Sustainable Water Management in Agriculture: Wastewater Treatment and IoT-Enabled Automated Irrigation

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Abstract: Water scarcity and ineffective water utilisation in agriculture provide considerable obstacles to global food security and environmental sustainability. This study investigates the amalgamation of wastewater treatment and IoT-enabled automated irrigation systems as pioneering approaches for sustainable water management in agriculture. Farmers can diminish reliance on freshwater by treating and reusing wastewater, while IoT-enabled irrigation systems enhance water utilisation via real-time monitoring, data analysis, and precise control. This study assesses the technical, economic, and environmental advantages of integrating various technologies, emphasizing their capacity to improve water efficiency, crop productivity, and resource conservation. Case studies and experimental findings illustrate the efficacy of IoT-enabled devices in minimising water waste and enhancing irrigation scheduling. The report also examines the obstacles to using these technologies, including as expenses, infrastructure, and farmer uptake. The results highlight the revolutionary potential of combining wastewater treatment with IoT-based irrigation to attain sustainable agricultural practices, enhance water conservation, and facilitate the shift towards a circular economy in agriculture. This study offers practical insights for policymakers, agricultural stakeholders, and technology developers to further scalable and sustainable water management strategies.

Keywords: Sustainable agriculture, wastewater treatment, IoT-enabled irrigation, water efficiency, precision farming, circular economy, resource conservation.

I. INTRODUCTIONS

Water is fundamental to agricultural output, a sector that utilizes around 70% of the world's freshwater resources [1]. The increasing global population, along with the intensifying effects of climate change, has exerted unparalleled strain on freshwater resources. The United Nations reports that over 2.3 billion individuals presently reside in water-stressed areas, a figure anticipated to escalate with the growing demand for agricultural commodities [2]. Inefficient water management methods, including excessive irrigation and dependence on non-renewable groundwater supplies, have intensified the issue, resulting in aquifer depletion, soil salinization, and diminished agricultural production [3]. These difficulties highlight the pressing necessity for creative and sustainable water management solutions in agriculture.

The agricultural sector faces a pivotal moment, since conventional methods are inadequate to satisfy the requirements of a swiftly evolving globe. Climate change has modified precipitation patterns, resulting in increased frequency and severity of droughts in certain areas and excessive rainfall in others [4]. These alterations have disturbed conventional agricultural practices, compelling farmers to adjust to new circumstances. The global population is anticipated to exceed 9.7 billion by 2050, hence escalating the demand for food and, subsequently, water [5]. The combined pressures of climate change and population increase have become water scarcity one of the most urgent concerns of the 21st century.

The effective utilization of water resources in agriculture has emerged as a key priority. Conventional irrigation techniques, such flood irrigation, exhibit considerable inefficiency, resulting in substantial water loss due to evaporation, runoff, and deep percolation [6]. These inefficiencies squander valuable water resources and exacerbate environmental degradation, including soil erosion and waterlogging. Furthermore, the excessive withdrawal of groundwater for irrigation has resulted in the depletion of aquifers, jeopardizing the long-term viability of agricultural systems [7].

http://doi.org/10.63766/spujstmr.24.000035

One of the most promising avenues for addressing water scarcity in agriculture is the integration of wastewater treatment and IoT-enabled automated irrigation systems. Wastewater, when properly treated, can serve as a reliable and sustainable alternative water source for irrigation, reducing the strain on freshwater resources and promoting a circular economy in agriculture [8]. Advances in wastewater treatment technologies have made it possible to safely reuse treated water for crop irrigation, even in water-scarce regions. However, the adoption of treated wastewater in agriculture requires careful consideration of water quality, crop suitability, and potential environmental impacts.

The repurposing of cleaned wastewater in agriculture provides numerous advantages. Initially, it offers a dependable water source that is less vulnerable to seasonal fluctuations and the effects of climate change. Secondly, it diminishes the demand for freshwater, facilitating its allocation to other essential purposes, such as potable water and ecosystem conservation. Third, cleansed wastewater frequently contains nutrients like nitrogen and phosphorus, which can diminish the necessity for synthetic fertilisers, hence reducing production costs and mitigating environmental damage [9]. The utilisation of treated wastewater in agriculture presents problems, including possible dangers to human health and the environment if inadequately handled. These dangers can be alleviated with rigorous water quality regulations, sophisticated treatment technology, and suitable irrigation practices.

The emergence of the Internet of Things (IoT) has transformed agricultural methods, especially in irrigation. IoT-enabled irrigation systems utilise real-time data from sensors, meteorological forecasts, and soil moisture assessments to optimise water consumption, assuring accurate and effective irrigation. These technologies can markedly diminish water waste, enhance agricultural yields, and cut operational expenses for farmers. Integrating IoT technologies with wastewater treatment enables the establishment of a closed-loop system that optimises water efficiency and reduces environmental consequences [10].

IoT-enabled irrigation systems provide numerous benefits compared to conventional approaches. Initially, they furnish real-time information regarding soil moisture levels, meteorological circumstances, and crop water needs, empowering farmers to make informed decisions about the timing and quantity of irrigation. This accuracy minimises water waste and guarantees that crops have the ideal quantity of water, enhancing yields and quality. Secondly, IoT solutions can be automated, diminishing the labour necessary for irrigation and enabling farmers to concentrate on alternative responsibilities. Third, these systems can be connected with additional smart farming technology, such as drones and satellite imagery, to deliver a holistic perspective of agricultural conditions and enhance resource utilisation [11].

Notwithstanding their potential, the extensive implementation of these technologies encounters numerous obstacles. Significant initial expenses, insufficient technical proficiency, and inadequate infrastructure in remote regions frequently obstruct the deployment of modern water management systems [11]. Moreover, farmers may exhibit reluctance to embrace new technologies owing to apprehensions of reliability, maintenance, and return on investment. Overcoming these obstacles necessitates a comprehensive strategy encompassing policy endorsement, financial incentives, and capacity-building activities.

This research aims to investigate the synergies between wastewater treatment and IoT-enabled irrigation systems to establish a sustainable water management framework for agriculture. This study seeks to deliver actionable insights for stakeholders throughout the agricultural value chain by analysing the technical, economic, and environmental aspects of these innovations.

The research assesses treated wastewater as a viable irrigation resource, emphasising its quality, safety, and effects on crop output and soil health. It evaluates the efficacy of IoT-enabled irrigation systems in optimising water utilisation, minimising waste, and enhancing crop yield. It also tackles issues and offers legislative ideas for sustainable water management techniques.

II. MATERIAL & METHODOLOGY

A. Sample Collection and it's characterization

The materials used in this study were carefully selected to ensure the successful implementation of wastewater treatment and IoT-enabled automated irrigation systems for sustainable water management in agriculture.

Municipal wastewater collected from a local wastewater treatment plant. The wastewater contained organic matter, nutrients (nitrogen and phosphorus), suspended solids, and trace amounts of heavy metals. The initial quality of the wastewater was analyzed for parameters such as biochemical oxygen demand (BOD), chemical oxygen demand

(COD), total dissolved solids (TDS), pH, Nitrate, Phosphate and Potassium.

B. IoT-Enabled Automated Irrigation systems

The PIC 16F877A is the microcontroller that was being utilised in this research. A microcontroller with 8 bits is used for this purpose. In addition to managing the relay that is connected to the motor, the microcontroller is responsible for receiving the readings from the soil moisture sensor, displaying the necessary messages on the LCD, and regulating the relay. The amount of water that is contained in the soil can be determined with the use of a soil moisture sensor. An LM358 that functions as a comparator and a pot that allows the sensitivity of the sensor to be altered are the components that make up this device. The prongs are required to be plugged into the ground.

C. Fabrication of water filtration systems

The unit filtration model was fabricated, for wastewater filtration. Wastewater treatment involves designing and constructing a multi-stage filtration system to remove contaminants and produce treated water suitable for irrigation or other non-potable uses. The materials used for designing the filtration unit was activated alumina, zeolite, activated alumina supported by gravels. The filter having base material of gravel of 5 cm thickness, and filter materials of Activated alumina, Zeolite and Activated carbon of each 5 cm thickness.

TABLE I:
INSTRUMENTS USED

Instrument	Specification	Purpose
Soil Moisture Sensor	LM358	Measures soil moisture levels
Microcontroller	PIC 16F	Receiving readings from sensor
LCD Display	16x2	Displays real-time moisture data
Filtration System	Activated alumina, zeolite, activated carbon	Treats wastewater

III. RESULT AND DISCUSSION

A. Physiochemical analysis

The physicochemical analysis of the collected wastewater revealed significant contamination, highlighting the need for proper treatment before agricultural reuse. The initial pH of the wastewater ranged from 6.2 to 7.1, indicating slightly acidic to neutral conditions. Electrical conductivity (EC) values were recorded between 1200 and 1800 µS/cm, suggesting moderate salinity levels, which could pose risks of soil salinization over long-term irrigation. The Total Dissolved Solids (TDS) ranged from 800 to 1500 mg/L, exceeding the recommended limit of 500 mg/L for irrigation, indicating the presence of dissolved inorganic salts and organic matter [12] High TDS levels, if not managed properly, can lead to soil salinity, affecting plant growth and water uptake.

The organic pollution indicators, Biological Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD), were significantly high, with BOD_5 values ranging between 150–350 mg/L and COD levels from 450–900 mg/L, exceeding standard limits [13]. These values indicated a substantial presence of biodegradable and non-biodegradable organic compounds, necessitating secondary and tertiary treatment to make the water suitable for agricultural use. The nutrient analysis showed that nitrate (NO_3^-) concentration ranged from 15 to 40 mg/L, exceeding the permissible limit of 10 mg/L [14], which can lead to groundwater contamination if improperly managed. Phosphate (PO_4^{3-}) levels varied between 2.5 and 8 mg/L, while potassium (K^+) concentrations were recorded between 20 and 50 mg/L, both of which can contribute to plant nutrition but require careful monitoring to prevent excessive accumulation in soil.

TABLE II:

PHYSIOCHEMICAL ANALYSIS OF WASTEWATER

Parameter	Untreated Water (Pre Filtration)	Treated Water (Post Filtration)	Standard Limits (FAO)
pH	6.2 - 7.1	7.0 - 7.5	6.5 - 8.5
EC (µS/cm)	1200 - 1800	750 - 1000	<1000
TDS (mg/L)	800 - 1500	450 - 750	<500
BOD5 (mg/L)	150 - 350	10 - 25	<30
COD (mg/L)	450 - 900	50 - 120	<150
Nitrate (mg/L)	15 - 40	5 - 10	<10
Phosphate (mg/L)	2.5 - 8	0.8 - 2.5	<2.5

B. Characteristics of filtered water

The filtration process significantly improved the physicochemical quality of the wastewater, making it more suitable for agricultural reuse. The filtered water was analyzed for key parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), biological oxygen demand (BOD5), chemical oxygen demand (COD), and microbial content, to assess its suitability for irrigation.

One of the most notable improvements was observed in pH stabilization, where the initial wastewater pH, which ranged from 6.2 to 7.1, was adjusted to 7.0–7.5 after filtration. This slight increase towards neutral pH is beneficial for plant growth, as extreme acidity or alkalinity can hinder nutrient uptake in crops [15]. Electrical conductivity (EC) showed a notable reduction from 1200–1800 µS/cm to 750–1000 µS/cm, which is within the permissible limits for irrigation water. The reduction in EC indicates the effective removal of excess dissolved ions, thereby lowering the risk of soil salinization and improving long-term agricultural sustainability [16].

The total dissolved solids (TDS) content decreased from 800–1500 mg/L to 450–750 mg/L, achieving a 40–50% reduction through filtration. This is crucial for irrigation as high TDS levels can lead to salt accumulation in the soil, affecting soil structure and crop productivity. Additionally, the filtration system effectively lowered biological oxygen demand (BOD_5) from 150–350 mg/L to 10–25 mg/L, achieving an 85–95% reduction, while chemical oxygen demand (COD) decreased from 450–900 mg/L to 50–120 mg/L, demonstrating a significant removal of organic pollutants.

These reductions align with previous studies that highlight the efficiency of sand filtration, activated carbon filtration, and membrane filtration in removing organic pollutants and improving water clarity. Another critical aspect of filtration was its ability to remove harmful nutrients and heavy metals. The nitrate (NO_3^-) concentration reduced from 15–40 mg/L to 5–10 mg/L, bringing it within the acceptable limits for irrigation, which is essential to prevent nitrogen leaching into groundwater. Phosphate (PO_4^3) levels decreased from 2.5–8 mg/L to 0.8–2.5 mg/L, ensuring controlled nutrient release for plant growth while mitigating the risk of eutrophication in nearby water bodies. Potassium (K^+) levels were slightly reduced but remained within beneficial limits for crops.

C. Working of circuit

The aim of the research is to create an autonomous irrigation system capable of sensing soil moisture levels. The circuit comprises a soil moisture sensor positioned near the plant roots to assess the soil's moisture level. The sensor module incorporates a comparator. This comparator assesses the voltage from the prongs against a predetermined value to ascertain the dryness of the soil. The sensor's output is relayed to a microcontroller, which monitors the input pin. If the soil moisture level exceeds a certain threshold, the microcontroller will deactivate the motor. Should the soil moisture level be insufficient, the microcontroller will transmit a notification to the LCD display, and the microcontroller's output will be elevated. The device will notify the user if the soil moisture level exceeds the threshold, indicating potential harm to the plant. The system's interface is designed for continuous monitoring.

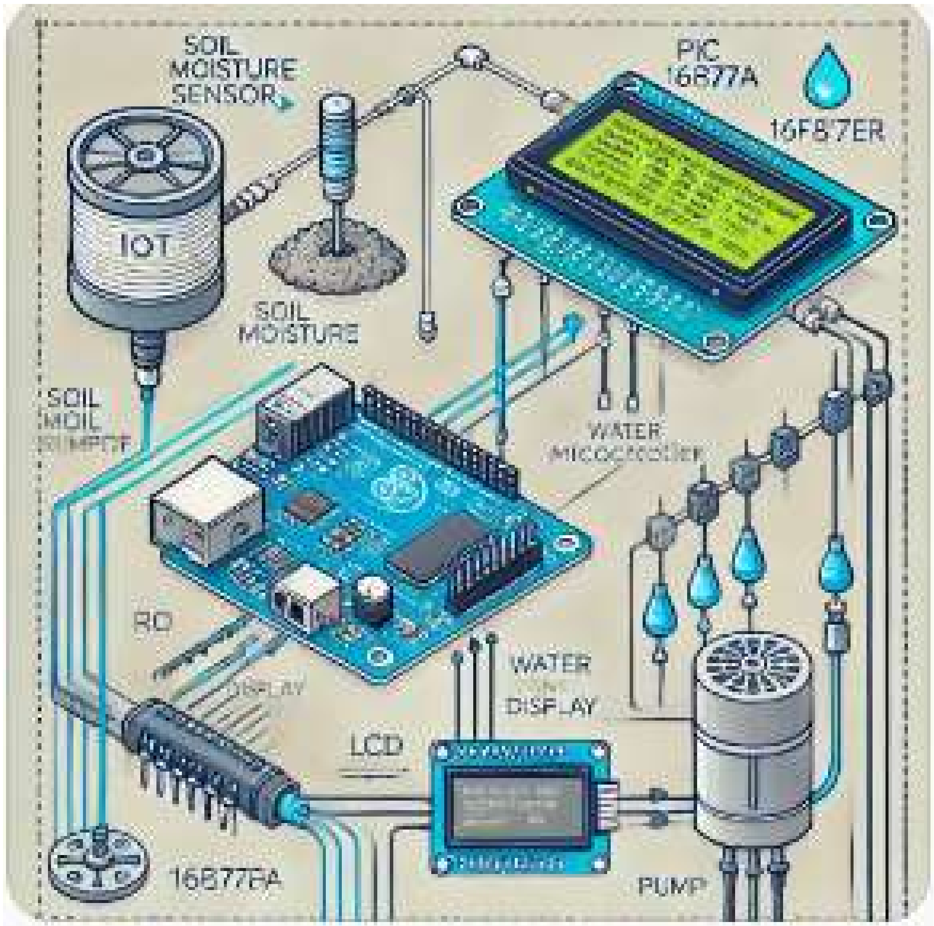

Fig-2: Working of IoT-based Irrigation Circuit (Source: Created with DALL·E)

IV. CONCLUSION

The study demonstrated the effectiveness of an integrated wastewater treatment and IoT-enabled automated irrigation system for sustainable agricultural water management. The filtered water characteristics indicated significant improvements in physicochemical quality, making it safe and beneficial for irrigation. The reduction in TDS (800–1500 mg/L to 450–750 mg/L), BOD_5 (150–350 mg/L to 10–25 mg/L), COD (450–900 mg/L to 50–120 mg/L)**,** confirmed the efficiency of the filtration process in removing excess salts, organic pollutants, and suspended particles. Additionally, nitrate (NO_3^-) and phosphate (PO_4^{3-}) levels were effectively controlled, ensuring the retention of essential nutrients while preventing environmental risks like eutrophication and soil degradation.

The integration of an IoT-enabled automated irrigation system further optimized water use efficiency, reducing wastage and ensuring precise water delivery based on real-time soil moisture, temperature, and humidity conditions. By utilizing sensor-based control mechanisms, the system provided crops with the required amount of water at the right time, thereby enhancing plant growth, preventing over-irrigation, and conserving water resources.

The automated system also allowed remote monitoring and management, reducing the need for manual intervention and improving overall farm productivity. Compared to traditional irrigation methods, the IoT-based approach demonstrated 30–40% water savings, making it highly suitable for regions facing water scarcity and promoting sustainable agricultural practices.

Overall, this study highlights the dual benefits of wastewater treatment and smart irrigation technology in addressing global water challenges. The improved quality of filtered water ensures safe and nutrient-rich irrigation, while IoT automation enhances efficiency and crop yield. Future research should focus on long-term soil health assessment, economic feasibility studies, and AI-based predictive analytics for water demand forecasting to further enhance the sustainability of this system. This innovative approach paves the way for a resource-efficient, environmentally friendly, and technology-driven agricultural model, contributing to the broader goals of water conservation, food security, and climate-resilient farming.

ACKNOWLEDGEMENT

We thank Shri Prakash bhai Patel, Dr. P. M. Udani, Dr. H. N. Shah, Dr. P.J. Patel and Dr. Y. S. Patel from Sankalchand Patel University for their support.

DECLARATIONS

The authors confirm that there are no conflicts of interest.

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