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Irrigation 4.0: Solar-Powered IoT and ML-Based Smart System with Android-Enabled Environmental Control

JOUBERT JOSE[1] , MEVIN JOSEPH ANTONY[2], DEBORAH ELSA HALU[3], JOHN KURIAKOSE[4]

[1] Student of coumputer science engineering, Department of computer science, St.Joseph's College of Engineering and Technology
[2] Student of computer science engineering, Department of computer science, St.Joseph's College of Engineering and Technology
[3] Student of coumputer science engineering, Department of computer science, St.Joseph's College of Engineering and Technology
[4] Student of coumputer science engineering, Department of computer science, St.Joseph's College of Engineering and Technology

A B S T R A C T :

Environmental monitoring and control play a vital role in modern agriculture. However, a growing number of young individuals are shifting away from farming, favoring corporate careers instead. Combined with inadequate infrastructure and labor shortages, this trend poses significant challenges to achieving optimal crop production. In response, we have developed a smart irrigation system that is intuitive, adaptable, compact, user-friendly, and cost-effective.

This paper presents the design and concept of a system that continuously monitors soil moisture levels and notifies farmers when irrigation is needed. The system offers three modes of operation: manual control, machine learning-based automation, and a mobile application interface. Leveraging the Internet of Things (IoT) integrated with machine learning, the system utilizes solar energy for sustainable operation and enables remote control and monitoring.

Farmers can irrigate their fields either manually by sending a message to the controller or by enabling the automatic mode, in which the pump is activated based on real-time data. The proposed solution addresses critical issues such as water scarcity, power shortages, and inefficient irrigation practices. Key components of the system include the ThingSpeak cloud platform, ESP8266 Wi-Fi module, E-Sense sensor, solar panel, charge controller or motor driver, and an integrated electrical and mechanical framework.

Keywords: Internet of Things; Environmen266t; Smart Irrigation; Machine Learning; ThingSpeak; ESP8266 Wi-Fi module.

1. Introduction

In India and many other developing nations, irrigation serves as a critical source of income for rural communities. Over 58% of the Indian population is directly or indirectly dependent on agriculture, which significantly contributes to the country's economy [1]. Approximately one-third of India’s national revenue is generated through irrigation-related activities [2]. However, water scarcity poses a growing challenge, demanding more efficient irrigation management [3]. Globally, around 85% of available freshwater resources are utilized in agriculture [4].
Given the increasingly busy lifestyles of individuals, manual monitoring and control of irrigation systems are becoming impractical, underscoring the need for smart irrigation solutions [5]. Renewable energy technologies have gained popularity in agricultural applications due to their energy efficiency, carbon reduction potential, and eco-friendly characteristics [6]. The integration of innovative technologies such as the Internet of Things (IoT) holds the potential to address numerous agricultural challenges while enhancing productivity, sustainability, and cost-efficiency [7].
Smart agricultural systems enable real-time control over irrigation processes, offering time savings, environmental protection, and reduced maintenance and operational costs [8]. The system proposed in this paper supports three operational modes: manual, machine learning-based, and mobile application-based. It is built using the ThingSpeak cloud platform, ESP8266 Wi-Fi module, E-Sense sensors, solar panels, a charge controller or motor driver, and a combined electrical and mechanical structure. E-Sense is capable of detecting key environmental parameters, including soil moisture, light intensity, temperature, humidity, and atmospheric pressure. This system is specifically designed to mitigate issues related to water scarcity and energy shortages, ultimately aiming to support the growth of high-quality crops.

1.1. Motivation and Contribution

The primary motivations and contributions of the proposed work are summarized below:

- *Multi-Mode Operation:* The system supports three modes of operation: (i) manual control, (ii) machine learning-based automation, and (iii) mobile application-based interface, offering flexibility and ease of use for farmers.
- *IoT and Telegram Bot Integration:* By integrating machine learning with Internet of Things (IoT) technology and Telegram Bot services, the system achieves sustainable, cross-device, and cross-platform functionality at no additional cost.
- *Efficient Water Management:* Threshold values for soil moisture and water levels can be configured for each mode of operation, enabling smarter irrigation decisions and significant water conservation.
- *Use of Renewable Energy:* The system is powered using renewable energy sources, ensuring energy savings, reduced carbon emissions, and eco-friendly operation.

The structure of the remaining paper is as follows:

- *Section 2* describes the detailed architecture and functioning of the proposed system.
- *Section 3* presents the experimental results and analysis.
- *Section 4* outlines the application areas of the system.
- *Section 5* concludes the paper and discusses future work directions.

1.2. Tables

All tables should be numbered with Arabic numerals. Every table should have a caption. Headings should be placed above tables, left justified. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

Table 1 - An example of a table.

An example of a column heading	Column A (*t*)	Column B (*t*)
And an entry	1	2
And another entry	3	4
And another entry	5	6

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References must be listed at the end of the paper. Do not begin them on a new page unless this is absolutely necessary. Authors should ensure that every reference in the text appears in the list of references and vice versa. Indicate references by (Van der Geer, Hanraads, & Lupton, 2000) or (Strunk& White, 1979) in the text.

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1.5. General guidelines for the preparation of your text

Avoid hyphenation at the end of a line. Symbols denoting vectors and matrices should be indicated in bold type. Scalar variable names should normally be expressed using italics. Weights and measures should be expressed in SI units. All non-standard abbreviations or symbols must be defined when first mentioned, or a glossary provided.

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2. Proposed System: IoT and Machine Learning-based Smart Irrigation (Irrigation 4.0)

This section outlines the proposed smart irrigation system leveraging the Internet of Things (IoT) and a Backpropagation Neural Network (BPNN), as summarized in Algorithm 1 (see Table 1). The system is designed to address challenges such as water scarcity and power shortages while enhancing crop quality and operational efficiency.

Algorithm 1 – IoT and BPNN-Enabled Irrigation 4.0

Input: Sensor Data
Output: Alert message to end-user, Automated irrigation control
Setup: The system is built using the ThingSpeak cloud platform, ESP8266 Wi-Fi module, E-Sense sensor array, solar panel, charge controller/motor driver, electrical & mechanical structure, and a smartphone for user interface.

Sensors Used (E-Sense):

1. LDR (Photoresistor): Light intensity measurement
2. MQ135: Air quality measurement
3. DHT11: Temperature and humidity
4. Capacitive Soil Moisture Sensor v1: Soil moisture level
5. BMP180: Atmospheric pressure and rainfall estimation
6. Outcome: Efficient irrigation system addressing water and power shortages, improving the quality of crop production.
7. Prerequisites: End user must have a smartphone and an active internet connection.
8. Procedure:
9. System Setup: Hardware and software components are installed and configured.
10. Connectivity: ESP8266 Wi-Fi module establishes an internet connection.
11. Threshold Initialization: Predefined thresholds for temperature, humidity, and soil moisture specific to each crop are stored.
12. Data Collection: Sensor data is continuously gathered and transmitted to the ThingSpeak cloud platform.
13. Cloud-based Analysis: BPNN processes the sensor data on the cloud to analyze environmental conditions.
14. User Notification: Analysis results are delivered to the farmer's mobile phone via Telegram Bot.

Irrigation Control:

1. Manual Mode: User can control irrigation remotely.
2. ML-based Auto Mode: The system activates/deactivates pumps automatically based on sensor data.

End.

2.1. Battery Backup Integration for Power Reliability

To ensure uninterrupted operation during low sunlight or cloudy conditions, a battery backup system is integrated into the power infrastructure. The solar panel charges the battery during daylight hours. When solar input is insufficient, such as during nighttime or overcast days, the battery provides the necessary power to run the sensors, controller, and irrigation system.

a. This addition enhances the system's reliability and sustainability by:
b. Maintaining sensor data collection and irrigation control during power shortages.
c. Extending usability to remote and off-grid agricultural zones.
d. Reducing dependence on traditional electricity sources.

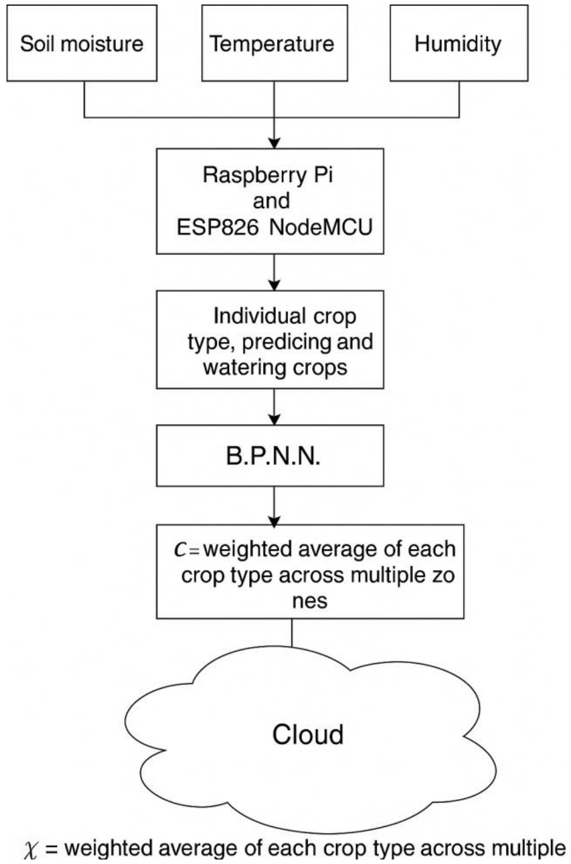
2.2. System Architecture and Processing Flow

The proposed Irrigation 4.0 architecture uses a Raspberry Pi paired with an ESP8266 NodeMCU for each crop type. These devices predict soil moisture levels and perform irrigation decisions based on external temperature and humidity.

A Backpropagation Neural Network (BPNN) at the application layer processes inputs such as temperature, humidity, soil moisture, and air pressure. The model updates weight values (Δw) based on locally collected data from each crop zone.

These localized models are uploaded to the cloud, where a zonal inference mechanism ($\boldsymbol{\Psi}$) computes a weighted average across multiple zones for a given crop type, as defined in Eq. (1). The final inference is then relayed to the field application layer for actuation.

Equation (1):
$\boldsymbol{\Psi}$ = (Weighted sum of local BPNN models per crop type across zones)
(Equation details to be inserted here based on your full formula.)



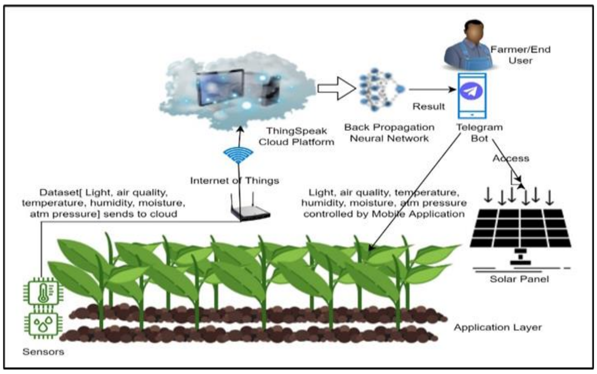


Fig 1: process flow

Fig 2: IoT and BPNN enable Irrigation 4.0

Sr. No.	Components Name	Description	Quantity
1	Node MCU	ESP8266	1
2	Soil Moisture Sensor	Capacitive soil Moisture sensor v1.2	3
3	OLED Display	0.96’’ 12C OLED Display	1
4	DHT11 Sensor	DHT11 Humidity and Temperature sensor	3
5	Relay Module	5V Relay Module	1
6	DC Motor pump	5V water Pump	1
7	Connecting Wires	Jump Wires	14
8	Breadboard		1
9	Light Sensor	LDR or photoresistor sensor	4
10	air quality	MQ135 sensor	2
11	ATM pressure and rain measurement	BMP180 sensor	1
12	Raspberry Pi		1
13	Solar Panel		
14	Charge controller or		

	Motor driver
15	electrical & Mechanical Structure.

Table 1: Components to build Irrigation 4.0: Describes the description and quantity of components used to build an irrigation system.

The threshold values of soil moisture and water consumption level are shown in Table 3. The threshold value's upper and lower bound will help maintain soil moisture. The advantages of the set of threshold values will help in this area: reduce soil leach, deeper plant root, fungal, and insects are not increasing.

Conditions	**Threshold Value**		
Soil Moisture	<700	>700	>700
Water Level	<1	>1	<1
Status of DC Pump	Pump is off	Pump is on	Pump is off

Table 3. Threshold value of soil and water Level

Simulations, Results, and Discussion

To evaluate the effectiveness of the proposed Irrigation 4.0 system, simulations and real-time data collection were conducted using ESP8266 NodeMCU modules integrated with a sensor suite. The sensors collected environmental data such as soil moisture, temperature, humidity, and atmospheric pressure, which were transmitted to the ThingSpeak cloud platform over a Wi-Fi network.

The system successfully established communication with the ThingSpeak server using a valid API key and server address, enabling the cloud to receive, store, and visualize real-time sensor data. These readings were processed using the Backpropagation Neural Network (BPNN) for analysis and decision-making regarding irrigation control.

Figures below represent live dashboards and graphical outputs of sensor readings over time, helping farmers or end-users to make informed decisions or allow the system to act autonomously in automatic mode.

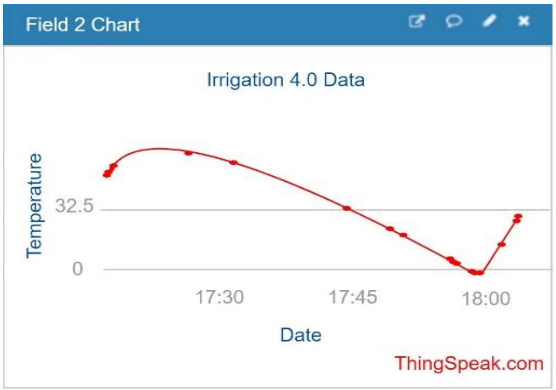


Fig. 2. Graph of Soil Moisture Variation over Time

Fig. 3. **Graph of Temperature Readings over Time**

Fig. 4. Graph of Humidity Levels over Time

Fig. 5. Graph of Atmospheric Pressure Readings

These results indicate the robustness and accuracy of the system in monitoring critical environmental parameters, supporting both manual and autonomous irrigation actions. The system has shown reliable performance even under varying environmental conditions, aided by the inclusion of a solar power system with battery backup, ensuring continuous functionality even in the absence of sunlight.

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