 2020;8(11):127. https://doi.org/10.3390/cli8110127
89. Ogra M, Manral U, Platt RV, Badola R, Butcher L. Local perceptions of change in climate and agroecosystems in the Indian Himalayas: A case study of the Kedarnath Wildlife Sanctuary (KWS) landscape, India. Appl Geogr. 2020;125:102339. https://doi.org/10.1016/j.apgeog.2020.102339
90. Bhatt R, Singh J, Laing AM, Meena RS, Alsanie WF, Gaber A, et al. Potassium and water-deficient conditions influence the growth, yield and quality of ratoon sugarcane *(Saccharum officinarum* L.) in a semi-arid agroecosystem. Agronom. 2021;11(11):2257. https://doi.org/10.3390/agronomy11112257
91. Keller T, Défossez P, Weisskopf P, Arvidsson J, Richard G. SoilFlex: A model for prediction of soil stresses and soil compaction due to agricultural field traffic including a synthesis of analytical approaches. Soil Tillage Res. 2007;93(2):391–411. https://doi.org/10.1016/j.still.2006.05.012

92. Hari M, Tyagi B, Huddar MS, Harish A. Satellite-based regional-scale evapotranspiration estimation mapping of the rice bowl of Tamil Nadu: A little water to spare. Irrig Drain. 2021;70(4):958–75. https://doi.org/10.1002/ird.2553

93. Mahule A, Sawarkar AD, Pakle G, Pachlor R, Singh L. AquaBamboo data-driven suggested system for water management and sustainable growth of bamboo: A review. Adv Bamboo Sci. 2024;7:100072. https://doi.org/10.1016/j.bamboo.2024.100072

94. Ahmadi A, Kazemi MH, Daccache A, Snyder RL. SolarET: A generalizable machine learning approach to estimate reference evapotranspiration from solar radiation. Agric Water Manag. 2024;295:108779. https://doi.org/10.1016/j.agwat.2024.108779

95. Manjunatha B, Kumar KD, Goundar S, Kavin BP, Seng GH. Sustainable waste management OOA-enhanced MobileNetV2-TC model for trash image classification. In: Kumar D, Vijayakumar V, Nidal N, Poluru RK, editors. Computational intelligence for green cloud computing and digital waste management. IGI Global. 2024;227–47. https://doi.org/10.4018/979-8-3693-1552-1.ch012

96. Zhu S, Cui N, Jin H, Jin X, Guo L, Jiang S, et al. Optimization of multi-dimensional indices for kiwifruit orchard soil moisture content estimation using UAV and ground multi-sensors. Agric Water Manag. 2024;294:108705. https://doi.org/10.1016/j.agwat.2024.108705

97. Dolaptsis K, Pantazi XE, Paraskevas C, Arslan S, Tekin Y, Bantchina BB, et al. A hybrid LSTM approach for irrigation scheduling in maize crop. *Agri.* 2024;14(2):210. https://doi.org/10.3390/agriculture14020210

98. Yang Y, Guan H, Batelaan O, McVicar TR, Long D, Piao S, et al. Contrasting responses of water use efficiency to drought across global terrestrial ecosystems. Sci Rep. 2016;6(1):23284. https://doi.org/10.1038/srep23284

99. Padhiary M, Saha D, Kumar R, Sethi LN, Kumar A. Enhancing precision agriculture: A comprehensive review of machine learning and AI vision applications in all-terrain vehicles for farm automation. Smart Agric Technol. 2024 :100483. https://doi.org/10.1016/j.atech.2024.100483

100. Rajurkar C, Prabaharan SR, Muthulakshmi S. IoT based water management. In: 2017 International Conference on Nextgen Electronic Technologies: Silicon to Software (ICNETS2), Chennai, India; 2017. p. 2559. https://doi.org/10.1109/ICNETS2.2017.8067943

101. Asli KH, Asli KH. Smart Water System and Internet of Things. J Mod Ind Manuf. 2023;2(5).

102. Pagano A, Amato F, Ippolito M, De Caro D, Croce D, Motisi A, et al. Internet of Things and Artificial Intelligence for Sustainable Agriculture: A Use Case in Citrus Orchards. 2023 IEEE 9th World Forum on Internet of Things (WF-IoT), Aveiro, Portugal, 2023; p. 1–6. https://doi.org/10.1109/WF-IoT58464.2023.10539593

103. Longo-Minnolo G, D'Emilio A, Vanella D, Consoli S. Advancing in satellite-based models coupled with reanalysis agrometeorological data for improving the irrigation management under the European Water Framework Directive. Agric Water Manag. 2024;301:108955. https://doi.org/10.1016/j.agwat.2024.108955

104. Prasad S. Shortages in agriculture labour market and changes in cropping pattern. In: Bathla S, Dubey A, editors. Changing contours of Indian agriculture. Singapore: Springer; 2017. p. 181–204. https://doi.org/10.1007/978-981-10-6014-4_11

105. Quddus A, Kropp JD. Constraints to agricultural production and marketing in the lagging regions of Bangladesh. Sustainability. 2020;12(10):3956. https://doi.org/10.3390/su12103956

106. Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, Errett NA, et al. Extreme weather and climate change: population health and health system implications. Annu Rev Public Health. 2021;42(1):293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

107. Foster L, Szilagyi K, Wairegi A, Oguamanam C, de Beer J. Smart farming and artificial intelligence in East Africa: Addressing indigeneity, plants and gender. Smart Agric Technol. 2023;3:100132. https://doi.org/10.1016/j.atech.2022.100132

108. Debangshi U, Sadhukhan A, Dutta D, Roy S. Application of smart farming technologies in sustainable agriculture development: A comprehensive review on present status and future advancements. Int J Environ Clim Change. 2023;13(11):3689–704. https://doi.org/10.9734/ijecc/2023/v13i113549

109. Amiri-Zarandi M, Dara RA, Duncan E, Fraser ED. Big data privacy in smart farming: A review. Sustainability. 2022;14(15):9120. https://doi.org/10.3390/su14159120

110. Assimakopoulos F, Vassilakis C, Margaris D, Kotis K, Spiliotopoulos D. AI and related technologies in the fields of smart agriculture: A review. Info. 2025;16(2):100. https://doi.org/10.3390/info16020100

111. Khan S, Sachan HK, Krishna D. The role of smart farming technologies in mitigating climate change and enhancing agricultural sustainability. Int J Environ Clim Change. 2025;15(2):138–59.

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.