AMERICAN JOURNAL OF BIOMEDICINE AND PHARMACY
https://biojournals.us/index.php/AJBP
ISSN: 2997-7177

Article

Mechatronic Technologies for Water and Energy-Efficient Agricultural Pumping Systems: A Systematic Review

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Citation: Manfi A. Mechatronic Technologies for Water and Energy-Efficient Agricultural Pumping Systems: A Systematic Review. American Journal of Biomedicine and Pharmacy. 2026, 3(11), 146-156.

Received: 10th Aug 2026
Revised: 11th Sep 2026
Accepted: 20th Oct 2026
Published: 24th Nov 2026

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Abstract: The combination of mechatronic technologies, the Internet of Things (IoT), Artificial Intelligence (AI) and photovoltaic (PV) technology presents potential opportunities for enhancing water and energy efficiency in agricultural irrigation systems. Traditional water pumping technologies typically rely on diesel fuel and electricity, which can be expensive, polluting, and challenging in remote or off-grid locations. Solar-powered water pumping systems offer a sustainable solution, and sensors, data acquisition systems, microcontrollers, and embedded systems allow for real-time monitoring, remote control, and automated irrigation management. In addition, AI and Machine Learning (ML) can aid in intelligent irrigation scheduling, soil moisture and nutrient prediction, and better water resource management. Water efficient irrigation technologies such as drip irrigation, subsurface drip irrigation, and sensor-based irrigation help to minimize water losses and optimize the use of agricultural resources. This review explores the application of mechatronic technologies in agricultural pumping and irrigation, highlighting energy efficiency, smart irrigation, and the integration of IoT and AI. It also points out the possibilities of synergies between these technologies for precision agriculture, sustainable water management and automated agricultural production. But there are issues of sensor accuracy, system integration, compatibility, implementation costs, energy needs and technical skills that are still significant for future development.

Keywords: Mechatronic Systems; Solar-Powered Water Pumping; Smart Irrigation; Internet of Things (IoT); Artificial Intelligence (AI).

Introduction

Agriculture is water and energy intensive; traditional irrigation methods waste water, and lack of electricity and increasing diesel prices puts pressure on water pumping. Efficient water management and optimization of water use in sustainable agriculture are more important due to water scarcity, climate change and inefficient irrigation practices. In this context, the efficiency of water and energy use becomes more important, and the role of agricultural irrigation and pumping systems becomes more prominent [1]- [5].

Solar water pumping systems are based on photovoltaic (PV) technology that transforms solar energy into electricity to drive DC or AC motor water pumps. Photovoltaic (PV) technology is a renewable solution for irrigation and water supply. Moreover, smart irrigation and fertigation are based on sensors, data acquisition systems, IoT protocols and architectures, and Artificial Intelligence models for decision making and predictions. These systems support smart irrigation, artificial intelligence, urban agriculture, rural agriculture, soil crops, and agricultural automation, as well as intelligent irrigation scheduling, agricultural management, farm management, and crop field-scale applications [1], [2], [6]- [10].

With the development of these systems, the need for mechatronics technologies and smart systems has become increasingly important. Smart irrigation management integrates IoT sensors, Remote Sensing (RS), Artificial Intelligence (AI), and irrigation management tasks. Automated irrigation, precision agriculture, sensor integration, real-time irrigation management, and autonomous irrigation systems further contribute to efficient agricultural management and resource use [4], [9], [11]- [13].

The Importance of IoT, AI, Sensors, and Automated Control in Smart Irrigation Systems is reflected in their ability to optimize water and resource use, support sustainability, enable real-time data acquisition, and provide insights for improved decision-support systems and predictive irrigation. They conserve water, increase productivity through targeted fertigation, improve efficiency, enable remote control, and provide high-precision monitoring and decision-making. Furthermore, they optimize water use, maximize crop yields, enable automation, support scalable irrigation management, and improve integration with precision agriculture technologies. They also enable real-time monitoring, optimize water allocation, support precision irrigation, provide rapid data collection and crop water-use insights, and improve transparency and trust in agricultural water management [4], [7]- [10], [13], [14].

Although numerous studies have addressed smart irrigation techniques and solar-powered water pumping individually, a critical research gap remains: the absence of an integrated framework that combines smart mechatronic systems and artificial intelligence algorithms with photovoltaic (PV) technology into a single, holistic system—one that optimizes water and energy use efficiency in real-time, in response to fluctuating climatic and field conditions [1], [2], [4], [6], [11], [12].

Methodology

This research paper employs a literature review methodology to examine the evolution of agricultural irrigation systems, ranging from traditional methods to automated irrigation.

Relevant scientific studies were reviewed to investigate key characteristics, developmental stages, and the distinctions between these systems.

The review focused on topics concerning sustainable agriculture, mechatronics, and intelligent systems. Furthermore, the selected studies were analyzed and compared to identify existing research gaps and to understand the challenges associated with integrating intelligent mechatronic systems, artificial intelligence algorithms, and solar photovoltaic (PV) technologies into a single, comprehensive system—one designed to optimize water and energy efficiency in real time, in response to fluctuating climatic and field conditions.

The findings are organized according to primary research dimensions, providing a holistic overview of recent advancements, current limitations, and future research prospects in the field of energy-efficient agricultural pumping systems.

Agricultural Pumping Systems and Energy Efficiency

Agriculture is one of the most water- and energy-intensive sectors of the economy, consuming about 70% of global freshwater withdrawals. Traditionally, water pumps are powered by diesel, electricity, or gasoline. However, due to an increase in the price of oil, harmful emissions from burning fossil fuels, high maintenance costs, short lifetime, insufficient electricity, and soaring diesel costs, solar-powered water pumping systems are becoming a promising alternative. [1]- [3].

Solar water pumping systems work on electricity generated using photovoltaic (PV) technology, which converts solar energy into electrical energy to run a DC or AC motor-based water pump. As solar is available in large amounts and almost everywhere, even in remote locations, these systems can be used for irrigation, livestock, domestic, and industrial purposes, especially in areas without access to the electric grid. Solar water pumping systems are more economical, eco-friendly, and reliable, with less maintenance and a long lifespan in comparison to diesel-powered water pumps, with a 4–6 years of payback period found for some systems [1]- [3], [6].

Different types of motors, converter systems, and control techniques have been studied to further improve the performance of solar water pumping systems, with emphasis on induction motor-based solar pumping systems and their control methodologies. The drastic drop in photovoltaic (PV) module prices has also made the technology competitive for on-grid applications, supporting the decarbonization of the irrigation sector and contributing to water and food security, affordable and clean energy, and climate action. [1], [2], [6], [11].

Improvement of photovoltaic array and electric motor interaction, and electric motor and pump interaction against the backdrop of irradiance variation, in conjunction with consumption optimization and control improvement [2], [11].

Conserves water, increases productivity through targeted fertigation, improves efficiency, enables remote control, and provides high-precision monitoring and decision-making. The need to improve agricultural water use efficiency and crop productivity through real-time, end-to-end, smart, and automated irrigation management [4], [7]- [10], [13].

Table 1. Factors Affecting Agricultural Pumping Systems and Energy Efficiency

Factor	Description	Impact	Application
Solar Energy	Solar energy is available in large amounts and almost everywhere	Reduces dependence on fossil fuels	Irrigation and water pumping
PV Technology	Converts solar energy into electrical energy	Provides energy for water pumps	Solar water pumping systems
Motor Type	DC, AC, and induction motors	Improves pumping system performance	Water pumping
Control Techniques	Different control techniques are used	Improves system performance and efficiency	Solar pumping systems
Solar Irradiance Variation	Variation in solar irradiance affects motor and pump interaction	Requires improved system interaction	Solar water pumping
Energy Consumption Optimization	Optimization of energy consumption	Improves energy efficiency	Agricultural pumping
Water Use Efficiency	Improvement of agricultural water use efficiency	Conserves water	Irrigation
Remote Control	Enables remote control	Improves irrigation management	Smart irrigation

Monitoring & Decision-Making	High-precision monitoring and decision-making	Improves system management	Smart irrigation
Economic Performance	4–6 years payback period for some systems	Improves economic feasibility	Solar water pumping
Environmental Impact	Eco-friendly and supports decarbonization	Reduces environmental impact	Irrigation sector



Figure 1. Overview of Factors Influencing Solar-Powered Agricultural Water Pumping Systems.

Mechatronic Technologies in Agricultural Irrigation

Sensors and Data Acquisition

Efficient soil moisture monitoring is fundamental to precision agriculture, enabling improved irrigation management, enhanced crop productivity, and sustainable water use. Soil moisture sensing technologies are classified into invasive and non-invasive approaches. Invasive methods, including dielectric sensors, matric potential devices, heat-pulse sensors, and microstructured optical fibres, offer high-resolution data but require careful installation and calibration to account for soil-specific variables such as texture, salinity, and temperature. Non-invasive technologies, such as microwave remote sensing, electromagnetic induction, and ground-penetrating radar, enable large-scale monitoring without disturbing the soil profile; however, they face challenges in resolution, cost, and data interpretation. Installation method, environmental sensitivity, spatial representativeness, and integration with decision-support systems are key performance factors. New advancements include sensors that are biodegradable and Micro–Electro–Mechanical Systems, Internet of Things platforms, and artificial intelligence for improved data analysis and sensor calibration [9], [13], [14].

The water crisis, global warming, and climate change have made saving and conserving water an imperative for water resources' sustainability. In this context, Precision Agriculture and smart irrigation have received increasing attention. A systematic review categorized smart irrigation research into three conceptual clusters: field measurements based on IoT sensors, Remote Sensing (RS), and Artificial Intelligence (AI) methods. These technologies provide different inputs and outputs for irrigation management and support the development of smart irrigation systems [4], [7], [8], [10].

Due to insufficient electricity and soaring diesel costs, solar energy-based water pumping systems have emerged as an alternative to conventional electricity- and diesel-based pumping systems. Solar water pumps use electricity generated through photovoltaic (PV) technology, which converts solar energy into electrical energy to run DC or AC motor based water pumps. The performance of

these systems is affected by environmental conditions and photovoltaic materials, while different motor, converter, and control techniques are used to improve system performance [1]- [3], [6], [11].

Smart irrigation systems are crucial in addressing global water crises exacerbated by climate change. This review categorizes 610 studies into three clusters: IoT-based field measurements, remote sensing, and AI methods. By integrating these technologies, we enhance irrigation efficiency, offering precise water management and sustainability solutions for agriculture through advanced data collection, real-time insights, and predictive analytics [7]- [9], [13].

Microcontrollers and Embedded Systems

Microcontrollers and embedded systems play a crucial role in smart irrigation systems, enabling real-time data collection, remote monitoring, and automated irrigation management. The use of low power, scalable and cost-effective platforms is growing, highlighting the need for flexible technologies in agriculture.

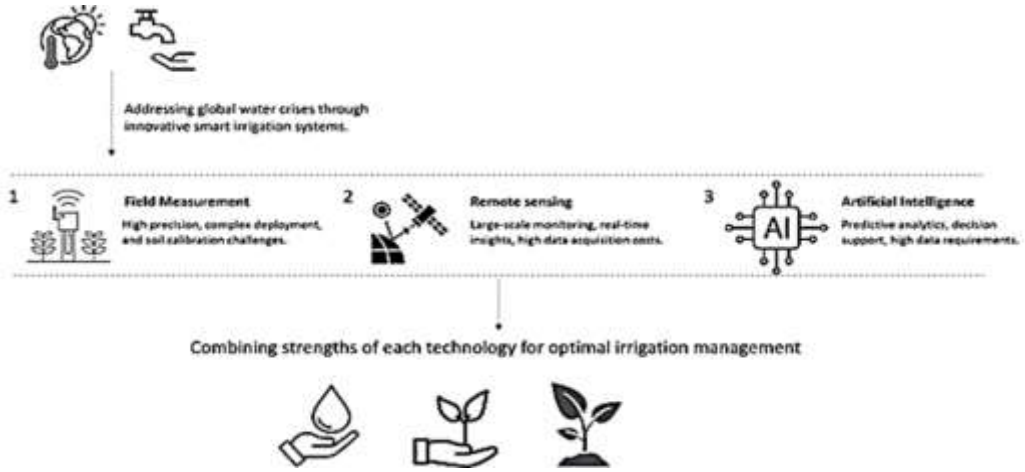

Figure 2. Classification of Smart Irrigation Technologies Based on IoT Sensors, Remote Sensing, and Artificial Intelligence.

Arduino, Raspberry Pi, ESP8266 and ESP32 are some of the most popular microcontrollers and embedded platforms. These platforms are often chosen for their flexibility, affordability, and compatibility with sensors and communication systems. They allow for the measurement and analysis of soil moisture and weather conditions, which can be used to make real-time decisions about irrigation. [7], [9], [13], [14].

Communication technologies are also an important part of embedded irrigation systems. Although Wi-Fi remains widely used, the growing adoption of LoRa and ZigBee indicates an increasing preference for energy-efficient and long-range communication, particularly in large-scale agricultural applications. Microcontrollers can be paired with sensors and communication protocols, allowing for remote control and monitoring, and minimizing manual effort [4], [9], [10], [13].

In summary, the advancement of microcontroller- and embedded-system-based irrigation technologies is a positive step toward better water-use efficiency, energy efficiency, and sustainable agriculture. These systems can be further enhanced with artificial intelligence and edge computing in the future to offer more adaptive and predictive irrigation strategies [8]- [10], [12].

Artificial Intelligence and Machine Learning for Irrigation Control

In recent years, Artificial Intelligence (AI) and Machine Learning (ML) have been proven to be used in smart irrigation and fertigation systems. The systematic review, conducted following the PRISMA 2020 protocol, included 130 scientific publications, which showed significant variation in datasets, AI models, and irrigation-related tasks. The reviewed methods were Decision Support

Systems (DSS), fuzzy logic, machine learning, and deep learning methods. The most frequently predicted variables were soil moisture and nitrogen, and relatively few studies considered advanced deep learning techniques like Transformers. The review also noted that there was not enough research on advanced cultivation techniques, such as soilless farming and aquaponics, or on predicting a broader spectrum of soil and plant properties. The results suggest that AI and ML could enhance irrigation management and facilitate more efficient water and nutrient use, and highlight the need for additional research on the use of more sophisticated AI models, cultivation methods and sensor technologies [4], [7]- [10].

Table 2. Artificial Intelligence and Machine Learning Approaches for Irrigation Control.

AI/ML Approach	Application	Controlled Parameters
Decision Support Systems (DSS)	Irrigation decision-making and control	Irrigation requirements
Fuzzy Logic	Irrigation control under uncertain conditions	Irrigation parameters
Machine Learning	Modeling and prediction of irrigation-related parameters	Soil and plant characteristics
Deep Learning	Advanced prediction and modeling	Soil moisture, nitrogen, and other characteristics
Transformers	Advanced deep learning for prediction	Potentially complex soil and plant features
Sensor-based AI	Data acquisition and intelligent irrigation	Soil moisture and nutrient-related parameters

Water-Efficient Irrigation Technology

Water-efficient irrigation technologies help to use water while still growing crops well. As shown in Table drip irrigation gives an application efficiency of 90 to 95 percent and uses little energy. This makes it very good for giving water to the roots of plants and stopping water from being wasted. Sprinkler irrigation has an efficiency between 70 and 85 percent. Needs more energy. It works well for fields. Subsurface drip irrigation is efficient, more than 90 percent because it gives water under the soil. This helps lower evaporation and runoff. Center pivot systems have moderate to efficiency and are good for big round farming areas. They do need a lot of energy. Micro-sprayers have an efficiency of about 85 to 90 percent. Are great for orchards and small areas. Smart sensor-based irrigation uses water-use efficiency and low energy by checking soil and plant conditions in real time. IoT-based intelligence (AI) irrigation systems can be very efficient by scheduling irrigation automatically based on real-time data. Deficit irrigation is efficient. Uses little energy. It is useful, in places where water's very scarce. Here irrigation can be. Still keep crop yields high. In the end choosing the irrigation technology depends on the land, the plants, how much water there is and how much energy is available. [2], [4], [6]- [10].

Table 3. Water-Efficient Irrigation Technologies and Their Applications in Agriculture.

Technology	Application Efficiency	Energy Demand	Best For
Drip Irrigation	90–95%	Low	Targeted root zone delivery
Sprinkler	70–85%	High	Large field-scale distribution
Subsurface Drip	High (>90%)	Low	Minimizing surface wastage
Center Pivot	Moderate/High	High	Large circular fields
Micro-sprayers	85–90%	Moderate	Orchards and specific zones
Smart Sensors	High	Low	Real-time monitoring/scheduling
IoT-Based AI	Very High	Moderate	Adaptive, automated scheduling
Deficit Irrigation	High	Low	Areas with severe water scarcity

Integration of Mechatronics, IoT and AI

The integration of Mechatronics Systems (MTS) the Internet of Things (IoT) and Artificial Intelligence (AI) represents a technological path for improving the efficiency, sustainability and intelligence of renewable energy and smart agricultural systems. MTS brings together mechanical, electronic, control and computational parts to create Renewable Energy Technologies (RETs), especially in solar wind, geothermal, hydropower and bioenergy applications [15]. Recent research based on over 150 studies published between 2020 and 2025 shows that MTS can increase renewable-energy efficiency by roughly 10–30% and cut payback periods by 20–30% compared to traditional systems. The addition of IoT improves these systems with real-time sensing, monitoring, communication and energy management while AI offers analysis, intelligent control, optimization, fault detection and self-directed decision-making. In agriculture, the use of mechatronic systems, IoT sensors, robotics and AI is increasingly playing a crucial role in precision farming, resource management, environmental monitoring and automated production. Experiences from the Netherlands and Japan show two paths: the Netherlands focuses on highly controlled agricultural environments using smart greenhouses, climate control, hydroponics, circular water systems, LED lighting and energy integration while Japan concentrates on robotics, automated machines, AI-based farm management and sensing technologies to solve labor shortages and population issues. Therefore the joining of MTS, IoT and AI creates a combined socio- system where energy systems, agricultural processes, digital infrastructures and intelligent control technologies work together to boost productivity and use resources better. However challenges such as system integration, compatibility, energy needs, cost, environmental factors, rules, skills, and technology spread remain obstacles. Solving these issues through technology integration and cooperation among engineers, companies, research centers and government officials is key, to building strong, sustainable and smart renewable-energy and food-producing systems.

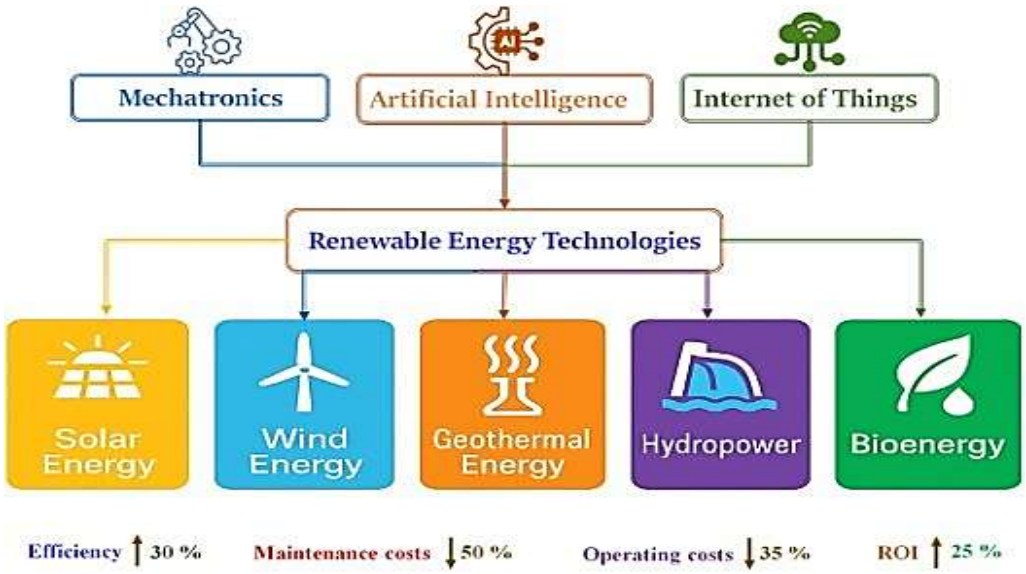

Figure 3. Integration of Mechatronic Systems, Internet of Things, and Artificial Intelligence in Renewable Energy and Smart Agriculture.

Result

The review encompassed research on topics related to agricultural irrigation, techniques for reducing water waste, and the application of mechatronics to achieve these goals. Consequently, the integration of these technologies contributes to supporting precision agriculture, environmental monitoring, and automated agricultural production. Nevertheless, significant challenges remain that

must be addressed—pertaining to soil moisture sensing accuracy, system integration, interoperability, implementation costs, energy requirements, environmental factors, regulatory frameworks, technical skills, and technology adoption—as illustrated in the table below.

Table 4. Comparative Review of Research Studies on Mechatronic Technologies and Smart Irrigation Systems.

#	Research Title	Problem	Tools Used	Solution	Year
1	Review of photovoltaic water pumping system research	Improving solar energy conversion efficiency requires coordinating system components from generation to consumption while considering consumer needs.	PV array and module configurations; pumps; inverters; MPPT; control and optimization methods.	Improving the interaction between PV arrays, electric motors, and pumps under varying irradiance, while optimizing consumption and control, beginning with maximum power point tracking.	2020
2	Solar PV powered water pumping system: A review	Electricity deficits and higher fuel costs affect water supply for irrigation.	Solar PV technology; water pumps; sprinkler irrigation systems.	Using photovoltaic technology to generate electricity for water pumps connected to sprinkler irrigation systems.	2021
3	Solar photovoltaic water pumping system – A comprehensive review	High oil prices, harmful emissions, high maintenance costs, and short lifetimes of diesel-powered pumps.	Solar PV systems; water pumps.	Using solar PV-powered water pumping systems as an alternative to diesel-powered pumps.	2016
4	Photovoltaic water pumping systems for irrigation: principles and advances	Agriculture is water- and energy-intensive, and affordable irrigation is challenging in remote areas without grid connections.	Photovoltaic modules; solar-powered pumping systems.	Using photovoltaic pumping systems as a renewable solution for irrigation and water supply.	2022
5	Smart Irrigation Systems in Agriculture: A Systematic Review	Identifying AI-based smart irrigation systems used or adaptable to urban and rural agriculture.	Modified PRISMA 2020; three search equations; VantagePoint.	Screening 170 articles and selecting 50 relevant sources for detailed systematic analysis.	2023
6	Towards efficient irrigation management at field scale using new technologies: A systematic literature review	Water scarcity and the need for intelligent irrigation strategies that consider field characteristics beyond soil	IoT; AI; ETo and Kc monitoring and prediction.	Using IoT and AI to monitor and predict evapotranspiration parameters and characterize field conditions for intelligent irrigation scheduling.	2024

		moisture.			
7	Internet of Things-enabled smart irrigation systems for precision water management: A systematic review	Inefficient water use in conventional irrigation and variability in smart irrigation outcomes under different conditions.	IoT; soil-moisture sensors; weather stations; cloud computing; machine learning; ET; NDVI; LAI.	Integrating sensors, weather data, cloud platforms, machine learning, evapotranspiration calculations, and vegetation indices.	2026
8	A Systematic Review and Meta-Analysis of Intelligent Irrigation Systems	Water scarcity, climate change, inefficient irrigation, and limitations in existing reviews and agricultural infrastructure.	PRISMA; IoT; AI; remote sensing; Big Data; Blockchain; drones.	Systematically classifying intelligent irrigation research and examining the potential of Fourth Industrial Revolution technologies for sustainable irrigation.	2024
9	IoT Sensing for Advanced Irrigation Management	The need for efficient water management and resource optimization in sustainable agriculture.	IoT sensors; microcontroller units (MCUs); low-power communication protocols.	Integrating IoT sensors and scalable, low-power communication systems for real-time agricultural data acquisition.	2025
10	Artificial intelligence and IoT for water saving in agriculture: A systematic review	The need for water conservation, higher agricultural productivity, and efficient irrigation and fertigation management.	Sensors; data acquisition systems; IoT protocols and architectures; AI models.	Using sensor networks, IoT architectures, and AI models to support irrigation and fertigation decisions and predictions.	2025
11	Internet of Things-Based Automated Solutions Utilizing Machine Learning for Smart and Real-Time Irrigation Management: A Review	Improving water-use efficiency and crop productivity while addressing gaps in real-time, end-to-end automated irrigation.	IoT; machine learning; sensor integration; real-time irrigation systems.	Integrating IoT and machine learning throughout irrigation management, from data collection to water application.	2024
12	Comprehensive Review On Solar Induction Motor Water Pumping System For Irrigation Application	Dependence on fossil fuels and utility grids, electricity shortages, and rising diesel costs in water pumping.	PV technology; DC/AC motors; converters; control techniques.	Using photovoltaic systems to power DC- or AC-motor-driven water pumps for irrigation.	2026

13	Soil Moisture Sensing Technologies: Principles, Applications, and Challenges in Agriculture	Challenges in accurate soil-moisture monitoring and technical, economic, and infrastructural barriers to sensor adoption.	Dielectric; matric potential; heat-pulse; optical fibre; microwave; electromagnetic; radar; biodegradable and MEMS sensors; IoT; AI.	Evaluating soil-moisture sensing technologies and integrating IoT and AI to improve data analytics and sensor calibration.	2025

Discution

The results of the current study provide significant insights into the applications of mechatronics in agricultural pumping and irrigation, highlighting energy efficiency, smart irrigation, and the integration of the Internet of Things (IoT) and artificial intelligence (AI). Recent research indicates that mechatronic systems can enhance energy efficiency by 10% to 30%. Furthermore, these technologies can be integrated to support precision agriculture, sustainable water management, and automated agricultural production. Nevertheless, substantial challenges remain for future development, particularly concerning sensor accuracy, system integration, interoperability, implementation costs, energy requirements, and the technical skills needed.

Conclusion

The review studies the importance of integrating photovoltaic (PV) technology, the Internet of Things (IoT), Artificial Intelligence (AI), and Mechatronic Systems (MTS) to improve agricultural irrigation and resource management.

Solar-powered water pumping systems provide a renewable alternative to conventional diesel-powered pumps, particularly in areas with limited electricity access .

Mechatronic technologies, sensors, data acquisition systems, microcontrollers, and embedded systems support real-time monitoring, remote control, and automated irrigation. IoT and AI, including Machine Learning (ML), contribute to irrigation scheduling, decision-making, evapotranspiration prediction, and water and nutrient management. Water-efficient technologies, including drip irrigation, subsurface drip irrigation, and sensor-based irrigation, help reduce water losses, while their selection depends on land, crops, water availability, and energy resources .

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